European Commission

EURADWASTE '19

9th European Commission Conference on EURATOM Research and Training in Radioactive Waste Management

Co-organised by the European Commission and the Romanian Presidency of the Council of the EU in 2019

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RATEN ICN PITEȘTI
INSTITUTUL DE CERCETĂRI NUCLEARE

in cooperation with

ENS
EUROPEAN NUCLEAR SOCIETY

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4-7 June 2019
Pitesti, Romania

CONFERENCE PROCEEDINGS

Research and Innovation

EURADWASTE '19 Conference Proceedings

European Commission
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CONFERENCE PROCEEDINGS
EURADWASTE '19

edited by Daniela Diaconu and Alina Constantin, RATEN ICN, Pitesti, Romania

Directorate-General for Research and Innovation
2020 Euratom Research and Training Framework Programme

FISA 2019
EURADWASTE '19

4-7 June, 2019
Pitesti, Romania

Foreword

It is our pleasure to introduce these proceedings of the 9th European Commission Conferences on EURATOM Research and Training in Safety of Reactor Systems and Radioactive Waste Management. FISA and EURADWASTE conferences have always been a major milestone on the EU/Euratom agenda, gathering on a regular basis research and training organisations, academia, industry, technology platforms, European fora and European civil society, and International Organisations, participating in Euratom Framework Programmes'. The key of their success lies in coherently summarising most activities and highlighting major achievements of the main pillars of the EU/Euratom Fission Programmes, on safety of reactor systems and radioactive waste management. Following the successful edition in 2013, in Lithuania, these two major events are organised jointly with the Romanian Presidency of the Council of the EU in 2019.

All balanced energy mix scenarios elaborated in Europe on a strategic long-term vision for a prosperous, modern, competitive and climate-neutral economy by 2050 include nuclear energy. While it is for each EU country to choose whether to make use of nuclear power, it remains the role of the European Union, together with its Member States and in the interest of all its citizens, to establish a framework to further develop and support EU/Euratom research and training. The European Union has since long recognised its importance and benefits also through international cooperation.

FISA 2019 EURADWASTE '19 plenary introduction and closure provided an opportunity for both communities to gather, to exchange their views on shared challenges and opportunities in EU/Euratom research and training. Stakeholders' and policy makers' participation contributed to setting the scene at EU / national / international levels and illustrating high benefits from cooperation by supporting, among others, today's Energy/Climate/Industrial policies and to tackle today's societal challenges. It also proved EU/Euratom constant success in pursuing excellence in R&D whilst facilitating pan-European collaborative efforts across a broad range of nuclear science and technologies, nuclear fission and radiation protection.

FISA 2019 EURADWASTE '19 parallel sessions facilitated detailed presentations and panel discussions on the latest achievements, main results and success stories, as well as key recommendations in the respective areas, of some 90 projects carried out, since the previous conference edition in 2013, as part of the 7th and Horizon 2020 Euratom Research and Training Framework Programmes (FP). They were aimed at demonstrating that the knowledge base has advanced significantly, and continuity between actions co-funded over time through the Euratom Framework Programmes guarantees a high impact and is of great added value to the scientific community. It also showed a capacity is maintained to suitably respond to any unexpected event or new EU/Euratom legislative Directives requirements such as the implementation of dedicated research and innovation (or coordinated and support) actions in response to the 2011 Fukushima Daichi accident.

With the incentive of Horizon 2020, Framework Programmes enhance further integration towards a European Research Area together with better prioritisation at European level, with the capitalisation of European Technology platforms and in close collaboration with International Organisations or Fora. Evolutions towards European Joint Programmes, together with Member States research and innovation programmes, were successfully illustrating the added value of a concerted European approach in nuclear safety research and training advocated by the European Commission and Member States.

FISA and EURADWASTE were also a unique opportunity for students, PhD, MSc or young professionals to take part in the ENEN PhD Event & Prize, FISA 2019 and EURADWASTE '19 Poster and PhD awards, and FISA 2019 thematic workshops addressing cross-cutting research and innovation areas of common interest and providing recommendations for the future. The finalists were selected and invited by a jury (Programme Committee) and awards were presented at the joint closing plenary session. The awarded paper were published in the European Physical Journal (EPJ N, EPJ Nuclear Sciences & Technologies), alongside this special edition of EPJ-N.

Participants were also able to participate in a technical tour of the nuclear facilities at Institute for Nuclear Research Pitesti (RATEN-ICN), the Nuclear Fuel Plant (FCN Pitesti), the Cernavoda Nuclear Power Plant and waste management facilities, or the Extreme Light Infrastructure – Nuclear Physics (ELI-NP) in Bucharest, one of the most advanced research facilities in the world focusing on the study of photonuclear physics and its applications.

The European Commission would like to thank the Romanian Presidency, the Ministry of Research and Innovation of Romania and the Institute for Nuclear Research (RATEN-ICN) for hosting the conferences in Pitesti and for the co-organisation of these events. We would also like to extend our gratitude to the speakers, chairs and co-chairs, expert reviewers of all papers and presentations, rapporteurs, projects coordinators, panel members, ENS but also all staff involved at any time whose contribution ensured that the FISA 2019 EURADWASTE '19 Conferences were engaged with the audience in an enjoyable, dynamic and interactive way, ensuring success of these conferences!

All reviewed papers were published in a special edition of EPJ-N and they are the result of a common effort of all partners involved. Thanks are due to many researchers, authors and the peer reviewers for the time and effort they spent to make this special issue possible, to Gilles Moutiers and Anne Nicolas, Editors in Chief of EPJ-N, for providing the opportunity to produce a special issue, to Mr Roger Garbil and Christophe Davies of the European Commission in Brussels for their active participation in the editorial process. Finally, Ms Daniela Diaconu of the Nuclear Research Centre RATEN-ICN has to be gratefully acknowledged for making the FISA 2019 EURADWASTE '19 Conferences a reality, in Pitesti, in Romania, and another key milestone of the Euratom Research community!

Roger Garbil and Christophe Davies
(EC DG RTD, FISA 2019-EURADWASTE '19 Co-chairs)

Daniela Diaconu
(RATEN-ICN and Romanian Presidency, Co-chair)

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FISA 2019
EURADWASTE '19

4-7 June, 2019
Pitesti, Romania

Hans FORSSTRÖM

International independent expert, Sweden - General Rapporteur

SUMMARY REPORT OF THE EURADWASTE ’19 CONFERENCE

Introduction

The EURADWASTE ’19 conference, which was the 9th European Commission Conference on EURATOM Research and Training (R&T) in Radioactive Waste Management was organised jointly with FISA 2019 on Research and Innovation for Nuclear Reactors. This provided a good opportunity for cross contacts between those who produce most of the radioactive waste and those who will take care of and dispose of the waste. In the FISA conference, information was provided on the development status for reactor and fuel management systems with the potential to alleviate the long-term challenges for disposal of the radioactive waste, while in EURADWASTE the developments on geological disposal were reported.

Since the earlier EURADWASTE conferences important developments have taken place and good progress has been made both in the actual implementation of management and disposal of radioactive waste in the EU Member States (MS), and in the organization of the cooperation in research and development and training between the EU MS.

In his keynote speech on the status of management and disposal worldwide Mr Pierre-Marie Abadie, CEO for the French waste management organisation ANDRA, made the following observations:

- Low Level Waste is already adequately and safely disposed in many existing facilities throughout the world.
- Intermediate and High Level Waste and Spent Nuclear Fuel can be safely disposed in deep geological repositories (DGRs). The knowledge exists and the development of DGRs is progressing. In three MS, Finland, France and Sweden, the projects are in advanced stages of implementation. Sites have been chosen and operation is planned for 2025/30. Other MS have a longer time schedule and are still in the siting or pre-siting phase. In the USA one repository for Intermediate Level Waste, the WIPP facility, is in operation.
- As more and more nuclear reactors and other facilities will be decommissioned and subsequently dismantled large volumes of Very Low Level and Low Level Waste are foreseen. As they will appear in a fairly short time span an efficient system for characterisation and treatment will be required to optimize the waste routes.
- Some long-lived waste with low activity, but with large volumes (e.g. graphite, depleted uranium and NORM), will require new appropriate disposal routes.

- In non-nuclear countries the most important radioactive waste is radioactive sources used in medicine, research and industry. Special appropriate solutions will be required for these, e.g. disposal in boreholes as developed by the IAEA.
- The long duration of disposal projects (>100 years) will require a strong knowledge management process to transfer knowledge and experiences between generations.

To support the development and implementation of safe management and disposal of different types of radioactive waste substantial R&D has been carried out and further R&D continues to be important. Although most of this R&D is financed nationally the EURATOM R&T programme in radioactive waste management plays an important role to foster collaborative R&D and improve coordination of R&D, as well as to transfer knowledge and experiences between the front runner countries and the countries with a smaller programme and/or a longer time schedule for implementing their disposal programme.

As stated in the EURATOM Framework Programme the objectives of the activities supported by the EURATOM research and training programme are:

"Contributing to the development of safe, longer-term solutions for the management of ultimate nuclear waste, including final geological disposal as well as partitioning and transmutation."

Over the years the EURATOM R&T programme has developed from supporting several projects for coordinated R&D on specific issues to an European Joint Programming of the R&D activities in radioactive waste management across Europe involving Waste Management Organisations (WMOs), Technical Support Organizations (TSOs), Research Entities (Res) and representatives from the civil society.

During the conference reports were presented on the activities leading up to the establishment of the European Joint Programming project (EURAD). Also reports on specific research projects supported by EURATOM were reported.

The EURADWASTE '19 conference was thus structured in four oral sessions:

- Overview and policy: International/EU/EURATOM status in radiation protection, safety of reactor systems and radioactive waste management (jointly with FISA 2019).
- Technology: Predisposal and disposal technology developments.
- Science: Radioactive waste source term and science for disposal safety.
- Organisation: Networking of research communities, joint programming of national programmes and integration of radioactive waste producers.

During these sessions the results from several recently finished and on-going research projects were presented orally and in posters. Especially encouraging was the many good quality PhD-posters that were presented, not least in view to ensure human capacity for the **future.**

2. Main messages from EURADWASTE '19

Recent developments

Since EURADWASTE '13 some important developments have taken place which influences the implementation of radioactive waste disposal and the accompanying R&D. Some of them are:

- The EURATOM Directive on responsible and safe management of spent fuel and radioactive waste has become operational. The first national reports on the implementation of the Directive nationally have been submitted to and evaluated by the European Commission, including the national programmes for management and disposal of all types of spent fuel and radioactive waste. The first report on the implementation of the Directive was presented to the Council and the European Parliament in 2017. A second report is due in 2019.

- The Directive requires that a peer review of the national situation and plans is performed at least every ten years. The IAEA has developed the ARTEMIS peer review service, which has already been used by a number of MS and is planned by others.
- In Finland a construction licence has been issued for a DGR and construction work has commenced. Good progress is being made in Sweden and France towards licensing of DGRs. In other MS progress can be seen on siting programmes.
- More reactors than earlier planned have been, or will in the short term be, shutdown in several MS, which means that the planning to manage and dispose of the waste from dismantling in an efficient way has become very important.
- The progress towards an European Joint Programming involving WMOs, TSOs, research entities and representatives from the civil society has been good and funding has been provided to the EURAD project to propose, plan and manage all EURATOM funded projects in radioactive waste management. For this purpose, a Strategic Research Agenda and a roadmap has been developed.

All these issues were presented and discussed during the EURADWASTE ’19 conference.

Main messages

The main messages from the conference can be summarised as follows:

- The EURATOM R&T programme in radioactive waste management remains very important, in spite that more than 90 % of the R&D funding is national. The programme helps to coordinate R&D, to transfer knowledge and experiences, and to foster cross-fertilisation between the front runner countries and the countries with a longer time scale.
- The landscape is changing as several DGRs are being implemented, but this doesn´t stop the needs for further development of science. Recurrent safety assessments will continue to be made. All countries thus need to keep abreast of the knowledge development.
- This development provides more opportunities for cross-fertilisation including transfer of knowledge and know-how to countries with longer time scales.
- The long time schedules for construction and operation of disposal facilities (> 100 years) puts important demands on knowledge management and the need to ensure the availability of capable people in the long future.
- In the context of knowledge management it is important to distinguish between information management, which can be handled with IT tools, and the management of know-how, which requires transfer of knowledge and experiences between people.
- The EURATOM programme has an important role in this regard, both to support R&D and collect important information, and to transfer of know-how through networking and mobility schemes.
- A step change has been introduced in the management of the EURATOM R&T programme in RWM, as the European Joint Programming project EURAD became

active in June 2019. This project involves all actors with an official role in their respective national programme in R&D for radioactive waste management, i.e. WMOs, TSOs, Research Entities and representatives from the civil society. EURAD has developed a Strategic Research Agenda and a road-map for implementation of activities of European added-value between Member States with support of the EURATOM Programme.

- The development of EURAD has a long history starting with the co-operation between WMOs through Implementing Geological Disposal –Technology Platform (IGD-TP), followed by similar cooperation between TSOs in the SITEX project. Both activities, which were originally supported with EURATOM funding, are now continuing through self-sustained fora. Also, the research entities have organised themselves and set up EURADSCIENCE.
- IGD-TP, SITEX and the Research Entities have developed their own Strategic Research Agendas, which have been introduced into EURAD. Input has also been given by civil society groups.
- The latest EURATOM R&T programmes have mostly dealt with issues connected to deep geological disposal. Taking into account interest expressed by several actors the programme is now being widened to also include pre-disposal radioactive waste management, decommissioning and legacy waste management.

In the following the main outcomes and conclusions from the different sessions are described. More details are given in separate reports later in this book.

3. Overview and policy session

The session on International/EU/EURATOM status in radiation protection, safety of reactor systems and radioactive waste management covered several topics:

- Implementation of the different EU/EURATOM Directives
- EU R&T programme in nuclear area and in particular on radioactive waste
- The view of the EURATOM Scientific and Technical Committee (STC), and
- A keynote speech on European and International status on RW management and disposal and challenges ahead.

The highlights and main messages were:

Waste Directive

The purpose of the Waste Directive is to ensure appropriate national arrangements for a high level of safety and to avoid imposing undue burdens on future generations. It should also ensure public information and participation.

Each MS shall have a national programme for the management and disposal of all types of spent fuel and radioactive waste.

The first national reports on the implementation of the Directive and the national programmes were made to the European Commission in 2016, The Commission subsequently reported to the Council and European Parliament in 2017. A new report is due in 2019.

Together with the EC, the IAEA has developed a peer review service, ARTEMIS, which has been used already by several States as required in the Directive.

Development of European Joint Programme

Since its start in 1975 the EURATOM R&T programme on radioactive waste management has progressed from a large number of uncoordinated projects to the call for one European Joint Programme in 2018, which brings together WMOs, TSOs, REs and representatives from the civil society.

This closer cooperation has developed successively over a long period, starting in the early 2000s between WMOs and then through platforms and networks like the IGD-TP for the WMOs, SITEX for TSOs and recently EURADSCIENCE for the REs.

In the European Joint Programme advanced programmes will be able to address specific cutting-edge science, while less advanced programmes will be able to plan, structure and implement the necessary R&D, with guidance, training and transfer of competence and knowledge from advanced programmes.

Views of EURATOM Scientific and Technical Committee (STC)

In its opinion in 2018 the STC advocated for an increased budget for nuclear R&D given the need to maintain capability in the nuclear field to ensure that nuclear gets an important role in the road-map towards a zero carbon society.

Keynote speech

The keynote speech was delivered by Mr Pierre-Marie Abadie, CEO of ANDRA.

In addition to describing the status of radioactive waste management, as mentioned above in the introduction, Mr Abadie highlighted the usefulness of international cooperation through IAEA, NEA and EC.

In particular as concerns RD&D the support by the EC is important and the developments towards a European Joint Programming are very good and the efforts of the EC to promote the sharing of ideas and plans between all actors concerned is commendable.

4. Predisposal and technology session

The session on predisposal and disposal technology included one keynote on the role of Research Entities in advancing knowledge, solutions and technologies for the management and disposal of RAW seen from the Czech perspective and five project presentations, three on pre-disposal and two on disposal technology:

- Nuclear site characterization for radioactive waste minimization. INSIDER
- Characterization of conditioned nuclear waste. CHANCE
- Thermal treatment for radioactive waste minimization. THERAMIN
- Tunnel plugs and shaft seals demonstrations. DOPAS
- Monitoring strategies & technologies for geological disposal. Modern2020

The session was concluded with a panel discussion on remaining research needs in pre-disposal

The highlights and main messages were:

- Pre-disposal is becoming a new pillar in the EURATOM programme. The results achieved in the pre-disposal project are promising and show that further improvements in characterization, minimization and treatment of waste can be achieved. This might lead to a higher safety and also have commercial benefits.

- Waste Acceptance Criteria are important and should be developed in dialogue between all concerned parties (WMOs, waste producers, regulatory bodies and other stakeholders). In this way, one can avoid creating a category of waste that cannot be taken care of.
- Specific waste streams, like bituminized waste, graphite and powder waste from the back-end require further investigations with regard of their disposability and long-term behaviour.
- Waste packages are important not only for long-term purposes but for transport and handling in the repository operational period as well. Few examples of real waste packages for SNF/HLW exist today. Continued R&D on the design and construction of such waste packages will be useful.
- The activities performed during construction and operation of a DGR will have an important impact on the long-term safety, e.g. plugs for tunnels and drifts as investigated in DOPAS.
- It is also important to be able to monitor the function of specific elements of the disposal facility. As was shown in Modern 2020 this is not only a technical issue. Here the involvement of representatives of civil society has been very useful.

5. Radioactive waste source term and science for final disposal

The session on Radioactive waste source term and science for disposal safety included one keynote on the role of science for the safety case now and in the future, and how to maintain knowledge and competence until final closure seen from the Swedish perspective and five presentations on R&D projects:

- Spent fuel dissolution. REDUPP and DISCO
- Carbon-14 source term generation and release from irradiated metals, ion-exchange resins and graphite. CAST
- Research and Innovation action on cement-based materials, properties, evolution and barrier functions. CEBAMA
- Bentonite erosion and Bentonite mechanical evolution. BELBAR and BEACON
- Microbiology in nuclear waste disposal. MIND

The session was concluded with a panel discussion on remaining challenges in science for the safety case of geological disposal.

The highlights and main messages were:

- The development of the safety case provides the platform to integrate the scientific and technical knowledge in a systematic and traceable manner to show the long-term safety of a repository. For licensing a DGR a sound scientific and technological basis and the ability to compile a convincing post-closure safety case is needed.
- Also, after receiving licenses and starting operation safety analyses will continue to be needed for periodic updates based on latest state of knowledge.
- As science will continue to develop also after the start of operation of a repository, there is a need to maintain oversight and knowledge in those areas of science that are important to post-closure safety until closure of the repository. This also

includes the capability to compile a safety case. These are issues where future cooperative activities can play an important role.

- The work done in the reported projects increases the knowledge (both scientific and technical) to be used for the licensing of the first HLW/SNF repositories in the advanced MS. This knowledge will also support the other MS in advancing their national programmes as rapidly as possible.
- All projects could to some extent build upon available experience and results from earlier projects. None of the projects did fundamentally change earlier understanding, but refinements have been made in all projects.
- Most projects include experimental work and modelling activities. This is important as adequate models help to transfer the evidence from experiments to the in-situ conditions of the repository analysed. The models also support the extrapolations for long-term evolution if needed and can provide information for sensitivity studies as part of the post-closure safety case.
- After completion of the reported projects some uncertainties will remain and should be specified. Whether these are acceptable or not, needs to be analysed within specific performance assessments and post-closure safety cases as the importance of remaining uncertainties depends upon the whole repository system and cannot be judged for one process alone in isolation.
- The time schedule from the start of a DGR project until the closing of the repository could be 100 years or more. Knowledge management was thus a key topic brought up during the science session. Knowledge management is also an important component in the new EURAD project.
- The difference between information and knowledge how to use the information should be recognised. For preservation of information different IT tools can be utilised. For preserving the knowledge how to use the information, active involvement in the work is needed. Here the recurrent safety assessments foreseen are important.
- The challenge to engage young people in R&D on radioactive waste management in the future remains. Challenging tasks are needed to attract young researchers and engineers.

6. Networking and organisation of future work

The session called Networking of research communities, Joint Programming of national programmes and Integration of radioactive waste producers mainly dealt with how the different actors have evolved and adhered to the concept and joined forces in the European Joint Programme on Radioactive Waste Management (EURAD) and the remaining issue to also integrate the waste producers.

Presentations were made of IGD-TP, representing the WMOs, SITEX, representing the TSOs and EURADSCIENCE, representing the Research Establishments.

Presentations were also made on the possible interaction with IAEA and OECD/NEA and on the interests and needs from countries with longer time scales for implementation.

Finally, a keynote speech was given from EDF on how to include the pre-disposal activities in the Joint Programme and in particular to ensure harmonization of standards in Europe to allow cross-country activities.

The highlights and main messages were:

- EURAD is a step change in the implementation of EURATOM R&T programme in radioactive waste management. Instead of many smaller R&D projects the Commission is now funding a large project that will be based on a European Joint Programming (EJP).
- EURAD involves all actors concerned in radioactive waste management R&D, i.e. WMOs, TSOs, Research Entities and representatives from the civil society. EURAD will implement its Strategic Research Agenda of activities of European added-value between Member States with support of the EURATOM Programme. In a second step also waste producers may be included.
- The development of EURAD has a long history starting with the co-operation between WMOs through IGD-TP, followed by similar cooperation between TSOs in SITEX. Both projects, which were originally supported with EURATOM funding, are now self-sustaining fora. The creation of EURAD is an achievement and has been successful thanks to the continuous support of the EURATOM programme over a decade.
- IGD-TP, SITEX and the Research Entities have developed their own Strategic Research Agendas, which have been introduced into EURAD as a basis for EURADs SRA. Input has also been given by civil society groups.
- In a first round EURAD will run 7 collaborative R&D projects, 2 strategic studies and 3 knowledge management projects.
- For WMOs focus remains on geological disposal, but the missions of EURAD are proposed to be expanded to also accommodate more upstream interests and cover a wider inventory (e.g. sealed sources and borehole disposal). However, it is important to recognise that WMO's R&D programmes have a much wider scope of activities than the commonly agreed EURAD strategic research agenda will address.
- For TSO/SITEX community, the condition for participating to an EJP is to develop the high quality expertise function independent from WMOs as well as expanding interaction with Civil Society towards integration in R&D projects, meaning that CS may express their view on the need for R&D activities..
- The European research organisations involved in RWM have organised themselves in a network, called EURADSCIENCE, with the vision of acting as an independent, cross-disciplinary, inclusive network providing scientific excellence and credibility to national radioactive waste management programmes.
- An important component of EURAD is knowledge management. These parts should lead to attract and train new competencies and new high level researchers, to allow a cross fertilization of ideas and to ensure that the competencies will be present all along the duration of the disposal project until closure of the disposal facilities.
- The involvement of representatives from the civil society is important in programming projects for radioactive disposal. Extensive support of past EURATOM programmes has enabled to define the key requirements and methods for involvement of civil society in radioactive waste disposal programmes.
- Civil society organizations were consulted in the preparations of EURAD, primarily through SITEX and the TSOs, but also in an advisory role to the project. The role of these organizations, however, needs to be clearly defined. Primarily they have a role to influence the Strategic Research Agenda. They can also assist in making the R&D results understandable by the public at large. In certain projects with a social impact direct participation can also be considered.

JOINT INTRODUCTION FISA 2019 - EURADWASTE '19

Chair : Şerban Constantin VALECA (RATEN ICN, RO)

Co-chair: Domenico ROSSETTI DI VALDALBERO (EC, DG RTD)

Rapporteur: Stefano MONTI (IAEA), Expert

FISA 2019
EURADWASTE '19

4-7 June, 2019
Pitesti, Romania

OPENING SPEECHES

PATRICK CHILD

Deputy Director General, Research and Innovation, DG RTD European Commission

Euratom Research and Training and Horizon Europe framework programmes

Dear Minister,

Dear Senator,

Dear Honorable members,

Ladies and gentlemen,

Thank you, Honourable Minister Hurduc for Research and Innovation of Romania, and the Institute for Nuclear Research (RATEN ICN) for co-organising together with the European Commission these events taking place this week, in Pitesti, in Romania, under the auspices of the Romanian Presidency of the Council of the EU.

It is a great honour to be here among so many of the world's leading scientific experts. Today I will speak to you about three things. Firstly, about the EU's ambition to become the world's 1^{st} major economy to go climate neutral by 2050; Secondly, about Euratom as a platform to work together and the results we have achieved so far; and finally, I will speak to you about the new features of the future Euratom program.

Decarbonisation: Clean Planet for All

The alarming findings of the recent International Panel on Climate Change (IPCC) special report call for unprecedented efforts and much higher emissions reductions in order to limit the global warming to 1.5 degrees Celsius.

This is a wake-up call to the world – policy-makers and business community alike. The powerful mobilisation of citizens, including youth, for the case of climate action cannot remain answered.

The EU committed to lead by example

With its 2050 decarbonisation strategy 'A Clean Planet for All', the EU unveiled the ambition to become the world's 1^{st} major economy to go climate neutral by 2050.

This calls for a range of new ground-breaking solutions and makes research and innovation a cornerstone to a carbon neutral world.

Member States have very different views on nuclear energy

Through the European Strategic Energy Technology Plan (SET-Plan), the implementation plan for nuclear energy is supported only by several member states.

Yet in the 'Clean Planet for All' communication, the European Commission recognises a continued contribution from nuclear energy to decarbonise the economy by 2050.

EURATOM as a platform to work together

EURATOM provides us a platform to work together on objectives where we do agree: ensuring the safe and sustainable use of peaceful nuclear energy technologies.

EURATOM has been the framework in which, for more than 60 years, knowledge and competence in nuclear science and technology have been developed in Europe, and through International Cooperation together with, among others, the OECD, the Nuclear Energy Agency and the International Atomic Energy Agency.

EURATOM would not have been possible if Europe was not continuously maintaining high competences, underpinned by sound and advanced research.

Today, all EU Member States meet equally high standards of safety, radiation protection, safeguards and security.

The EU became the first major regional actor with a legally binding regulatory framework for nuclear safety following the implementation of the latest Directives on safety, waste and basic safety standards.

As such, we can ensure that Member States can rely on one another, respect each other's choices and citizens in different Member States can rely on their neighbours across the border.

I would like to highlight a couple of benefits of the EURATOM Research and Training programme:

It focuses on basic and fundamental research but also on technological and industrial developments, as these are essential to face and overcome the Energy and Climate Change challenges that are lying ahead of us.

In the field of decommissioning we need to transfer the fundamental research into successful industrial projects while ensuring adequate training opportunities are available for this growing market.

In the field of waste management, we need to implement solutions that can help the society to understand issues linked to waste disposal and agree on the acceptability of proposed solutions.

The European Commission is proud to support the launch of a third COFUND European Joint Programme with co-funding of EUR 32 million from Euratom, supporting further integration of Waste Management Organisations, Technical Support Organisations and other Research Organisations in Joint Programming at European level.

Following the Council Regulation establishing the Euratom Research and Training Programme for 2019-2020, a specific 2 years' work programme has been published. The Fission call that opened on 15 May 2019 will benefit from a total budget of 139.9 million euros. Fusion actions include the extensions of EUROfusion and the contract of operation of JET with a total budget of 328 million euros.

This work programme focuses on the safety of nuclear systems, radiation protection and radioactive waste management. As in the previous work programme, education and training will be supported in two ways: through specific actions and through the requirement that each research and innovation action in this work programme dedicates at least 5 % of the total budget to education and training activities for PhD students, postdoctoral researchers and trainees.

This work programme gives particular attention to innovations in the safety of reactors and in decommissioning by supporting technology transfer from the research community to industry.

On radiation protection, the work programme focuses on further integration of research, preparation of a research roadmap for medical applications, and ensuring the safe use of these medical applications.

For research infrastructure, this work programme launches important actions aiming to maximise the safety of existing and future research reactors.

The work programme introduced two pilot actions with JRC on knowledge management and on open access to JRC nuclear research facilities with the objective to address better synergies between direct and direct actions.

Future Euratom programme and Horizon Europe

The new Euratom program will continue to improve safety, security and radiation protection and to contribute to the decarbonisation of the energy system in the long term. The budget we proposed is EUR 2.4 billion (2021-27), EUR 1.675 billion (2021-25).

The new elements that the European Commission are proposing in the next Euratom program include:

- non-power applications such as the uses of ionising radiation, not only for medical applications, but also for industry, agriculture and space research.
- the creation of stronger synergies between nuclear research and other research areas through joint activities within the new research and innovation framework for 2021-2027, Horizon Europe.
- a single set of objectives, combining the indirect and direct action and we will also offer to all projects the possibility for access to our Joint Research Centre facilities and expertise.
- One overarching element of research is the human capital. It is imperative that we maintain and further enhance the number, the competences and the excellence of our research community, especially in the nuclear sector. For this reason, the Marie Skłodowska-Curie Actions will be opened up to Euratom researchers.

Conclusion

I have unveiled to you today that with the 2050 decarbonisation strategy ‘A Clean Planet for All’, the EU unveiled the ambition to become the world's 1st major economy to go climate neutral by 2050. We see nuclear energy as part of the future energy mix to achieve this.

Even though there are clear differences between Member States about the role of nuclear energy, the Euratom program has given us a platform to work together on objectives we do agree on: ensuring the safe and sustainable use of peaceful nuclear energy technologies.

Joint Introduction FISA 2019 - EURADWASTE '19

EURATOM has been the framework in which, for more than 60 years, knowledge and competence in nuclear science and technology have been developed in Europe.

The current programme focusses on safety of nuclear systems, radiation protection and radioactive waste management. Education and training is supported too.

In the new Euratom programme we introduce a some new elements: a focus on non-power applications for medical and industrial use, a signle set of direct and indirect objectives, clear synergies with Horizon Europe and we will open up Marie Skłodowska-Curie Actions to nuclear researchers.

I would like to conclude by expressing all my gratitude for organising these successful events and I personally look forward to hear from the results of this dialogue.

Thank you, Chairman, Honourable Members, Ladies and gentlemen.

CHARLINA VITCHEVA

Deputy Director-General of the Joint Research Centre, European Commission

JRC role in Euratom Research and Training and Horizon Europe

Dear Minister,

Dear Senator,

Distinguished guests,

Ladies and gentlemen:

I am very glad to be here today in this joint opening session of the FISA 2019 and EURADWASTE ‘19 conferences.

I sincerely believe that bringing together the key stakeholders in nuclear research under these conferences, to discuss on where we stand with regards nuclear research, to identify the key challenges (at national, European and international levels) on research and innovation policies, as well as to exchange on synergies, partnerships, and future perspectives is fundamental to shape the future of European nuclear research.

Thank you, Honourable Minister Hurduc for Research and Innovation of Romania, and also to the Institute for Nuclear Research for hosting and making it possible.

The European Commission's Joint Research Centre

My name is Charlina Vitcheva and I am Deputy Director-General of the European Commission's science and knowledge service: the Joint Research Centre.

We support EU policies with independent multidisciplinary evidence throughout the whole policy cycle, as part the European Commission, in areas such as agriculture, food security, environment, climate change, innovation, growth, as well as in nuclear safety, safeguards and security.

Our researchers provide EU and national authorities with solid facts and independent support to help tackle the big challenges facing our societies today.

Established as the Joint Nuclear Research Centre by the Euratom Treaty 60 years ago, the JRC has broadened its field of research to non-nuclear disciplines, which now cover around 75 % of its research programme. We are dealing with large spectrum of activities such as Growth and Innovation; Energy, Transport and Climate; Sustainable Resources; Space, Security and Migration; Health, Consumers and Reference Materials; and Nuclear Safety and Security; We have a new focus on Knowledge Management and Competences.

The JRC is spread across six sites in five different countries within the EU: Brussels and Geel in Belgium, Petten in The Netherlands, Karlsruhe in Germany, Ispra in Italy, and Seville in Spain.

The JRC is funded by the EU's framework programme for research and innovation: Horizon 2020, and by its EURATOM Research and Training Programme for its work in the nuclear field.

JRC research in nuclear safety, safeguards and security.

Our Directorate for Nuclear Safety and Security employs about 460 scientists, technicians and administrative personnel in Petten, Karlsruhe, Geel and Ispra.

The JRC multi-annual work programme for nuclear activities fully reflects the specific objectives of the Direct Actions of the Euratom programme. It is structured in about 20 projects, allocating:

- 48 % of its resources to nuclear safety, waste management, decommissioning and emergency preparedness;
- 33% to nuclear security, safeguards and non-proliferation,
- 12% to reference standards, nuclear science and non-energy applications and
- 7% to education, training and knowledge management.
- From these areas of activity, one part is dedicated to supporting the policy of the Union on nuclear safety and security.

But we do not work alone. We do not work in silos, in an isolated fashion. Collaboration is the essence of the scientific effort.

And in our case, it is not just for the sake of scientific curiosity, but to align with and complement research and training in the Member States. Indeed, the JRC is continuously interacting with the main research and scientific institutions in the EU, such as the Technology Platforms SNETP, IGDTP, and ESARDA; with research institutions of Member States and third countries, and with international organisations such as the IAEA.

Globally, we work together with over a thousand organisations worldwide in more than 150 networks, both nuclear and non-nuclear.

JRC carries out research, training and knowledge management activities in nuclear safety, radioactive waste management, nuclear security and safeguards, nuclear data, reference materials and measurements, standardisation, and nuclear science applications.

JRC is the Euratom implementing agent of the Generation IV International Forum.

In addition to its competent staff, the JRC owns and operates scientific research infrastructure which is rare, and in occasions unique.

Students and researchers can access JRC nuclear research facilities through several programmes enabling them to perform research projects as part of their curricula. This will be enhanced in the future Horizon Europe framework programme.

Based on its relevant competence, infrastructures, its independence and neutrality of judgement, the JRC provides the scientific basis for nuclear-related Union policies across entire EU policy-making cycle, from policy anticipation and impact assessment up to policy implementation, monitoring and evaluation.

What lies ahead of us?

In spite of the different national options regarding the electricity mix, all scenarios considered in the forward looking for a low carbon economy in Europe include nuclear energy as a source of electricity generation in the long term.

The long-term safe, secure and sustainable use of nuclear energy must be ensured by a consistent approach to safety (implementation of appropriate and commensurate common principles, rules and standards); safeguards (verification, reporting and non-proliferation commitments such as export controls) and security (prevention, detection and response), as well as international acceptance and mutual trust (transparency).

This can only be based on sound scientific evidence, reliable nuclear measurements and appropriate control tools, as well as on public involvement, which at the same time can only be guaranteed if competence and technology leadership are maintained within the EU (research, education, training, and knowledge management).

The Commission's proposal for the next Euratom Research and Training Programme, which is currently being discussed at the Council aims at focusing in the same key research areas as the current programme, i.e. nuclear safety, security, radioactive waste and spent fuel management, radiation protection and fusion energy.

At the same time, the programme intends to expand research into non-power applications of ionising radiation, and make improvements in the areas of education, training and access to research infrastructure (including JRC's), as well as to better exploit the complementarity between research carried out by Member States scientific institutions, and research carried out by the Joint Research Centre.

Ladies and gentlemen, we are ready for that. We are ready to continue our cutting-edge research in nuclear safety, security and safeguards, putting at the disposition of the research community our competence, and our infrastructure. Ready to work together with you, the scientific community, in these very important topics for the future of Europe.

I wish you very successful conferences, and I am looking forward to hear from their outcomes.

Thank you very much.

NICOLAE HURDUC
Ministry of Research and Innovation, Romania

KEYNOTE

Dear participants,

Romania has an installed capacity of around 17 GWe characterized by a balanced mix, high share of low carbon electricity, availability of own natural resources, and independency

The national energy policies were oriented to capitalize: (1) the advantages of important internal energy resources (oil, natural gas, and coal), (2) the considerable potential for hydro-energy, solar, wind and bio-mass, (3) the existing uranium reserves. A well balanced energy mix was developed based on diversity and stability offering independence, security of supply, and capability to operate properly.

In the last decades the national electricity consumption was affected by three factors:

- restructuration of the economy (closing large consumers, growing up of the low intensive energy industry),
- demographic decline from 22 million (1990) to 19 mil. (2016) inhabitants,
- energy efficiency measures.

After a decline of consumption (from 60 TWh in 1990 to 40 TWh in 1999) it stabilized around 49 TWh (2016) with a trend of 1-2% annual growth.

Nuclear power contributes with 18-20% to the total electricity production. It is a stable, reliable and price affordable electricity. The peculiarity of nuclear sector in Romania is the natural uranium based on CANDU technology. The security of supply is strengthened by the fact our industry produces the nuclear fuel, the heavy water, nuclear equipment and a lot of services.

Very important is to note the contribution of the national research to this achievement. The nuclear fuel is a result of the national efforts, also the heavy water, and now the Tritium issue was deeply approached to find valuable solutions. Romanian research organizations have developed technics, methods, instruments and tools to support the national nuclear power. An important research infrastructure was developed together with research groups, teams and organizations, and important efforts were devoted to build the education and training system.

Nowadays the Romanian nuclear Agenda includes:

- operational safety of the the Nuclear Power Plant and other nuclear installations,
- the continuation of works at Cernavoda Unit 3 and Unit 4,

- Plant life extension for Cernavoda NPP Unit 1,
- Radioactive waste management (LILW repository construction, geological disposal strategy),
- ALFRED GenIV demonstrator implementation,
- Mining and environmental issues (site remediations).

On the short term the plant life extension of the nuclear units from Cernavoda NPP is a major decision to preserve the current share of free carbon electricity in the national system. The refurbishment of Unit 1 was approved and entered in the preparation phase. The project consists of the re-tubing of the CANDU core and it will be implemented from December 2026.

The continuation of the works at the Unit 3 and Unit 4 is considered as a feasible and optimal approach to significantly increase the free-carbon electricity production and a set of dedicated measures are included in the national energy strategy.

From the long term perspective, the National Strategy for Research, Development and Innovation (NSRDI) is oriented to stimulate the development of advanced technologies including nuclear technologies able to face the societal and climate challenges. The development of the lead-cooled fast reactors technology (LFR) is seen as an optimal option for the implementation of nuclear systems with great performances in safety, security, economics, and waste management. At the same time the synchronism of the national research with the major European themes, the enhancing of collaboration, the growth of the spin-off capacity, and the job creation are targeted.

Based on NSRDI, a separate subprogram (5.5 Program for research, development and innovation of 4th generation reactors-ALFRED) was started, in 2019, to support preparatory activities for the implementation of the LFR demonstrator. ALFRED project is also mentioned in the national energy strategy as an important development for the consolidation of the nuclear sector in Romania and for the development of advanced system able to cope with the societal, market, and climate challenges.

ALFRED is a European project, emerged from the Euratom supported projects. Our vision is to combine the European structural funds with national funds and industry contribution in order to transform the vision into a real infrastructure. After a large national consultation of the stakeholders, today ALFRED is present in the main national strategic documents. Based on thEm, the Ministry of research supports the efforts to include ALFRED in the planning of the future EU budget and to fulfill the full procedure to declare it as a major project.

FISA and EURADWASTE conferences will approach the success of the collaborative research in the frame of Euratom programme, how the critical mass on different very focused topics was created and worked, what kind of outcomes were produced, what are the directions for the future.

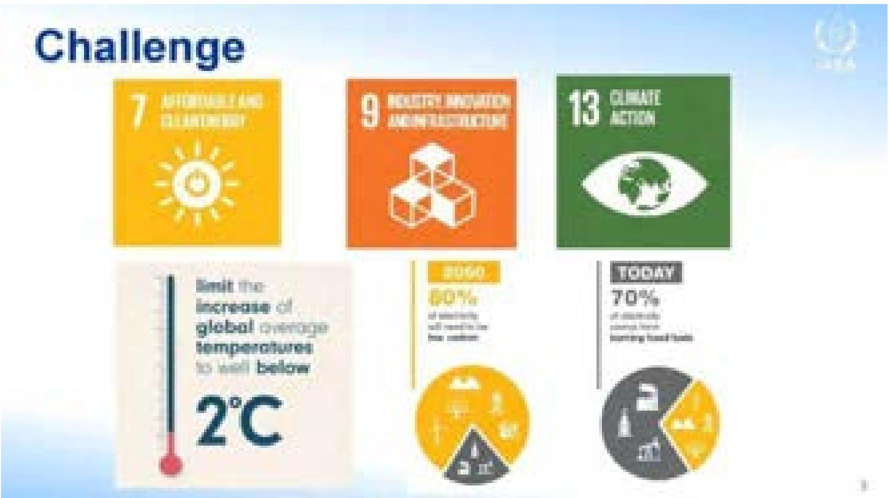
I hope the collaboration on the main topics of nuclear safety and radioactive waste management will be more and more fruitful producing valuable solution and helping the nuclear power to be more and more accepted by the society as a powerful contributor to de-carbonization of the energy sector.

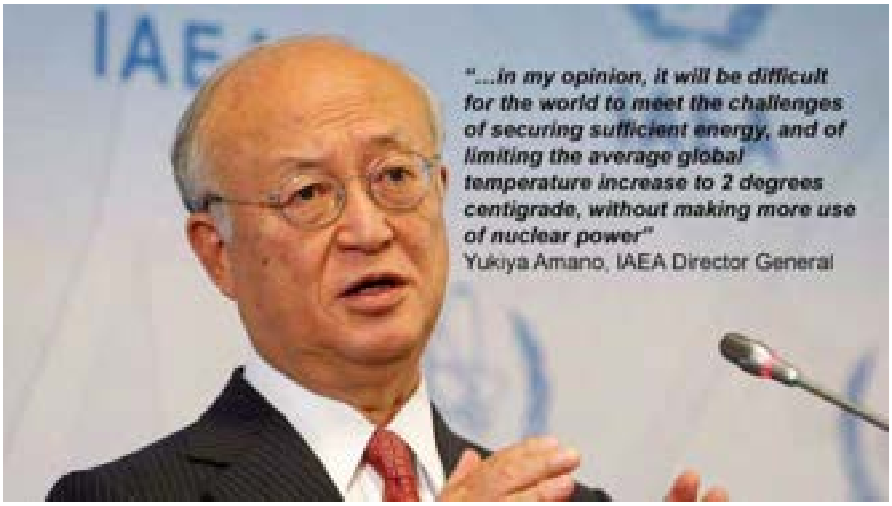
I wish a great success for your debate!

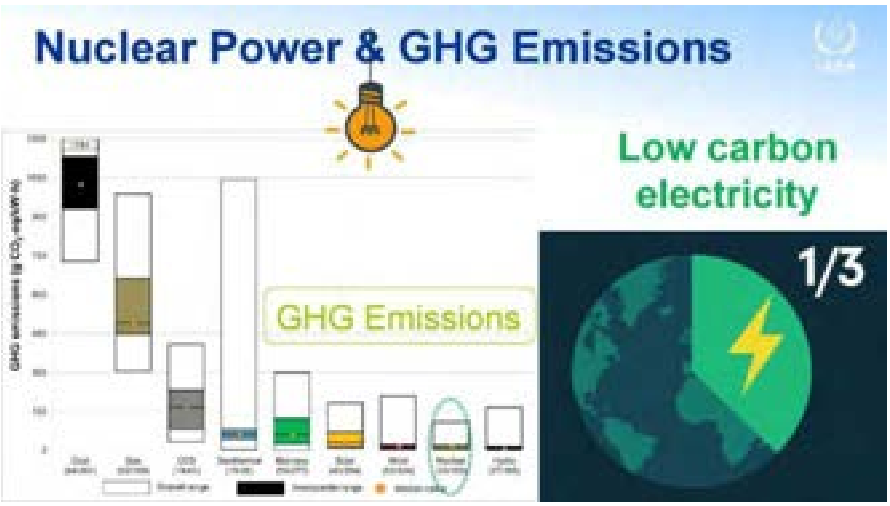
STEFANO MONTI

Section Head, Nuclear Power Technology Development section, Division of Nuclear Power, Department of Nuclear Energy

Research and Innovation for a safe, secure and safeguarded nuclear power in support of the UN Sustainable Development Goals


Challenge
limit the increase of global average temperatures to well below
2°C
2050
TODAY
70%


"...in my opinion, it will be difficult for the world to meet the challenges of securing sufficient energy, and of limiting the average global temperature increase to 2 degrees centigrade, without making more use of nuclear power"
Yukiya Amano, IAEA Director General


Nuclear Power & GHG Emissions
GHG Emissions
Low carbon electricity
1/3


Nuclear Power & Sustainability
CLIMATE CHANGE AND NUCLEAR POWER 2018
Impact
Innovation is key for the expanded role of nuclear power
GHG emissions
Ecosystem damages
Land occupation
Human health impacts
Water consumption
Material use
Nuclear
Coal
Coal CCS
Gas (CC)
Gas (CC) CCS
Hydro
Biomass
Wind onshore
Wind offshore
Solar PV
Solar thermal


United States
European Union
Russia
Japan
Korea
India
China
0%
20%
40%
60%
80%
100%
Source: IAEA PRIS and IEA
Less than 10 years
10-30 years
Over 30 years
Ageing NPPs


IAEA support of technical innovations to improve existing NPP fleet sustainability
Non-Baseload operation
Transitioning toward a future integrated grid
Energy storage, H2 production, district heating and other examples of loosely integrated energy systems relevant to the current fleet of reactors
Modernization
Deployment of wireless technology (CRP completed)
Digitalization (TWG-NPPI&C)
Condition-based monitoring and maintenance (TWG-NPPLM)
Innovative human-factors engineering
Overcoming supply-chain atrophy
Additive manufacturing
Innovations to improve procurement and supply logistics
International Partnership: Innovation for the future of Nuclear Energy. A Global Forum 10-12 June, Gyeongju, South Korea


Advanced Reactors - Fuel Cycles - Waste Management
An holistic view, from the start.
SMRs
EVOLUTIONARY
INNOVATIVE
Increasing focus to develop IAEA guidance regarding RWM, SNF and Decommissioning considerations during the design phase of new reactors, fuel types and advanced fuel cycles


IAEA Support for Advanced Nuclear Power Technology
IAEA
Supporting existing fleet along with the development of advanced nuclear power technologies
Advanced Reactors
Innovative Designs
Research & Innovation
Fuel Cycle and Waste Management
Hybrid Energy Systems
Cogeneration

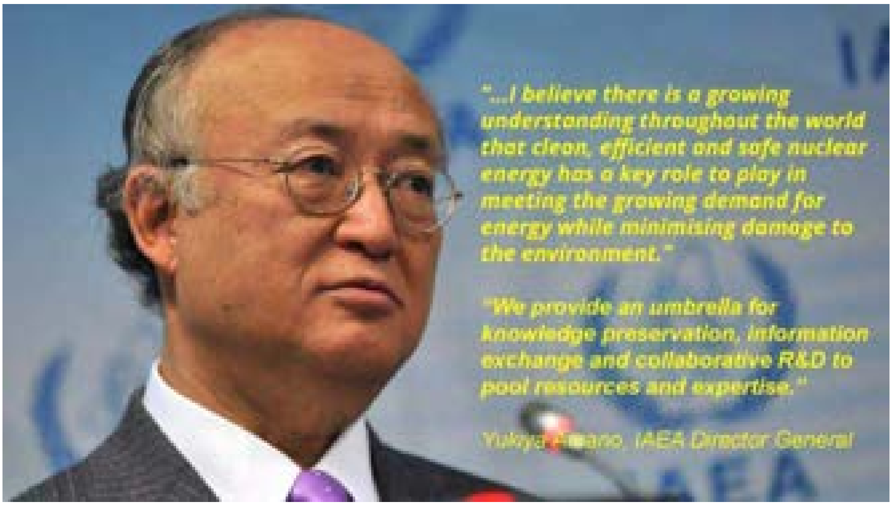

Supporting tools for Research and Innovation
Technical Cooperation
CRPs
Database & Toolkits
Collaborating Centers
International Forums & TWGs
ICERR
Safety & Security for Innovative NES


Coordinated Research Activities
Uniting the World through Research
~130 active CRPs (30 in NE), ~1600 research institutions involved
3%


Supporting tools for Research and Innovation
Safety for Innovative NES
SDC and SDG for FR and HTGR
SMR Regulators' Forum
Cooperation with GIF & NEA
Collaborating Centres
EPFL
CRPs
Advanced Reactors
Non Electrical Applications
ATF
Fuel Cycle and Waste Technology
Research Reactors
NE & Climate Change Mitigation Strategies
Database and Toolkits
Nuclear Data Libraries
ARIS, PRIS, THERPRO, LMFNS
SF and Waste Information Tool
Toolkits for non-electric applications
Knowledge Preservation Portals
Simulators


Global Scenario
Scenario modelling, decision analysis and road-mapping tools
01
Collaborative Projects
Investigate innovations in selected nuclear energy technologies, related R&D, innovative institutional arrangements to facilitate their development and deployment
02
INPRO
Sustainability assessment & strategies
Nuclear Energy System Assessment (NESA) using the INPRO Methodology
03
Dialogue and Outreach
INPRO Dialogue Forum
Regional Trainings
04


International Conference on
Climate Change and the Role of Nuclear Power
7–11 October 2019
Vienna, Austria
#Atoms4Climate
Atoms4Climate@iaea.org
1. Advancing energy policies that achieve the climate change goals
2. The increasing contribution of nuclear power in the mitigation of climate change, including synergies with other low-carbon power generation sources
3. Development and deployment of advanced nuclear power technologies to increase the use of low-carbon energy
4. Shaping the future of the nuclear industry in regulated and deregulated energy markets to address climate change
5. Enhancing international cooperation and partnership in nuclear power deployment
6. Public and non-nuclear stakeholders' perception of the role of nuclear power in climate change mitigation
CN-275


"...I believe there is a growing understanding throughout the world that clean, efficient and safe nuclear energy has a key role to play in meeting the growing demand for energy while minimising damage to the environment."
"We provide an umbrella for knowledge preservation, information exchange and collaborative R&D to pool resources and expertise."
Yukiya Amano, IAEA Director General


Thank you for your attention!
Contact:
Stefano MONTI
Atoms for peace and Development


Overview
Innovation
IAEA
Advanced Reactors
Research
SDG
Safety
Nuclear Power
Climate Change

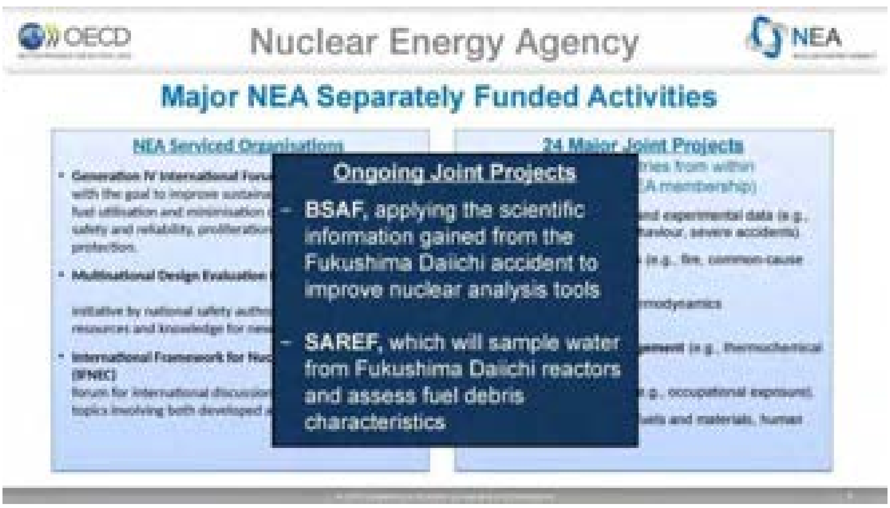
DANIELA LULACHE

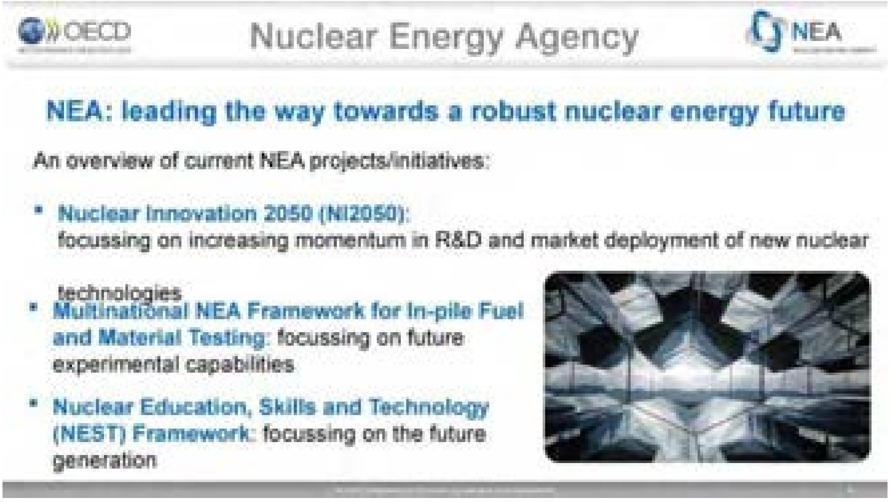
Head of Office of Policy and Coordination, OECD Nuclear Energy Agency

Nuclear Research and Innovation successes and accomplishments looking to the future

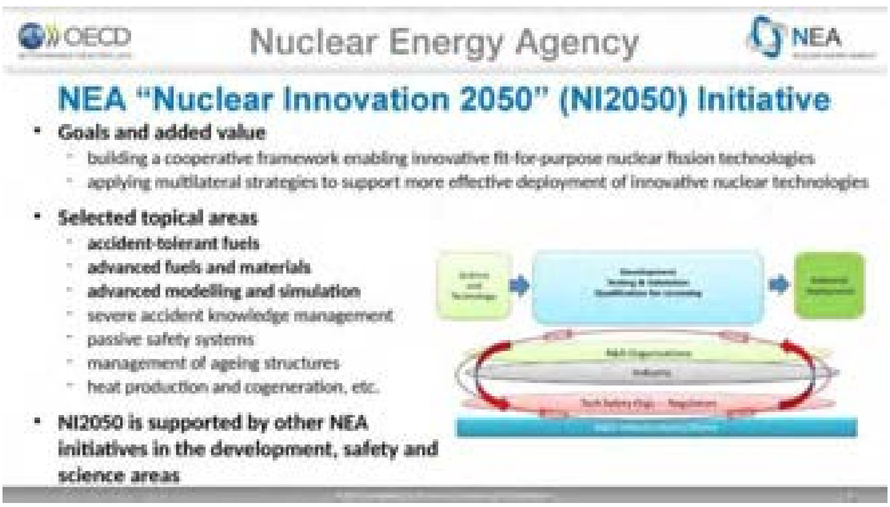

OECD
Nuclear Energy Agency
NEA
The NEA Serves as a Framework to Address Global Challenges
The Role of the NEA is to:
• Foster international co-operation to develop the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes
• Develop authoritative assessments and forge common understandings on key issues as input to government decisions on nuclear technology policy
• Conduct multinational research into challenging scientific and technological issues
33 NEA countries operate nearly 82% of the world's installed nuclear capacity


OECD
Nuclear Energy Agency
NEA
NEA Standing Technical Committees
Steering Committee for Nuclear Energy
CNRA Committee on Nuclear Regulatory Activities
CSNI Committee on the Safety of Nuclear Installations
RWMC Radioactive Waste Management Committee
CDLM Committee on Decommissioning of Nuclear Installations and Legacy Management
CRPPH Committee on Radiological Protection and Public Health
NLC Nuclear Law Committee
NDC Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle
NSC Nuclear Science Committee
MBDAV Management Board for the Development, Application and Validation of Nuclear Data and Codes
The NEA's committees bring together top governmental officials and technical specialists from NEA member countries and strategic partners to solve difficult problems, establish best practices and to promote international collaboration.

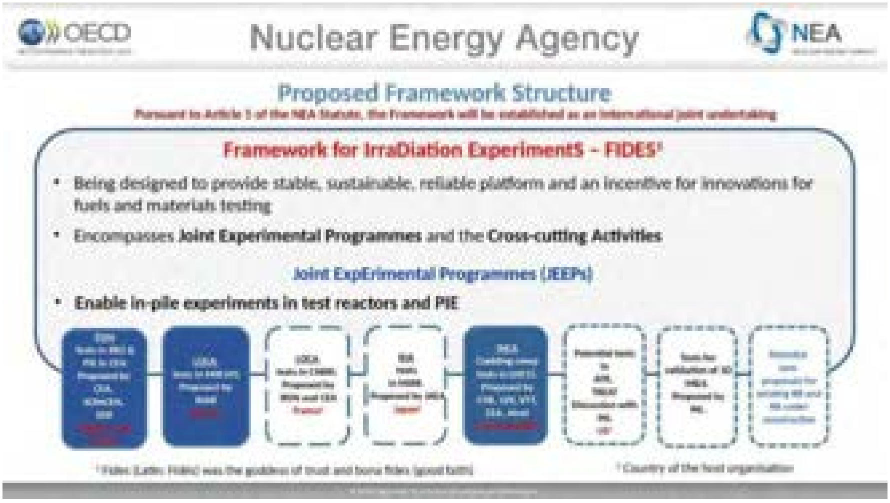

OECD
Nuclear Energy Agency
NEA
Major NEA Separately Funded Activities
NEA Serviced Organisations
24 Major Joint Projects
Ongoing Joint Projects
- BSAF, applying the scientific information gained from the Fukushima Daiichi accident to improve nuclear analysis tools
- SAREF, which will sample water from Fukushima Daiichi reactors and assess fuel debris characteristics

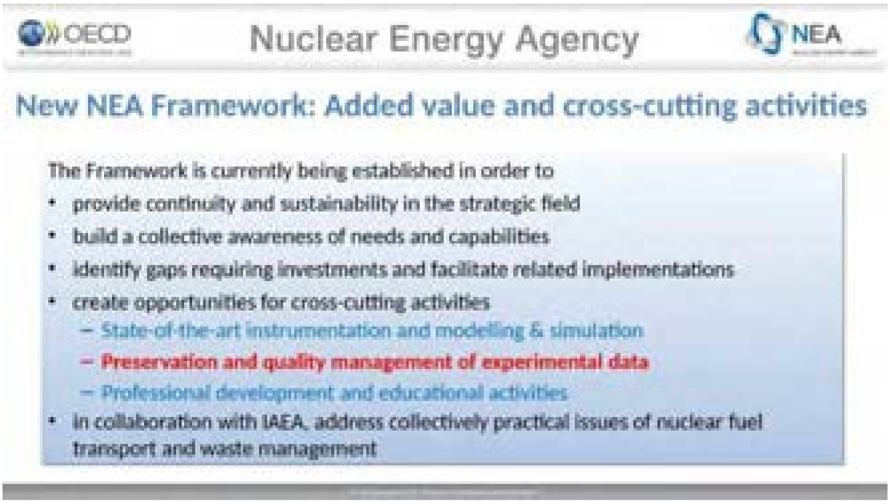

OECD
Nuclear Energy Agency
NEA
NEA: leading the way towards a robust nuclear energy future
An overview of current NEA projects/initiatives:
• Nuclear Innovation 2050 (NI2050): focussing on increasing momentum in R&D and market deployment of new nuclear technologies
• Multinational NEA Framework for In-pile Fuel and Material Testing: focussing on future experimental capabilities
• Nuclear Education, Skills and Technology (NEST) Framework: focussing on the future generation

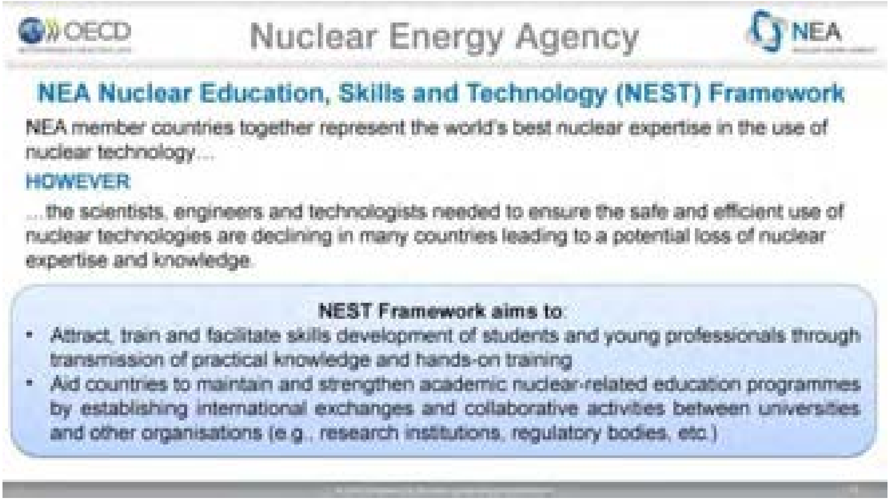

OECD
Nuclear Energy Agency
NEA
Nuclear Innovation 2050: moving ideas into reality
• Need for new nuclear technologies which are:
• able to compete in future global energy markets
• cheaper
• more flexible and faster to deploy
• NI2050 involves industry and safety authorities to facilitate the transformation of R&D to market readiness → all stakeholders need to be on board
Three major barriers to overcome:
• Financing: nuclear innovation timeline is long; industry and private investors need to contribute
• Regulatory framework: not active in the technology development process; national dimension of regulatory processes can hinder wider market deployment
• Availability of infrastructure to support nuclear technology development


OECD
Nuclear Energy Agency
NEA
NEA "Nuclear Innovation 2050" (NI2050) Initiative
• Goals and added value
- building a cooperative framework enabling innovative fit-for-purpose nuclear fission technologies
- applying multilateral strategies to support more effective deployment of innovative nuclear technologies
• Selected topical areas
- accident-tolerant fuels
- advanced fuels and materials
- advanced modelling and simulation
- severe accident knowledge management
- passive safety systems
- management of ageing structures
- heat production and cogeneration, etc.
• NI2050 is supported by other NEA initiatives in the development, safety and science areas


OECD
Nuclear Energy Agency
NEA
New Multinational NEA Framework for
In-pile Fuel and Material Testing
• Motivation
- Strengthen fuel- and material-related experimental capabilities for the benefit of industry, safety and science
- Address the post-Halden situation
- Develop a coordinated approach and a new paradigm for experimentation
• Goals and added values
- Create and maintain awareness regarding experimental capacities
- Perform key experiments using facilities around the world using mechanism of NEA Joint Projects
- Coordinate the analysis, preservation and management of experimental data
- Enable training and education via NEST project


OECD
Nuclear Energy Agency
NEA
Proposed Framework Structure
Pursuant to Article 5 of the NEA Statute, the Framework will be established as an international joint undertaking
Framework for IrraDiation ExperimentS – FIDES¹
• Being designed to provide stable, sustainable, reliable platform and an incentive for innovations for fuels and materials testing
• Encompasses Joint Experimental Programmes and the Cross-cutting Activities
Joint ExpErimental Programmes (JEEPs)
• Enable in-pile experiments in test reactors and PIE
¹ Fides (Latin: Fidēs) was the goddess of trust and bona fides (good faith)
¹ Country of the host organisation

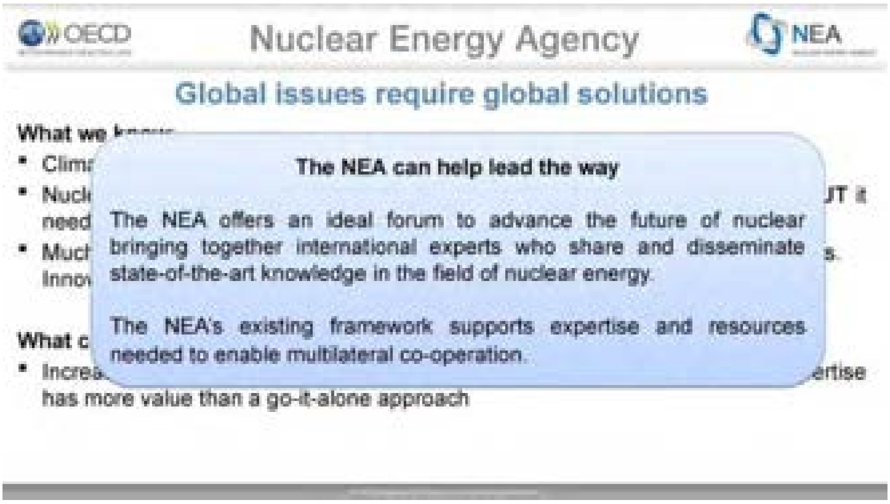

OECD
Nuclear Energy Agency
NEA
New NEA Framework: Added value and cross-cutting activities
The Framework is currently being established in order to
• provide continuity and sustainability in the strategic field
• build a collective awareness of needs and capabilities
• identify gaps requiring investments and facilitate related implementations
• create opportunities for cross-cutting activities
– State-of-the-art instrumentation and modelling & simulation
– Preservation and quality management of experimental data
– Professional development and educational activities
• in collaboration with IAEA, address collectively practical issues of nuclear fuel transport and waste management


OECD
Nuclear Energy Agency
NEA
NEA Nuclear Education, Skills and Technology (NEST) Framework
NEA member countries together represent the world's best nuclear expertise in the use of nuclear technology…
HOWEVER
…the scientists, engineers and technologists needed to ensure the safe and efficient use of nuclear technologies are declining in many countries leading to a potential loss of nuclear expertise and knowledge.
NEST Framework aims to:
• Attract, train and facilitate skills development of students and young professionals through transmission of practical knowledge and hands-on training
• Aid countries to maintain and strengthen academic nuclear-related education programmes by establishing international exchanges and collaborative activities between universities and other organisations (e.g., research institutions, regulatory bodies, etc.)


OECD
Nuclear Energy Agency
NEA
NEST: an investment in the next generation
Tacit knowledge needs to be preserved, transferred and shared with the next generation
To achieve this:
• Young generation needs to be exposed to challenging projects and real-world problems through hands-on training
• Leading experts in the field will work alongside the NEST Fellows (Masters, PhD, Postdoc students and young professionals)
• NEST Fellows will work within a network of organisations encouraging cross-fertilisation of ideas and development of new projects to advance new innovative nuclear technology


OECD
Nuclear Energy Agency
NEA
Entry into force of the NEST Agreement: 15 February 2019
SCK•CEN
cea
IRSN
PSI
10 Countries
15 Parties
GRS
INFN


OECD
Nuclear Energy Agency
NEA
NEST current projects
PSI
NEST HYMERES (HYdrogen Mitigation Experiments for Reactor Safety, Phase 2) project
• addresses safety relevant phenomena in containments during accidents, hands-on training at PANDA, one of the world's most advanced containment test facilities
McMaster University
SMR project
• aims to integrate SMR research projects from individual participating organisation countries into a broader and more impactful program
CLADS
NEST-CLADS (Collaborative Laboratories for Advanced Decommissioning Science) project
• dedicated to advanced remote technology for decommissioning under intense gamma-ray radiation environments (e.g robotics, virtual reality)
NEST-PDC UGR (Pilot & Demonstration Center for Decommissioning of Uranium-Graphite Nuclear Reactors) project
• addresses main issues of i-graphite management, including characterisation, decontamination and disposal


OECD
Nuclear Energy Agency
NEA
Global issues require global solutions
What we know
• Clim
• Nucl
need
• Much
Innov
What c
• Increa
has more value than a go-it-alone approach
The NEA can help lead the way
The NEA offers an ideal forum to advance the future of nuclear bringing together international experts who share and disseminate state-of-the-art knowledge in the field of nuclear energy.
The NEA's existing framework supports expertise and resources needed to enable multilateral co-operation.

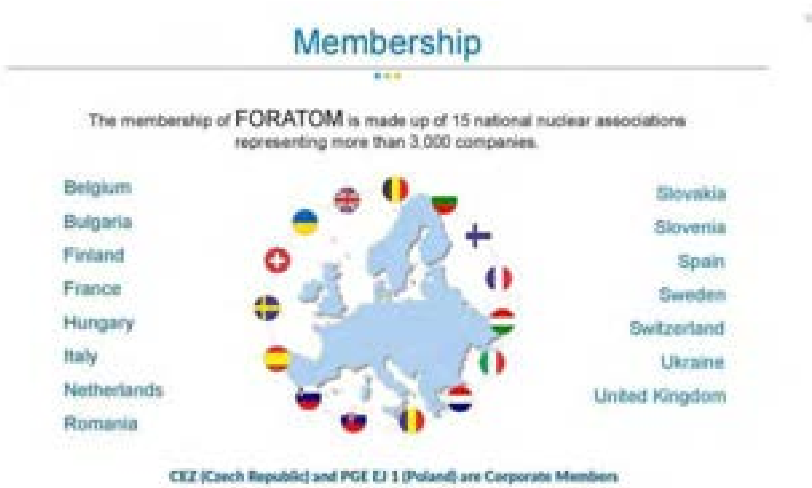

OECD
Nuclear Energy Agency
NEA
Thank you for your attention
More information @ www.oecd-nea.org
All NEA reports are available for download free of charge.
Follow us:

TEODOR CHIRICA

President of the European Nuclear Industry Association - FORATOM

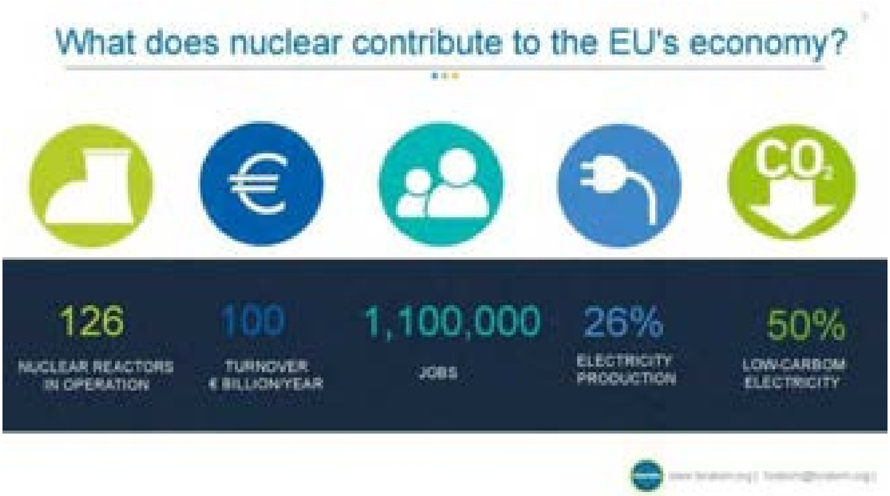
Research and Innovation benefits for a low-carbon economy, Industrial Competitiveness and sustainable development

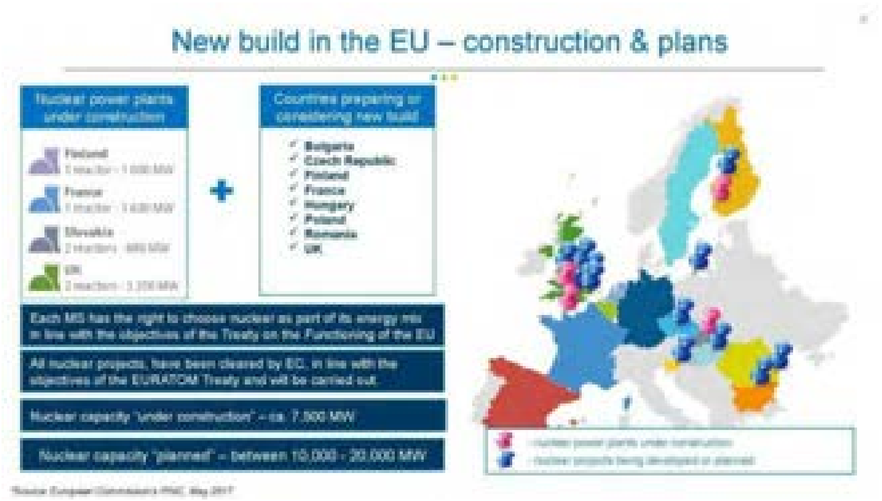

Who we are
FORATOM acts as the voice of the European nuclear industry in energy policy discussions with EU Institutions & other key stakeholders
FORATOM


Membership
The membership of FORATOM is made up of 15 national nuclear associations representing more than 3,000 companies.
Belgium
Bulgaria
Finland
France
Hungary
Italy
Netherlands
Romania
Slovakia
Slovenia
Spain
Sweden
Switzerland
Ukraine
United Kingdom
CEZ (Czech Republic) and PGE EJ 1 (Poland) are Corporate Members

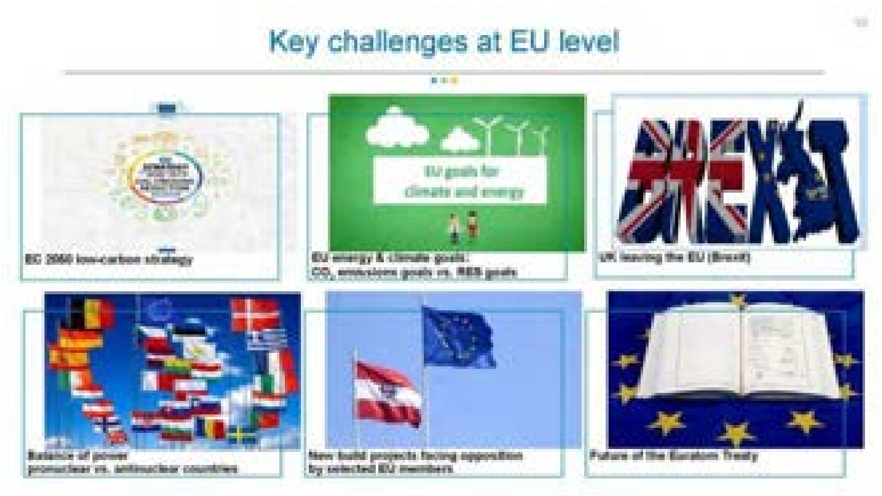

Key topics
EU Energy Policy:
Economics of nuclear
EU energy mix
Environment
Euratom Treaty
Security of energy supply
Special projects - Brexit
Nuclear technology:
Nuclear safety
Nuclear transport
IRD
Supply Chain
Waste disposal
FORATOM

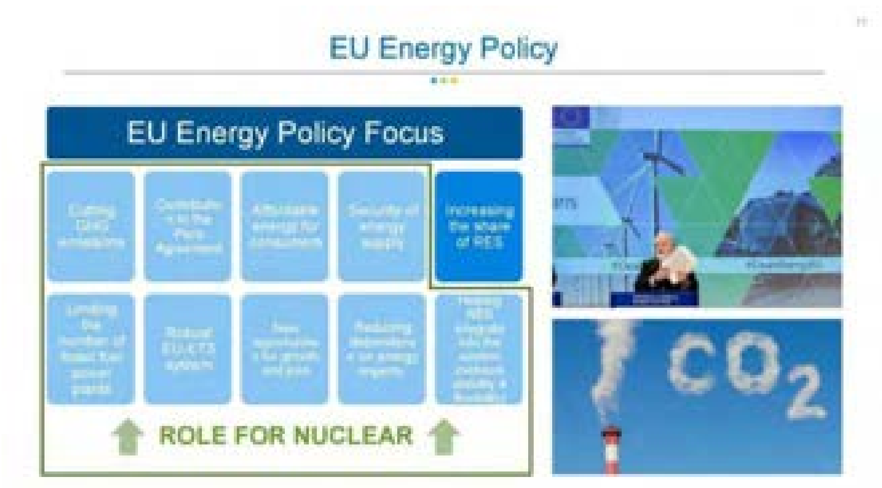

NUCLEAR IN THE EU


What does nuclear contribute to the EU's economy?
CO_2
126
NUCLEAR REACTORS IN OPERATION
100
TURNOVER € BILLION/YEAR
1,100,000
JOBS
26%
ELECTRICITY PRODUCTION
50%
LOW-CARBON ELECTRICITY

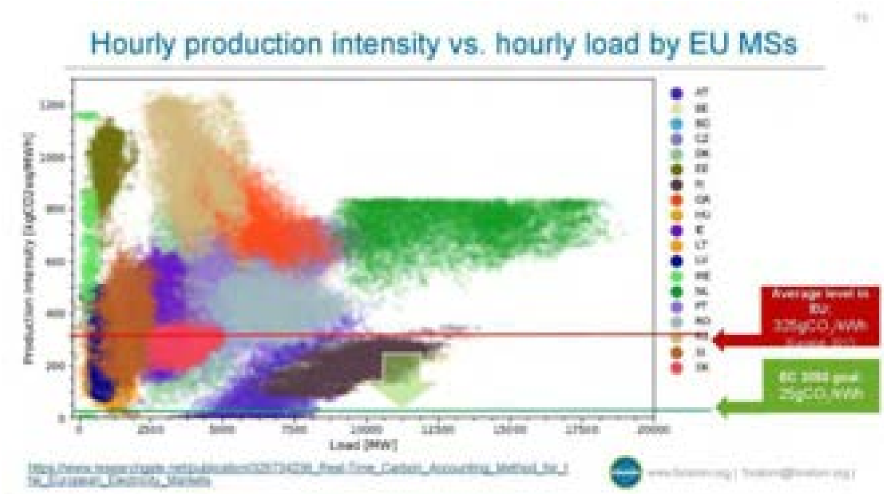

New build in the EU – construction & plans
Bulgaria
Czech Republic
Finland
France
Hungary
Poland
Romania
UK


EU ENERGY POLICY

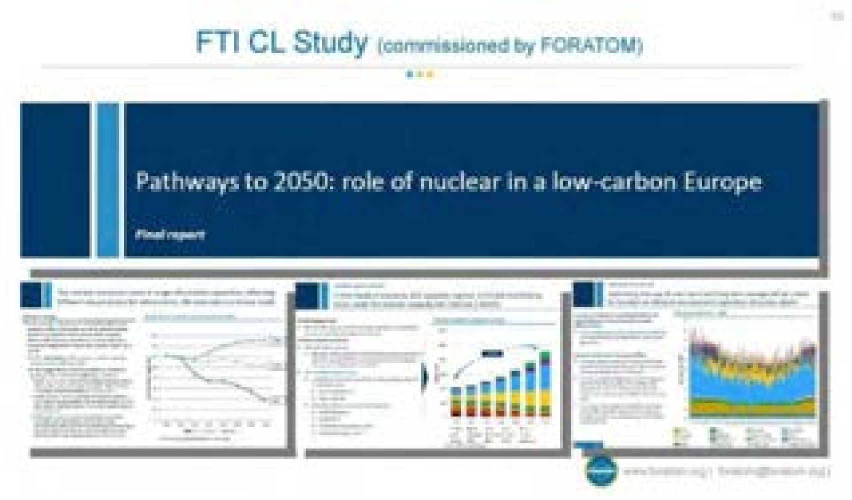

Key challenges at EU level
EU goals for
climate and energy
UK leaving the EU (Brexit)
Future of the Euratom Treaty

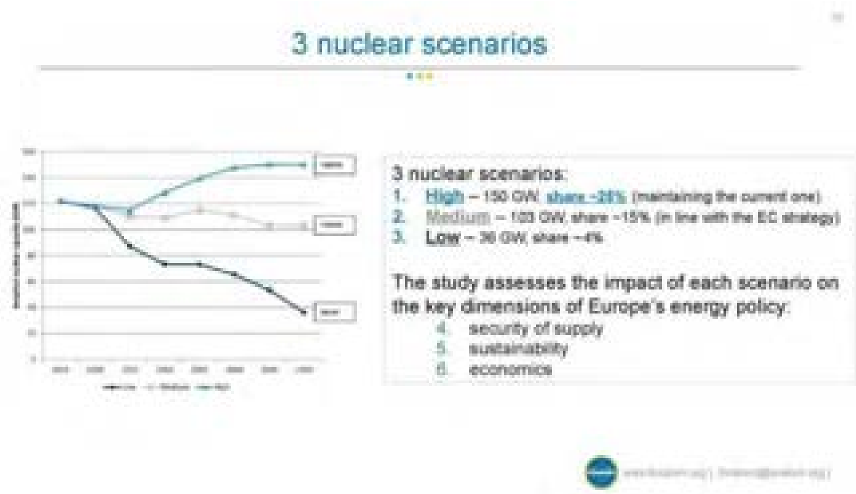

EU Energy Policy
EU Energy Policy Focus
Increasing the share of RES
ROLE FOR NUCLEAR
CO2

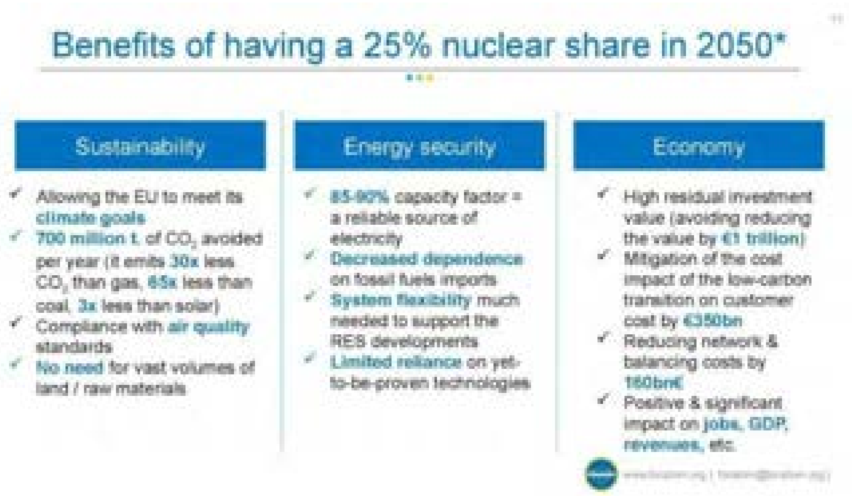

Nuclear energy in the EC strategy (Nov 2018)
EC Communication*:
"Renewables together with nuclear energy will be the backbone of a carbon-free European power system"
EC in-depth analysis**:
Nuclear will remain an important component in the EU 2050 energy mix
Capacity of nuclear in 2050 – between 99-121 GW
Share of nuclear in the electricity mix in 2050 – ca. 15%
"The consumption of natural gas is expected to be severely reduced by 2050 in all scenarios"
"In the baseline, hydrogen use develops only as a niche application for road transport and industry"
Authors of the strategy referred directly to the study commissioned by FORATOM


Hourly production intensity vs. hourly load by EU MSs
Load [MW]


EXPERT STUDIES


FTI CL Study (commissioned by FORATOM)
Pathways to 2050: role of nuclear in a low-carbon Europe
Final report

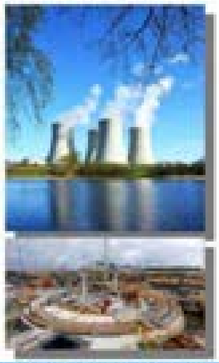

3 nuclear scenarios
3 nuclear scenarios:
1. High – 150 GW, share ~25% (maintaining the current one)
2. Medium – 103 GW, share ~15% (in line with the EC strategy)
3. Low – 36 GW, share ~4%
The study assesses the impact of each scenario on the key dimensions of Europe's energy policy:
4. security of supply
5. sustainability
6. economics


Benefits of having a 25% nuclear share in 2050*
Sustainability
✓ Allowing the EU to meet its climate goals
✓ 700 million t. of CO_2 avoided per year (it emits 30x less CO_2 than gas, 65x less than coal, 3x less than solar)
✓ Compliance with air quality standards
✓ No need for vast volumes of land / raw materials
Energy security
✓ 85-90% capacity factor = a reliable source of electricity
✓ Decreased dependence on fossil fuels imports
✓ System flexibility much needed to support the RES developments
✓ Limited reliance on yet-to-be-proven technologies
Economy
✓ High residual investment value (avoiding reducing the value by €1 trillion)
✓ Mitigation of the cost impact of the low-carbon transition on customer cost by €350bn
✓ Reducing network & balancing costs by 160bn€
✓ Positive & significant impact on jobs, GDP, revenues, etc.

Deloitte Study (commissioned by FORATOM)

Key findings

2019 Impact of the nuclear sector on EU economy	
1,129,900*	numbers of jobs
47%	of the total numbers of jobs in the nuclear sector are highly skilled, equaling a number of 531,900
€507.4 bn	in EU GDP, which equals ~ 3-3.5% share of 2019 EU GDP
€383.1 bn	disposable household incomes
€124.2 bn	public revenues generated through tax payments
€1,092.3 bn	investments undertaken in the EU
€18.1 bn	trade surplus within the EU

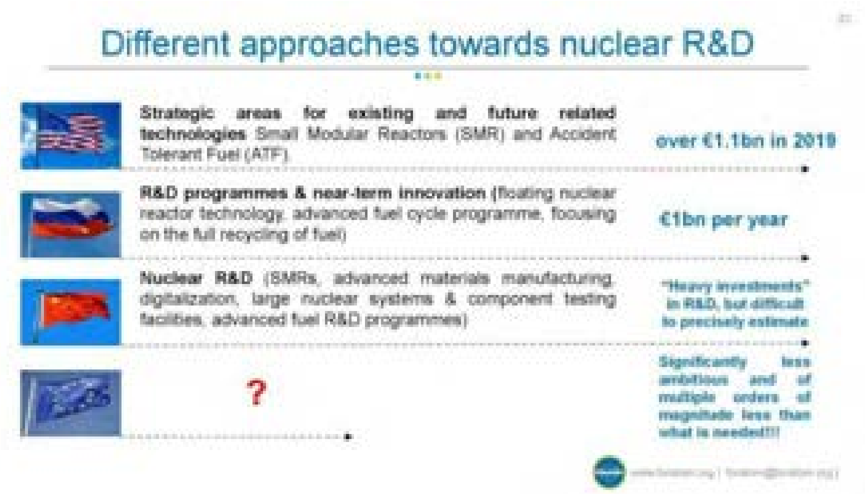


*This figure does not include the full spectrum of jobs in fission R&D, therefore the actual number is even higher

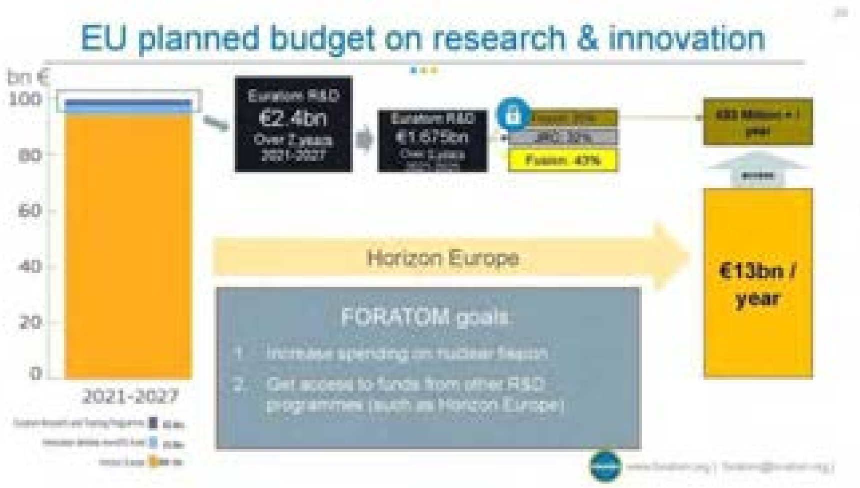
Nuclear energy's economic impact

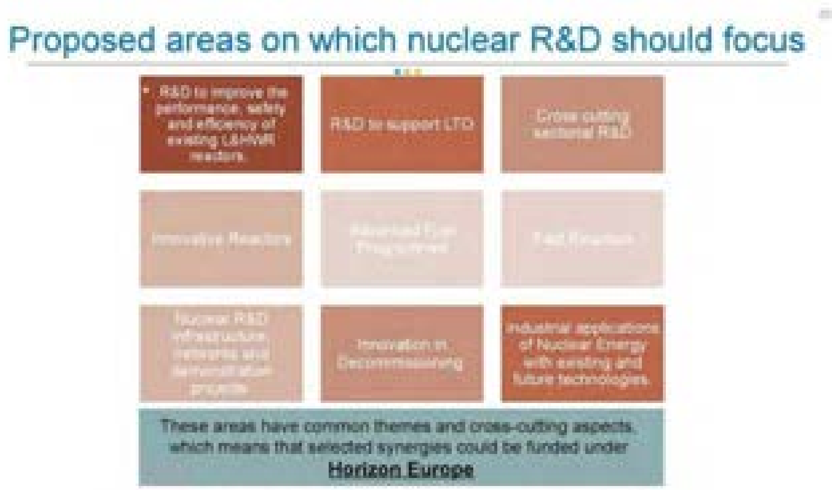
2019	2050
• **1,129,900** jobs in the EU • **€507.4 billion** in EU GDP	• **1,321,600** jobs in he EU • **€576 billion** in EU GDP*


RESEARCH & INNOVATION CHALLENGES


Different approaches towards nuclear R&D
Strategic areas for existing and future related technologies Small Modular Reactors (SMR) and Accident Tolerant Fuel (ATF)
over €1.1bn in 2019
R&D programmes & near-term innovation (floating nuclear reactor technology, advanced fuel cycle programme, focusing on the full recycling of fuel)
€1bn per year
Nuclear R&D (SMRs, advanced materials manufacturing, digitalization, large nuclear systems & component testing facilities, advanced fuel R&D programmes)
"Heavy investments" in R&D, but difficult to precisely estimate
?
Significantly less ambitious and of multiple orders of magnitude less than what is needed!!!


Challenge: Expand value added R&D outside of Euratom
Euratom R&D H2020 Avg Spend Over calls 2019-2020
Just over half of the fission R&D budget is dedicated to fission power R&D projects:
~ €40-50m / year !!


EU planned budget on research & innovation
bn €
100
80
60
40
20
0
2021-2027
Euratom R&D
€2.4bn
Over 7 years
2021-2027
Euratom R&D
€1.675bn
JRC 32%
Fusion 43%
Horizon Europe
€13bn / year
FORATOM goals
1. Increase spending on nuclear fission
2. Get access to funds from other R&D programmes (such as Horizon Europe)


Proposed areas on which nuclear R&D should focus
R&D to improve the performance, safety and efficiency of existing L&HWR reactors
R&D to support LTO
Cross cutting sectorial R&D
Innovative Reactors
Fast Reaction
Innovation in Decommissioning
Industrial applications of Nuclear Energy with existing and future technologies
These areas have common themes and cross-cutting aspects, which means that selected synergies could be funded under Horizon Europe


Colaboration outside of the Nuclear Sector:
Case study – RIMA project
RIMA
RIMA - European project to drive innovation in robotics for I&M by establishing a pan-European network of Digital Innovation Hubs
The objective of RIMA is to reinforce the leadership of Europe in I&M robotics by connecting technology to industrial/sectorial needs and foster efficient cross border cooperation in Europe
Project funded under the Digitising European Industry Call of Horizon 2020
FORATOM role
Member of the RIMA consortium
Bridge the gap between:
SMEs within the robotics community
Potential end users within the nuclear industry (licencees, I&M service providers, operators, etc.)


KEY TAKEAWAYS


Importance of investing in nuclear R&D
1. Euratom 2021-2025 funding for fission R&I should be increased
2. Horizon Europe & Euratom 2021-2025 should be set up to complement each other (common themes & cross-cutting aspects)
3. Cohesion and synergy with R&D in the SET Plan Action 10 'Nuclear' must be considered & support given for shared benefits across R&D programmes
4. The scope of the WP Euratom 2021-2025 should be reflective of the direction of Member States, industry & academia stakeholders


FORATOM IRD WG planned activities
Opportunities for the Euratom R&T 2021-2025 & Horizon Europe Programmes


Thank you
FORATOM
Nuclear in a changing world

PIERRE JEAN COULON

President of the Transport Energy and Networks section, European Economic and Social Committee

Research and Innovation missions and benefits to Civil Society to tackle today's Societal Challenges

The EESC is a body representing the views of organized civil society in Europe, thereby fulfilling advisory functions to the legislating EU institutions. It can be seen as the voice of the whole organized civil society in Europe.

Since the beginning of European Union – EESC was created in 1958 - it was associated to the EURATOM treaty and its work: see EURATOM art. 31 – 40 – 41 – 96 – 98 …

The EESC and its Section for Transport Energy Infrastructures and Information Society, I am the President have produce several opinions related to nuclear as energy source and on research programmes led in these fields: December 2018 , we adopted an opinion on the research and training programme of the atomic energy community for period 2021 – 2025. January 2019 two opinions, one about EU budget for ITER, another one on nuclear decommissioning and radioactive waste management. The EESC has also worked on opinions on the Nuclear Illustrative Programme (PINC) and called to accelerate innovation in the field of clean energy. Don't forget also that the European Commission is formally required to request and take into account/respond the Committee's opinions on nuclear illustrative program.

Beyond these opinion, EESC has contributed since its start in 2007 and myself as member of the steering committee, to the development of the European Nuclear Energy Forum (ENEF) organized under the auspices of EC, the SK and CZ governments. We also have recently fact finding missions to the ANDRA laboratory for radio-active waste storage, as well one to the ITER fusion reactor in Cadarache – France but worldwide work - in order to ensure that EESC's knowledge is updated and civil society involved in these fields.

The EESC does not take a conclusive position in favour or against nuclear power generation, but it recognizes that almost 30% of the EU-28's electricity is produced from nuclear energy in more than 14 member states. This fact will be during a forthcoming very long period a part of European Energy Mix, it is why organized civil society is very interested in the different topics as nuclear safety, radioactive waste production and management, social and climate implications, also…

Nuclear energy is one option to decarbonize economies…

Dear colleagues and friends, don't forget that without acceptance or better support of civil society – I say the whole civil society- it will be difficult to move forward: this is why we have to clearly say:

Let's work together for the citizens, with the citizens, by the citizens…

DORU VISAN

Secretary of State, Ministry of Energy, Romania

KEYNOTE

Mr Minister,

Dear representatives of the European Commission,

Dear Participants,

Ladies and Gentlemen,

Today, I am pleased to represent the Ministry of Energy at the Open Session of the FISA and EURADWASTE Conferences, jointly organized by the European Commission and the Romanian Presidency of the Council of the EU in 2019.

I am honored that the Institute for Nuclear Research, entity under the authority of the Ministry of Energy, was entrusted with the co-organization of this event, as a proof and acknowledgment of its contribution to the EURATOM projects.

Established in 1971, RATEN ICN has continuously provided the technical and scientific support for the National Nuclear Program from its launch until its implementation, by commissioning Units 1 and 2 from Cernavoda, delivering equipments and services for the safety of operations.

The outstanding performance of the Cernavoda Nuclear Power Plant is also due to the contribution of the ICN researchers, starting with the manufacturing of the first CANDU fuel elements, their testing in the TRIGA research reactor, the performance analysis in the post-irradiation examination laboratories.

Through their experience and competence gained over the years, RATEN, through its subsidiaries ICN and CITON, is now ready to respond to the current priorities of the Nuclear Power Program regarding the refurbishment of Cernavoda Unit 1, the construction of the near surface disposal and the implementation of the ALFRED demonstrator in Romania.

RATEN participation in the EURATOM Framework Programs has supported the national nuclear energy priorities, particularly in the field of nuclear safety, life time extension of the nuclear installations, radioactive waste management, transfer of knowledge and dissemination of research results.

I am convinced that this scientific event will summarizes research results that has been achieved so far and will identify new research directions, thus for the nuclear energy to meet the objectives of the European Union's policy initiative "20-20-20", through security, sustainability and competitiveness.

I wish a successfully Meeting!

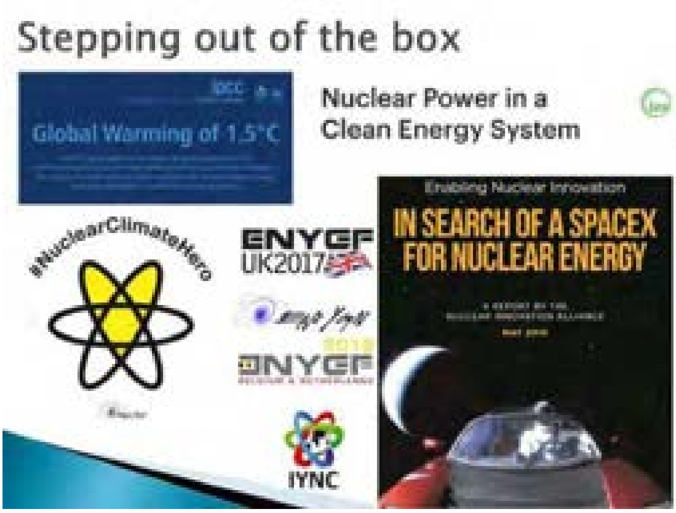
NATHAN PATERSON
Chair European Nuclear Society Young Nuclear Generation, Belgium

The future of Nuclear: Collaboration, Vision and Innovation – perspectives from the YGN


21 Member Societies
Observer Partners
WiN
World Nuclear Association
IYNC
IAEA

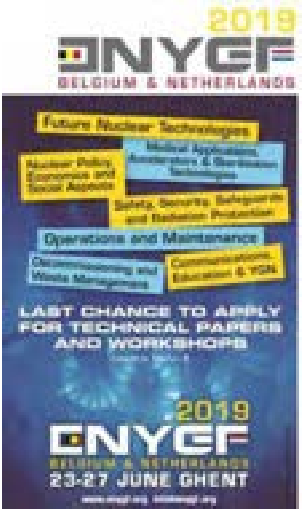

Who are we and what we stand for!!
The global population is growing and the demand for **safe, clean** and **reliable electricity** is more important than it has ever been.
We must continue developing the global **nuclear industry** and strive for more **collaboration**, **innovative technologies** and **harmonization** of **best practices** to meet the needs of our **future.**
UN SDGs Extract

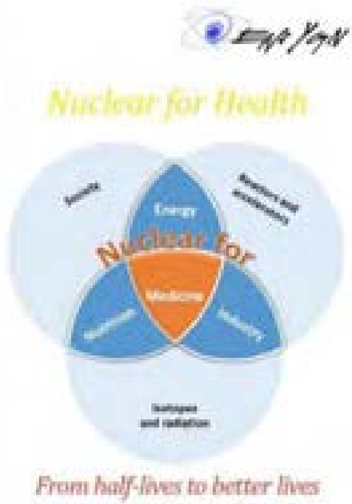

Words or Actions?
Innovation
Vision
Collaboration

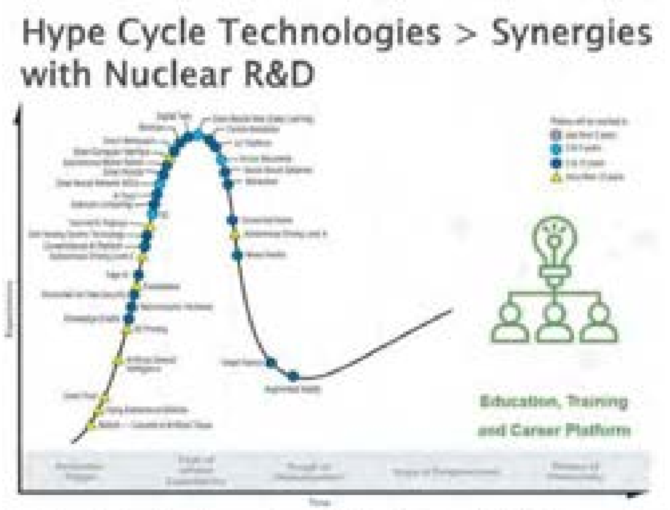

Stepping out of the box
Global Warming of 1.5°C
Nuclear Power in a
Clean Energy System
#NuclearClimateHero
ENYGF
UK2017
ENYGF
IYNC
Enabling Nuclear Innovation
IN SEARCH OF A SPACEX FOR NUCLEAR ENERGY


Sharing knowledge between generations:
Active ongoing campaign on Twitter and Facebook – Please follow us with #Nuclear4Climate
Presence at COP with N4C booth and side events as official UN registered delegation of around 40 persons
CLIMATE
NUCLEAR
SOLUTION

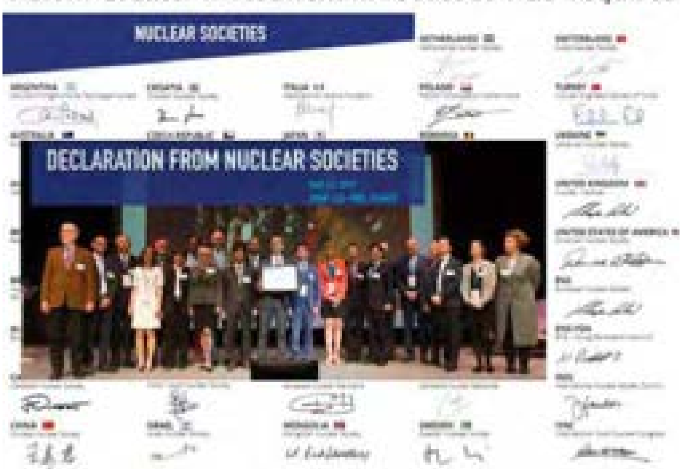

Nuclear technologies for the benefit of society
H2
District and Industrial heating
NUCLEAR MEDICINE
NUCLEAR
SOLUTION







Vision: Greater Investment in focussed R&D required



JOERG STARFLINGER

Vice-president of ENEN, University of Stuttgart, Germany

The future of Nuclear: Collaboration, Vision and Innovation – perspectives for the Young Generation

Royal Flemish Academy, Brussels, March 1, 2018

ENEN: European Nuclear Education Network

ESTABLISHED in 2003

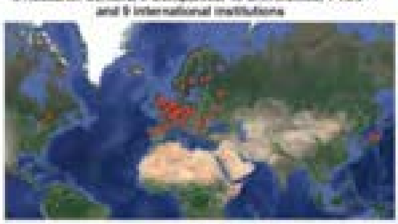
Steady support by European Commission through projects

OBJECTIVE

Preservation and further **development** of expertise in the nuclear fields by higher Education & Training.

ENEN Members in 2018

76 Members from 25 Countries:
8 Research Centers, 9 Companies, 48 Universities, 1 TSO and 9 international institutions



Selected Achievements of ENEN

Established

- Exchange of information, best practices, teachers and students
- Voluntary accreditation in academic education (quality control, quality assurance)

Ongoing: Projects ANNETTE, ENEN+

- Facilitating communication and cooperation between nuclear stakeholders and access to research infrastructures, to projects and internships
- Innovative teaching an learning methods (MOOCs, flipped-classroom approaches, etc.)
- Coordination of ETKM activities (Education, Training, Knowledge Management) among different NUCLEAR communities

PhD Event & Prize and Mobility

- Key success indicators:
  - ENEN+ mobility program „living the European idea of exchange and networking" **1,000,000 €** for mobility of B.Sc., M.Sc., Ph.D. and teachers plus.enen.eu
  - ENEN PhD event (Wednesday at FISA19)

- The number of students is decreasing. **Is Nuclear E&T a cause of concern?** See you E&T workshop at 14h in "Ametist Room"

June 4-7, 2019 FISA conference, Pitesti, Romania 6

Thank you for your attention

www.enen.eu

European Nuclear Education Network AISBL
Rue d'Egmont 11, 1000 Brussels, Belgium

Telephone: +32 484 20 15 04
Email: secretariat@enen.eu

June 4-7, 2019 FISA conference, Pitesti, Romania 7

SERBAN CONSTANTIN VALECA

President of the Scientific Council in RATEN ICN, Professor at the University of Pitesti, Romania

KEYNOTE

Dear guests, dear participants, in fact, dear nuclear workers, both those with long experience and the younger ones who are at the beginning,

It is a great honour for me to have some opening remarks and to chair the first session.

First of all, I wish you welcome in Romania and in Arges County, a county that in history has 2 very old capitals of our country. At the same time for Pitesti, the capital of Arges County the first documentary attestation is from 630 years ago.

Dear participants in FISA and EURADWASTE conferences,

The nuclear power is an important pillar of the Europe Union energy mix having a significant contribution to the reduction of the emissions, security and stability of the supply, and to affordable prices of electricity.

At the same time, the debate on the nuclear continued to express a set of opinions in relation with the challenges, difficulties, and opportunities of the nuclear power development in terms both of the global economy aspects and of the national contexts.

A strong stimulation of renewable (especially for the variable renewables: wind and photovoltaic), occurred mainly in the EU, are impacting the nuclear development. Today nuclear power has no enough capabilities to support the variable production and is necessary to work complementarily with them in order to ensure a complete free-carbon electricity production.

In Romania we discuss very openly on the equal treatment of nuclear power and renewables as energy options without carbon emissions. The Ministry of Energy proposed a common support scheme for all free carbon electricity. In this manner we intend to support nuclear on the basis of the same principle.

Despite of the complications of the decision-making process, it is clear that the nuclear represents an important solution to be managed in an appropriate way. The nuclear research and development have new opportunities such as the new systems (Gen III+, GenIV, and SMR) or challenging solutions for safety of the NPPs, geological disposal, etc.

FISA 2019 and EURADWASTE ’19 conferences in Safety of Reactor System and Radioactive Waste Management represent an opportunity to find some answers to these challenges through the proposed objectives:

- To present progress since the previous conference edition in 2013
- To stimulate discussions on the state of play of R&D, key challenges addressed at national, European and international levels
- To address the latest EC proposal for a new Framework Programme for Research and Innovation for the next period 'Horizon Europe' and 'Euratom Research and Training' programme.

In 2018 the Special Report of Global Warming of 1.5°C done by the Intergovernmental Panel on Climate Change above preindustrial levels and related global greenhouse gas emission pathways, in the context of strengthening global response of to the threat of climate change, sustainable development and efforts to eradicate poverty, the report state that limiting the global temperature increase to 1.5°C will prevent the worst impact of climate change, but will require rapid, far-reaching and unprecedent action on decarbonisation. Gen IV of nuclear reactors promise to be part of solution.

In this respect, Romania is deeply involved in the implementation of ALFRED LFR demonstrator. As hosting country, we are preparing the licensing and siting process, the education and training process for the future workforce, and participating in finding valuable solution for the open issues.

At decision-making level, the proposed funding scheme is based on a mix of European structural funds (for Romania), the national and industry contribution. Important steps were achieved by introducing ALFRED in the most important national strategic documents. Now the main effort will be devoted to negotiate the presence of ALFRED in the future EU budget, and the declaration as major project in the future EU-Romania partnership Agreement.

Dear participants,

The two EURATOM conferences will approach the most important achievements in the last years in nuclear RDI. Beyond of these I wish you a fruitful process to identify the best ways for new collaborations to drive the nuclear power toward a better future in the benefit of a more united Europe, based on independence in energy supply, and with zero carbon emissions.

I wish a full success for all the sessions of the conferences and to have a wonderful experience in Pitesti and Romania!

INTERNATIONAL/EU/EURATOM STATUS IN RADIATION PROTECTION, SAFETY OF REACTOR SYSTEMS AND RADIOACTIVE WASTE MANAGEMENT

Chair: Horia GRAMA (ANDR, RO)
Co-chair: Massimo Garribba (EC, DG ENER)
Rapporteur: Hans Forsström (SE)

FISA 2019
EURADWASTE '19

4-7 June, 2019
Pitesti, Romania

SESSION SUMMARY

HANS FORSSTRÖM

International independent expert, Sweden - General Rapporteur

SUMMARY REPORT OF THE SESSION ON INTERNATIONAL/EU/EURATOM STATUS IN RADIATION PROTECTION, SAFETY OF REACTOR SYSTEMS AND RADIOACTIVE WASTE MANAGEMENT

Horia Grama[1], Massimo Garribba[2], Hans Forsström[3]

[1]Agentia Nucleara si pentru Deseuri Radioactive, Romania
[2]European Commission, DG Energy
[3]International independent expert, Sweden

This report summarises the outcome of the session on International/EU/EURATOM Status in Radiation Protection, Safety of Reactor Systems and Radioactive Waste Management.

The Chairman introduced the session by highlighting the importance of the Euratom Directives for safe operation of the nuclear facilities and for defining and implementing strategies for spent fuel and radioactive waste management.

The session had three parts, Status of EU/EURATOM Directives, Radioactive Waste Management and Safety Reactor Systems.

In the first part presentations were made by Michael Hübel and Massimo Garribba from the Commission on the development the Euratom Directives on Basic Safety Standards (BSS) (2013), Nuclear Safety of Nuclear Installations (2014) and Spent Fuel and Radioactive Waste Management (2011), and on the implementation of the latter Directive. In addition, a presentation was made by the Andrew Orrell from IAEA on the ARTEMIS peer review service which is widely used by Member States to review their compliance with the spent fuel and radioactive waste Directive.

The main messages from these presentations were:

- Euratom provides a comprehensive framework to ensure a high level of radiation protection and nuclear safety across Europe.
- Significant changes have recently been introduced in the BSS and the Nuclear Safety Directives. In particular the BSS has been reworked to incorporate older Directives connected to radiation protection and conformity checks of MS legislations are underway. In the Nuclear Safety Directive Topical Peer Reviews (TPR) have been introduced in the revised Directive 2014, and the first TPR on ageing management has

taken place. As a result, national plans are being established to follow up on the TPR outcomes.

- The purpose of the Directive on Responsible and Safe Management of Spent Fuel and Radioactive Waste is to ensure appropriate national arrangements for a high level of safety and to avoid imposing undue burdens on future generations. It should also ensure public information and participation. An important component of the Spent Fuel and Radioactive Waste Management Directive is the requirement for countries to have a national programme for the management of all types of spent fuel and radioactive waste from generation to disposal. The first report on the implementation of the Directive was presented to the Council and European Parliament in 2017 and a new report is due in 2019. It notes the activities and plans of the MS, especially as concerns the timing of disposal of spent fuel or high level waste.
- The Spent Fuel and Radioactive Waste Management Directive requires that MS arrange for self-assessments of their national framework, competent regulatory authority, national programme and its implementation, and invite international peer review at least every ten years. Together with the EC, the IAEA has developed a peer review service, ARTEMIS, which includes both components of audit that the MS are fulfilling the requirements in the Directive and components of peer review and advice on the planned programme. Until now 6 EU MS have used the ARTEMIS. ARTEMIS is flexible in design and has also been utilised by non-EU countries for specific reviews.

The second part on Radioactive Waste Management consisted of a keynote presentation by Pierre-Marie Abadie from ANDRA, France on the European and International status on the management and disposal of radioactive waste, and a presentation by Christophe Davies from the European Commission on the Euratom research and training programme in radioactive waste management.

The main messages from the keynote presentation were:

- LLW from NPP operations are disposed of adequately in many existing facilities throughout the world.
- HLW, ILW and SNF can be disposed of in Deep Geological Repositories, and development of three such facilities is progressing in Finland, France and Sweden with ongoing or planned licensing, while siting activities are going on in several other countries, based on the availability of a strong scientific/technical knowledge base.
- Large volumes of waste from decommissioning will require optimisation of the management, where characterisation is a key point.
- Some long-lived radioactive waste with low level of radioactivity (e.g. graphite or depleted uranium and NORM) will require new appropriate disposal routes, which might depend on national policies.
- The long duration of disposal projects (>100 years) will require a strong knowledge management process.
- The activities of IAEA, OECD/NEA and EC strongly contribute to national efforts in a complementary and consistent way.
- In particular as concerns RD&D the support by the EC is positive and the developments towards a Joint European Programming are very good. This is also the case for the broadening of the activities from geological disposal to also include

management of other wastes, including predisposal and decommissioning. The EC has also promoted the sharing between all actors (Waste producers, Waste Management Organisations (WMOs), Technical Support Organisations (TSOs), Research Establishments (Res) and the Civil Society) in developing a Joint Strategic Research Agenda, collaborative R&D, joint knowledge management and training processes and joint strategic studies.

In the presentation of the Euratom R&T programme on radioactive waste management it was shown how the programme since the start in 1975 has progressed from a large number of uncoordinated projects to the call for one European Joint Programme in 2018, which brings together WMOs, TSOs, REs and representatives from the Civil Society.

The Joint Programming (JP) is in line with the strategy of the European Research Area, which is promoted by the European Commission since the early 2000's. JP should provide EU-added value, leverage and benefit to all national programmes. In working together, as part of a European Joint programme, advanced countries will be able to address specific cutting-edge science on very deep scientific topics, while less advanced programmes will be able to plan, structure and implement the necessary R&D, with guidance, training and transfer of competence and knowledge from advanced programmes.

This closer cooperation within the Euratom programme has developed successively over a long period, starting in the early 2000s between WMOs and then through platforms and networks like the IGD-TP for the WMOs, SITEX for TSOs and recently EURADSCIENCE for the REs.

In the latest calls also pre-disposal activities and decommissioning have been reintroduced in the Euratom programme in line with the recommendations from EURADWASTE '13.

The last part of the session called Safety of Reactor Systems included a report by Martin Murray from the Euratom Scientific and Technical Committee (STC) and a broader presentation of all activities in the Euratom programme in addition to radioactive waste management by Roger Garbil from the European Commission.

The STC is an advisory body within the Euratom Treaty providing advice to the Commission and the Council. In their latest opinion paper in 2018 they highlighted inter alia:

- Nuclear plays an important role as a component of low carbon electricity supply and should be a part of the road-map to a zero carbon society.
- Nuclear R&D is needed to maintain capability in the nuclear field and provide the basis for high standards of safety and non-proliferation and ensure competitiveness of the European industry. Education and training is an important component in the R&D.
- It is of interest for all EU MS as the impacts of nuclear energy pass borders.
- Given this situation it is time to increase the EU funding for nuclear R&D, but also to find funding possibilities in other EU programmes, e.g. concerning health and materials.
- Not only should the work on fusion and fission for electricity production be pursued but also work on non-electricity applications in industry and on production of radioisotopes for medical and industrial uses.
- Given the controversy about nuclear power and nuclear applications socio-economic research is needed.

International/EU/Euratom status

In June 2018 the Commission proposed a new Euratom R&T programme for 2021 – 2025. It has four headings:

- Improve the safe and secure use of nuclear energy and non-power applications of ionizing radiation, including nuclear safety, security, safeguards, radiation protection, safe spent fuel and radioactive waste management and decommissioning.
- Maintain and further develop expertise and competence in the Union.
- Foster the development of fusion energy and contribute to the implementation of the fusion roadmap.
- Support the policy of the Community on nuclear safety, safeguards and security.

The budget proposed is 1,675 billion € for a 5 –year period (2021 – 25). About 43 % will go to fusion research, 37 % to the JRC and the remaining 20 % for the co-operative research on safety of reactor systems, radiation protection, radioactive waste management and decommissioning. The proposal is now discussed in the European Parliament.

The issues covered in safety of reactor systems include:

- Safety of existing reactors
- Development of advanced reactors
- P&T and closed fuel cycle
- Cross-cutting research
- Other applications

At the end of the session a short panel discussion was held on the Role of the Euratom R&T programme and the Directives. In particular the added value of the programme was raised, and it was concluded that although most of the nuclear R&D is performed nationally the Euratom contribution makes it possible to build a common vision and to continue the work in a coordinated way across Europe. The example of the activities in P&T was given where it has been possible to go from lab scale towards semi-industrial application. Other topics raised to the panel concerned the need to increase activities on non-power applications to help develop the carbon free society and the need to look at the social impact of nuclear, not least in connection with transports.

STATUS OF EU/ EURATOM DIRECTIVES

FISA 2019
EURADWASTE '19

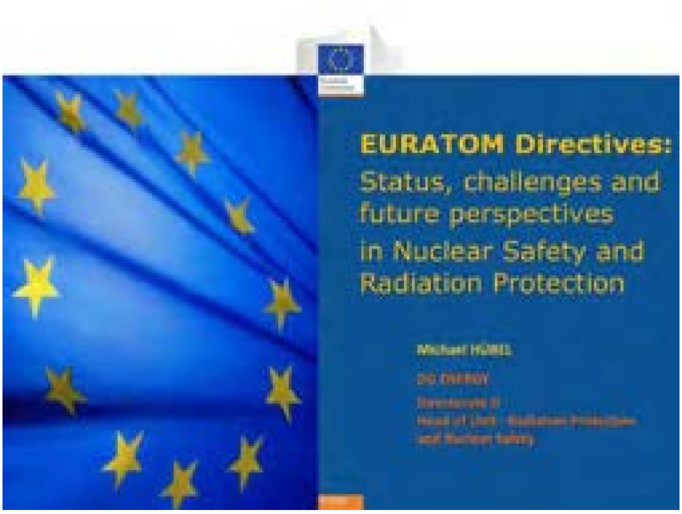
4-7 June, 2019
Pitesti, Romania

MICHAEL HUEBEL
Head of Unit - Radiation Protection and Nuclear Safety, DG ENERGY, Directorate D, EC

EURATOM Directives: Status, challenges and future perspectives in Nuclear Safety and Radiation Protection

MICHAEL HUEBEL

DG ENERGY, Directorate D, EC




Strengthening the legal framework
Directive 2009/71/Euratom
Nuclear Safety of nuclear installations
Directive 2011/70/Euratom
Spent Fuel and Waste Management
Directive 2013/51/Euratom
Euratom Drinking Water Directive
Directive 2013/59/Euratom
Basic Safety Standards
Directive 2014/87/Euratom
amending Directive 2009/71/Euratom


Nuclear Safety


Nuclear Safety
Follow up to Fukushima nuclear accident
European Council 24-25 March 2011
2 mandates
Risk and safety assessments of nuclear power plants ("stress tests")
Review of the legal and regulatory framework for the safety of nuclear installations – amended Directive


EU Stress Tests in 2012
ENSREG
All 14 EU Member States that operate nuclear power plants, plus Lithuania, Switzerland, Ukraine. Additionally, Taiwan (2013), Armenia (2016) and Belarus (2018).
Planned in Turkey and Iran.

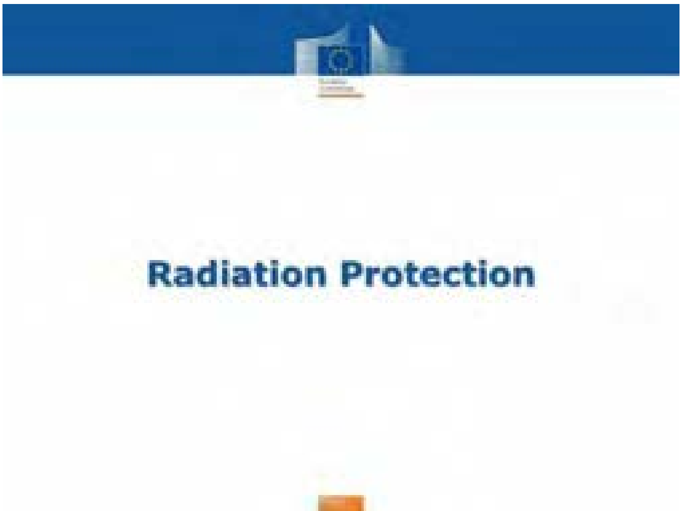

Amended 2014 Nuclear Safety Directive
New
Safety objective
Strengthened
Independent regulatory authority
Strengthened
Transparency
Continuous improvement of nuclear safety
New
Peer reviews
New
Emergency preparedness and response
New
Nuclear safety culture


Nuclear Safety objective
Design
Siting
Construction
Commissioning
Operation
Decommissioning
• Prevent accidents
• Mitigate consequences - avoid radioactive release


Main measures to achieve the safety objective
as provided for in the Directive
Defence-in-depth
Nuclear safety culture
Safety objective
Initial assessments and periodic safety reviews
Emergency preparedness and response


European system of Topical Peer Reviews
Introduced by amended Nuclear Safety Directive → every 6 years (and following severe accident)
Inspired by EU stress tests
1st Topical Peer Review in 2017/18 - Ageing management of nuclear reactors - final report published October 2018, National Action Plans to follow


TPR 2018 findings, challenges
Ageing management programmes in place for all nuclear power plants, based on IAEA safety standards and WENRA reference levels, although some differences of national approach.
Ageing management of research reactors to be brought in line with that for NPPs.
Challenges remain on means to evaluate the effectiveness of Ageing Management Programmes.
Use of international Peer Review Services is a good practice.
National Action Plans to be prepared by September 2019.

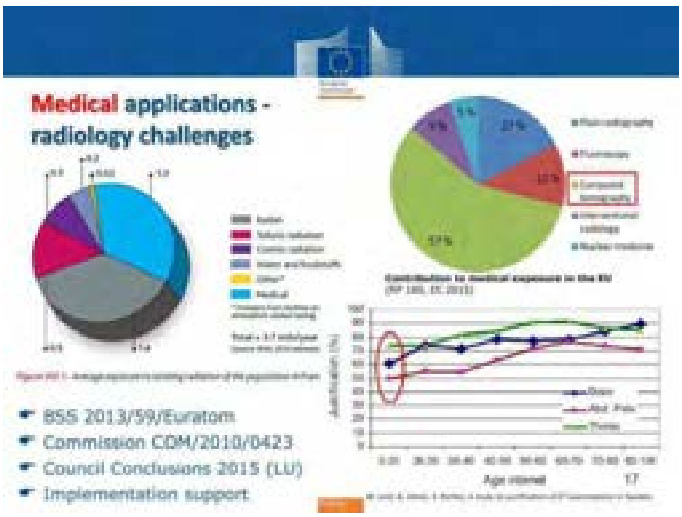

Radiation Protection

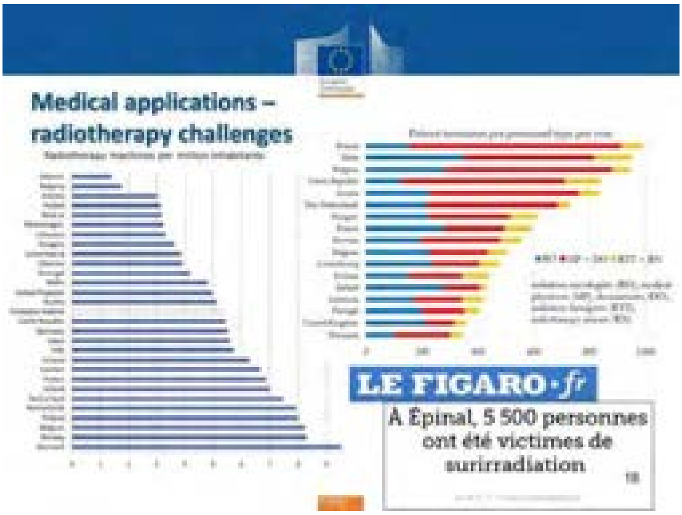

Basic Safety Standards
Euratom Treaty (1957)
Chapter on health and safety
Establish uniform basic safety standards for the protection of the health of workers and the general public against dangers arising from ionising radiations
... and ensure that they are applied.


Radiation Protection
Basic Safety Standards Directive (2013)
Justification
Dose Limits
Optimisation
Protection of workers, members of the public and patients
Regulatory Control
Emergency preparedness and response
Education and Training
Other requirements


Motivation and Objective of the 2013 Revision
Modernisation
Take account of latest scientific findings (e.g. ICRP 2007), technological development as well as operational experience since 1996
Cover all radiation sources – including natural radiation
Cover all exposure situations – planned, existing, emergency
Integrate protection of workers, members of the public, patients and the environment
Harmonise, to the extent possible, numerical values with international standards
Consolidation and streamlining- repealing:


Council Directive 2013/59/Euratom provides
Better protection of
workers,
medical staff,
emergency workers and
workers in workplaces with natural radiation sources (indoor radon), activities processing naturally occurring radioactive material (NORM);
Better protection of the public, in particular from:
radon in dwellings,
exposure from NORM activities and building materials
deliberate exposure for non-medical purposes;
Better protection of patients, in particular with regard to the avoidance of incidents and accidents in radio diagnosis and radiotherapy;
Strengthened requirements on emergency preparedness and response, especially with a view to the lessons learned from the Fukushima accident.
16

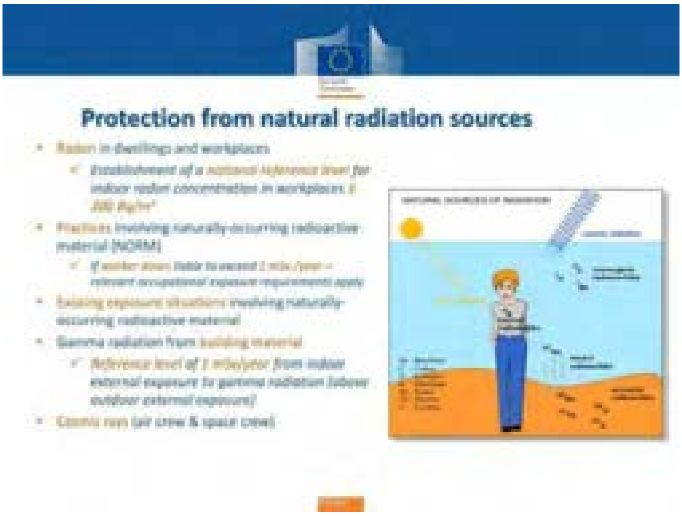

Medical applications - radiology challenges
57%
27%
BSS 2013/59/Euratom
Commission COM/2010/0423
Council Conclusions 2015 (LU)
Implementation support
Age interval
17


Medical applications –
radiotherapy challenges
LE FIGARO·fr
À Épinal, 5 500 personnes
ont été victimes de
surirradiation
18


BSS medical – main changes
Justification
• Transparency of justification for types of practice
• Equipment information – link with EU Medical Devices law
• Asymptomatic – guidelines, documenting, info to the 'client'
Optimisation
• DRLs – mandatory, regular review, applicable to IR
Responsibilities / Procedures
• Stronger MPE involvement in IR, CT, paediatric, screening
• Information to patients on benefits and risks
Equipment
• Dose-related information, transfer to examination record
Accidental and unintended exposures
• Risk assessments, recording, reporting, dissemination

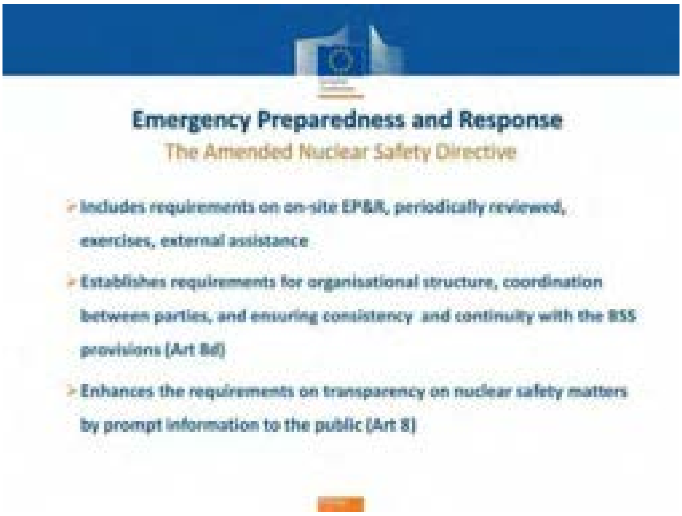

SAMIRA = Strategic Agenda for Medical,
Industrial and Research Applications
Objectives: systematically identify issues relating to the use of nuclear and radiation technology outside the nuclear energy sector and propose actions to address them
Cover: security of supply of radioisotopes, radiation protection and safety, research and innovation
20


Towards SAMIRA Action Plan
Where action is most needed
EU could add real value to Member State actions
Concentrated largely in the medical field
Secure supply of radioisotopes for Europe
Improve radiation protection and safety for patients and medical staff
Facilitate innovation in the medical practice
Strengthen human resources and facilitate capacity building


Protection from natural radiation sources
Radon in dwellings and workplaces
Establishment of a national reference level for indoor radon concentration in workplaces ≤ 300 Bq/m³
Practices involving naturally-occurring radioactive material (NORM)
If worker doses liable to exceed 1 mSv/year – relevant occupational exposure requirements apply
Existing exposure situations involving naturally-occurring radioactive material
Gamma radiation from building material
Reference level of 1 mSv/year from indoor external exposure to gamma radiation (above outdoor external exposure)
Cosmic rays (air crew & space crew)


National radon action plan
Establishment of a national radon action plan addressing long term risks from radon exposures (Article 103)
In dwellings, buildings with public access and workplaces
From any source of radon ingress – soil, building material, water
National action plan needs to take into account the issues set out in Annex XVIII of the BSS Directive
Ensure appropriate measures to prevent radon entry into new buildings, e.g. through specific requirements in building codes
Identify areas with a significant number of buildings expected to exceed the national reference level


Emergency preparedness and Response
The BSS Directive
Provisions of Basic Safety Standards Directive
• Assessment of emergency situations
• Management emergency exposures,
• Emergency response plans, protective measures, notification, emergency workers
• Cooperation across Member States
• Information to the public
• Transition from emergency to existing exposure situation
Council Conclusions on EP&R (Dec 2015)
➢ Coherent protective measures along adjacent national borders,
➢ MS's cooperate closely on EP&R,
➢ MS's intensify efforts for joint training and emergency exercises,
➢ Better cross-border coordination of protective measures


Emergency Preparedness and Response
The Amended Nuclear Safety Directive
➢ Includes requirements on on-site EP&R, periodically reviewed, exercises, external assistance
➢ Establishes requirements for organisational structure, coordination between parties, and ensuring consistency and continuity with the BSS provisions (Art 8d)
➢ Enhances the requirements on transparency on nuclear safety matters by prompt information to the public (Art 8)


Emergency Preparedness & Response
Commission role
➢ Information exchange
✓ inform Member States (ECURIE)
✓ EUropean Radiological Data Exchange Platform (EURDEP)
➢ Protection:
activate emergency measures (Food/feed Regulations)
➢ Response:
Contribute to EU-level response (civil protection, medical...)


The Euratom perspective
• Euratom provides a comprehensive framework to ensure a high level of radiation protection and nuclear safety across the EU
• NSD and BSS Directives – significant changes, strengthened legal framework
• Conformity checks of Member States' legislation and application are underway – will identify areas where joint actions are needed
• Science based provisions – research outcomes feed into the development of the legal framework


THANK YOU
https://ec.europa.eu/energy/en/home

MASSIMO GARRIBBA
DG ENER, European Commission

RESPONSIBLE AND SAFE MANAGEMENT OF SPENT FUEL AND RADIOACTIVE WASTE. THE COMMUNITY FRAMEWORK

MASSIMO GARRIBBA

DG ENER, European Commission


"WASTE & SPENT FUEL" DIRECTIVE
(Council Directive 2011/70/Euratom)
Major challenges addressed:
Sustainability
Safety
Transparency
• Avoid imposing undue burdens on future generations
• Appropriate national arrangements for a high level of safety
• Public information and participation


DIRECTIVE ON RESPONSIBLE & SAFE MANAGEMENT OF SPENT FUEL AND RADIOACTIVE WASTE
WHY
WHAT
WHO
HOW


COUNCIL DIRECTIVE 2011/70/Euratom
MEMBER STATES
• Establish national policies
• Have ultimate responsibility
• Establish a national legislative, regulatory and organisational framework
• Establish a competent regulatory authority
• Ensure the licence holders' prime responsibility
Policy
Framework
Programme
Reports
EUROPEAN COMMISSION roles:
• Guardian of the Treaties
• Legislative initiative
• Ensure compliance with EU regulatory framework
• Facilitate dialogue and cooperation between MS
• Report to other EU Institutions
COUNCIL OF EUROPEAN UNION role:
• Legislator
EUROPEAN COURT OF JUSTICE role:
• Jurisdiction


NATIONAL POLICIES have to ensure:
AVOID
REDUCE
REUSE
RECYCLE
RECOVER
TREAT
DISPOSE
• Generation kept to the minimum which is reasonably practicable
• Interdependencies shall be taken into account
• Safety management, including in the long term with passive safety features
• Graded approach
• Costs borne by those who generated those materials
• Evidence-based and documented decision-making process
Disposal in the Member State in which the waste was generated, unless an agreement is in force between the Member State and another country to use a disposal facility in its territory


1st COMMISSION REPORT
• Provides a comprehensive overview to the Council, European Parliament and EU citizens
• Brings the principle of avoiding undue burden on future generations
• Recognises MS' efforts and encourage pursuing them in several areas: policies, cost estimations, financing provisions and concrete projects for waste disposal.
• Main report COM(2017)236
• Staff Working Document SWD (2017)159 on MS implementation
• Staff Working Document SWD (2017)161 on inventories, prospects


WAY FORWARD
Different level of implementation by Member States
ADDITIONAL EFFORTS & SPECIFIC FOCUS NEEDED ON:
Policies, concepts and plans
Projections of inventories
Disposal facilities for intermediate and high level waste
Cost assessments of national programmes and financing mechanisms
Time-frames and key performance indicators for national programmes
Post-closure and knowledge preservation information
Self-assessments and international peer reviews
Availability of trained and competent staff
Shared disposal solutions' feasibility
Safety demonstrations
MS


IMPORTANCE OF THE R&D ON THE DIRECTIVE
Member States shall ensure that the national framework (for spent fuel and radioactive waste management):
Article 5 Obligations (5.2)
• is improved ...taking into account ... the development of relevant technology and research.
Article 8 Expertise and skills
• require all parties to make arrangements for ...research and development activities to cover the needs of the national programme...
Article 12 Contents of national programmes (12.1(f))
... shall include:
the research, development and demonstration activities that are needed in order to implement solutions


UNDERGROUND RESEARCH LABORATORIES
RESEARCH AND DEVELOPMENT
IN SPENT FUEL AND
RADIOACTIVE WASTE ACROSS THE EU


NATIONAL POLICIES
DEEP
GEOLOGICAL
DISPOSAL

PIERRE MARIE ABADIE

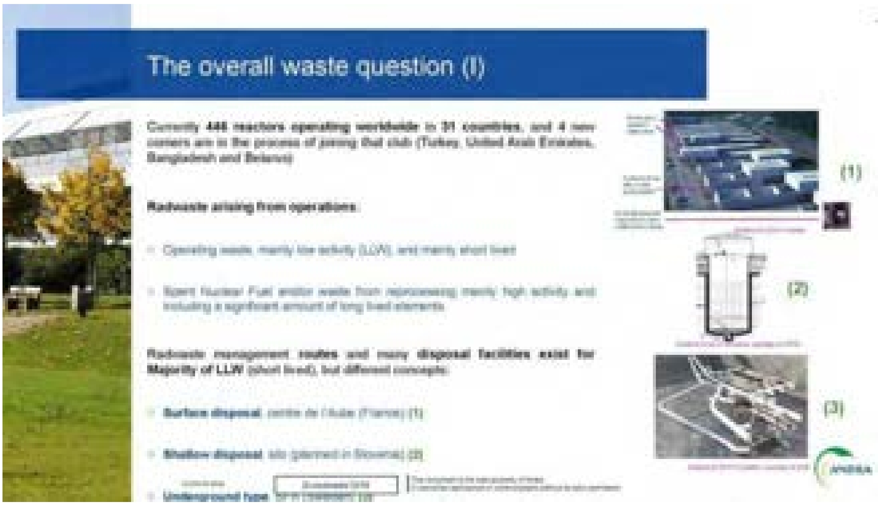
CEO, ANDRA, FRANCE

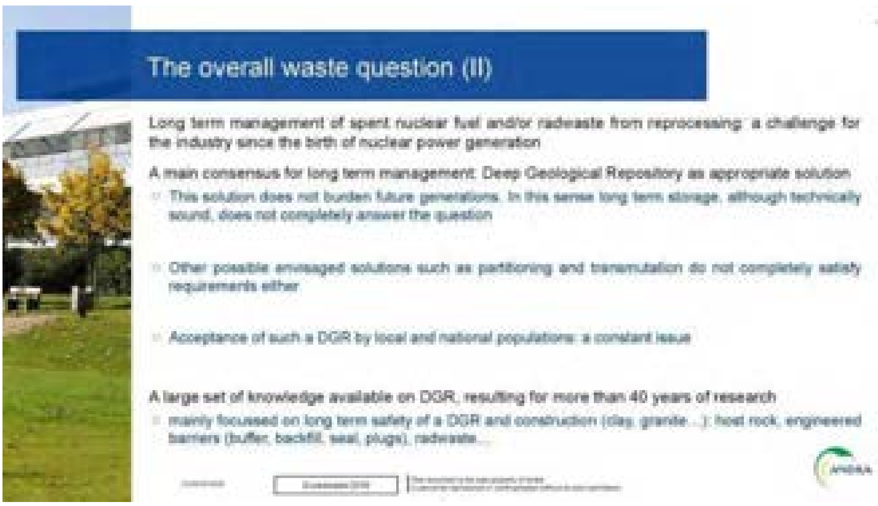
EUROPEAN AND INTERNATIONAL STATUS OF THE MANAGEMENT AND DISPOSAL OF RADIOACTIVE WASTE, DEVELOPMENTS AND CHALLENGES AHEAD

PIERRE MARIE ABADIE

ANDRA, FRANCE


Radioactive waste arising from power production
Operations

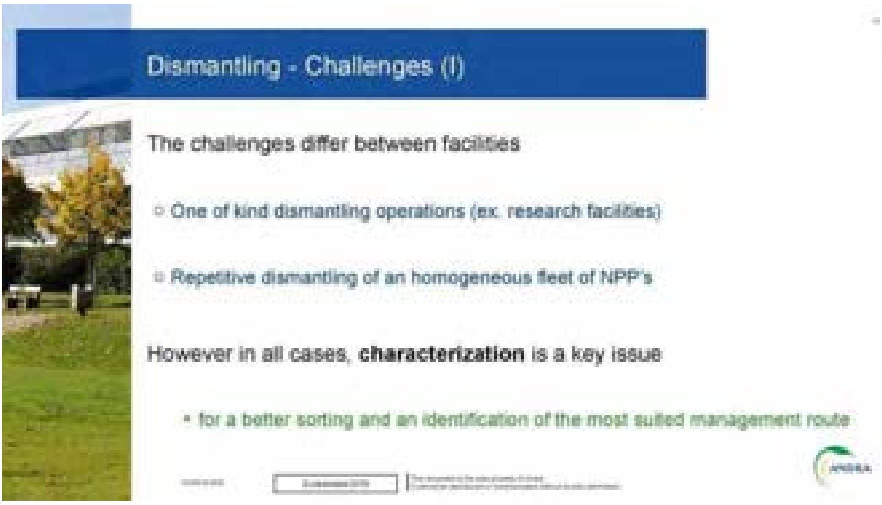

The overall waste question (I)
Currently 446 reactors operating worldwide in 31 countries, and 4 new comers are in the process of joining that club (Turkey, United Arab Emirates, Bangladesh and Belarus)
Radwaste arising from operations
Radwaste management routes and many disposal facilities exist for Majority of LLW (short lived), but different concepts
Surface disposal
Shallow disposal
Underground type
(1)
(2)
(3)


The overall waste question (II)
Long term management of spent nuclear fuel and/or radwaste from reprocessing: a challenge for the industry since the birth of nuclear power generation
A main consensus for long term management: Deep Geological Repository as appropriate solution
This solution does not burden future generations. In this sense long term storage, although technically sound, does not completely answer the question
Other possible envisaged solutions such as partitioning and transmutation do not completely satisfy requirements either
Acceptance of such a DGR by local and national populations: a constant issue
A large set of knowledge available on DGR, resulting for more than 40 years of research
mainly focused on long term safety of a DGR and construction (clay, granite ...): host rock, engineered barriers (buffer, backfill, seal, plugs), radwaste...

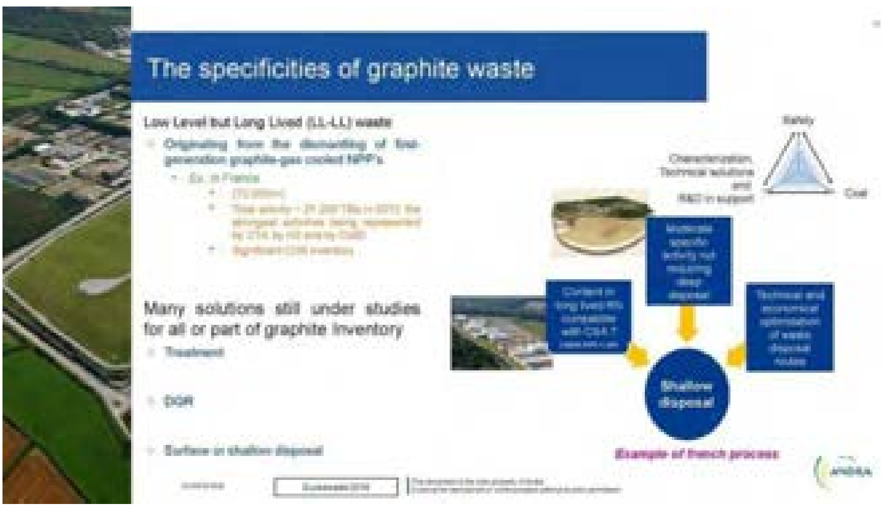

HLW, ILLW and Spent Nuclear Fuel: Situation regarding the DGR at 2019
Significant variety of situations
For 3 countries, established projects for disposal exist:
Finland has a license for excavating a facility (SNF in Crystalline host rock)
Sweden has applied for a license and the approval is pending (SNF in Crystalline host rock)
France has a target date for submitting a license application in 2020 (HLW and ILLW in clay host rock)
Other countries have started the siting process/work:
UK: government (BEIS) kicked off the siting in December 2018
Switzerland: siting process ongoing
Japan: METI produced a map of suitable sites in the summer of 2016
China and Russia: Underground Research Laboratories (URL) are being excavated in Crystalline rock
And URL's exist in Belgium, Switzerland and Hungary
With different schedules (can be very distant)
ANDRA


The challenges a waste manager faces
In all cases, the management of HLW/SNF lead up to R&D intensive projects:
A common development/realisation project duration: + 20-30 years
A common long operational duration: + 100 years
A significant overnight cost in the tens of billion Euro range, depending on inventory size
It also leads to managing an organisation that will have to adapt to the successive project phases:
Phase 0 : policy, framework and program establishment
Phase 1 : Site evaluation and site selection
Phase 2 : Site characterisation and Design
Phase 3 : Facility construction
Phase 4 : Facility operation and closure
(Phase 5 : Post-closure)
The feedback from the Swedish, Finn and French projects all point to the transition from 2 to 3
There is a needed adaptation of the organisation to go from science to design to realisation
This in turn requires changes in both skills and organisation
But RD&D/innovation remains for optimisation and adaptation of DGR, long term Knowledge Management
ANDRA


Radioactive waste arising from power production
Dismantling
ANDRA


Dismantling - Challenges (I)
The challenges differ between facilities
One of kind dismantling operations (ex. research facilities)
Repetitive dismantling of an homogeneous fleet of NPP's
However in all cases, **characterization** is a key issue
for a better sorting and an identification of the most suited management route

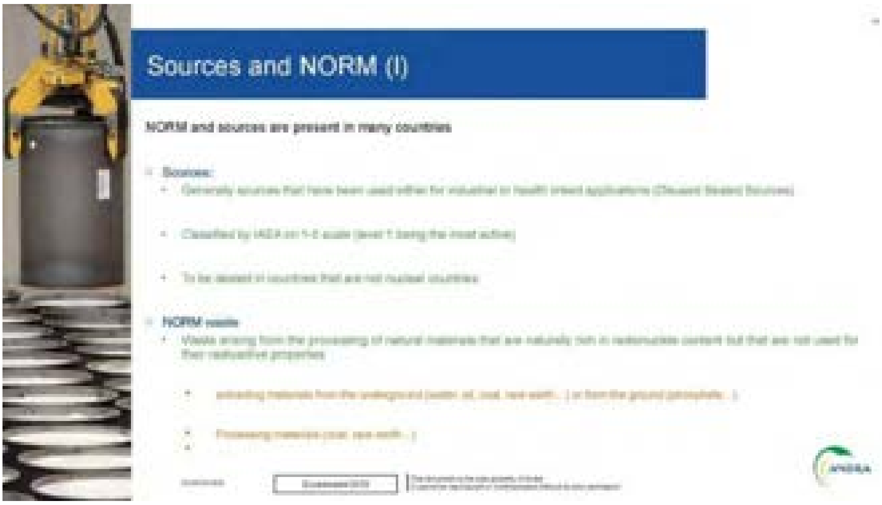

Dismantling - Challenges (II)
Strong need for **optimization of waste stream**
Optimization based on safety, waste volume and cost criteria
Requirement for a holistic approach of waste management chain and strong interaction between waste producer, operator and waste manager
Options that lead to optimization cover:
Waste valorization (of scrap metal, of rubble)
Volume reductions (metal fusion, incineration and compaction) including at the waste generation phase
Reorientation of waste streams to more appropriate solutions (ex. in situ disposal)
Options to be assessed as to their technical, economic, environmental efficiency and to their social acceptability
Existence of clearance levels must also be taken into account
These options are supported by a significant R&D effort

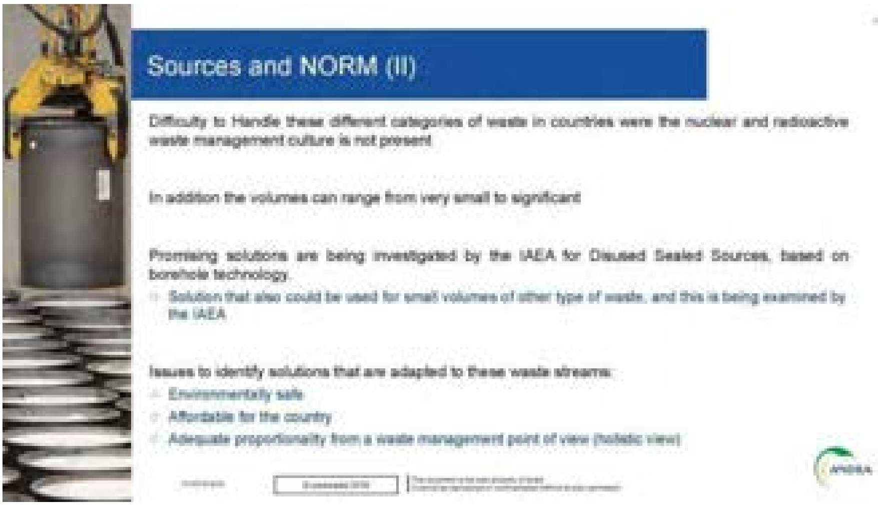

The specificities of graphite waste
Low Level but Long Lived (LL-LL) waste
Originating from the dismantling of first-generation graphite-gas cooled NPP's
Ex. in France
Many solutions still under studies for all or part of graphite inventory
Treatment
DGR
Surface or shallow disposal
Safety
Characterization, Technical solutions and R&D in support
Cost
Shallow disposal
Example of french process


Other elements in the LL-LL inventory in France
Part of legacy bituminized waste (40,000m3)
Originating from the treatment of liquid effluents, embedded in bitumen, in the process of being taken over by the CEA in Marcoule
Uranium - bearing waste (50,000m³) resulting from natural uranium conversion
NORM waste (2,000m³)
Disused sealed sources
Smoke sensors: Am, Ra
Surge protectors: H, Ra ...


A solution for disposal of LL-LL waste
Shallow disposal options in a geological layer with low permeability: 2 design options are under investigation
Open pit + man-made clay cover
Underground drifts
Alvéole de Stockage
Alvéoles de Stockage

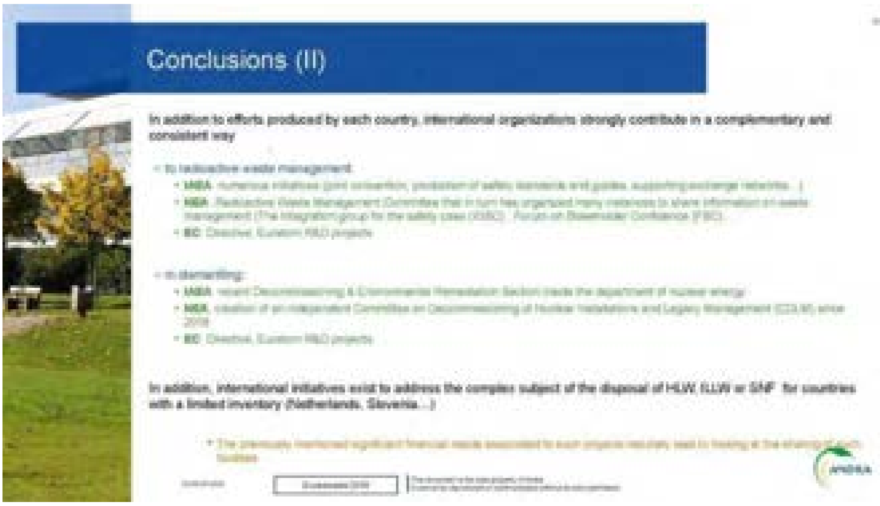

Norms and sources

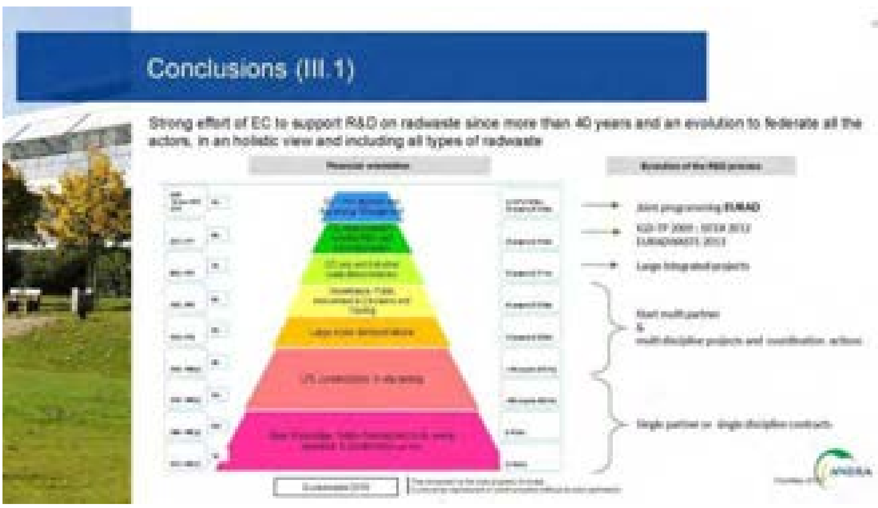

Sources and NORM (I)
NORM and sources are present in many countries
Sources:
Classified by IAEA on 1-5 scale (level 1 being the most active)
NORM waste
ANDRA

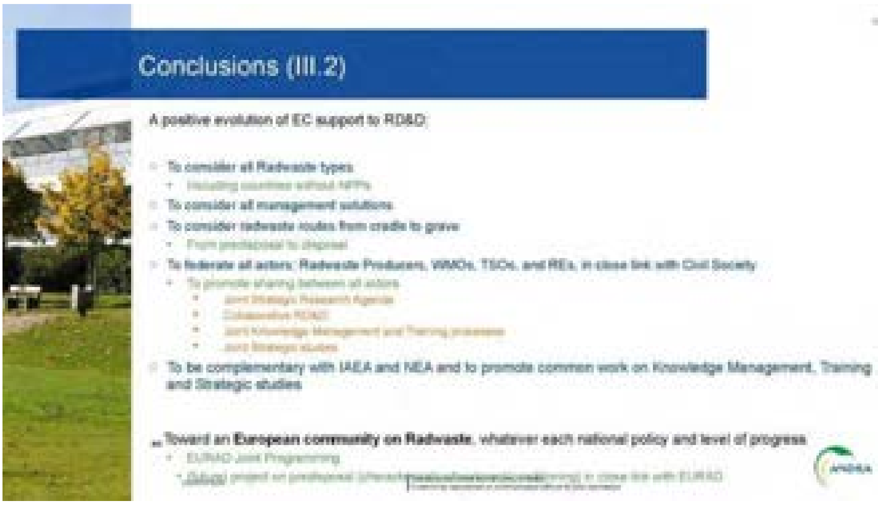

Sources and NORM (II)
Difficulty to Handle these different categories of waste in countries were the nuclear and radioactive waste management culture is not present
In addition the volumes can range from very small to significant
Promising solutions are being investigated by the IAEA for Disused Sealed Sources, based on borehole technology
Solution that also could be used for small volumes of other type of waste, and this is being examined by the IAEA
Issues to identify solutions that are adapted to these waste streams:
Environmentally safe
Affordable for the country
Adequate proportionality from a waste management point of view (holistic view)
ANDRA


CONCLUSIONS
ANDRA


Conclusions (I)
LLW from NPP operations are disposed adequately in many existing facilities throughout the world
ANDRA


Conclusions (II)
In addition to efforts produced by each country, international organizations strongly contribute in a complementary and consistent way
In addition, international initiatives exist to address the complex subject of the disposal of HLW, ILLW or SNF for countries with a limited inventory (Netherlands, Slovenia...)
ANDRA


Conclusions (III.1)
Strong effort of EC to support R&D on radwaste since more than 40 years and an evolution to federate all the actors, in an holistic view and including all types of radwaste
ANDRA


Conclusions (III.2)
A positive evolution of EC support to RD&D:
To consider all Radwaste types
Including countries without NPPs
To consider all management solutions
To consider radwaste routes from cradle to grave
From predisposal to disposal
To federate all actors: Radwaste Producers, WMOs, TSOs, and REs, in close link with Civil Society
To promote sharing between all actors
Joint Strategic Research Agenda
Collaborative RD&D
Joint Knowledge Management and Training processes
Joint Strategic studies
To be complementary with IAEA and NEA and to promote common work on Knowledge Management, Training and Strategic studies
Toward an European community on Radwaste, whatever each national policy and level of progress
EURAD Joint Programming


THANK YOU

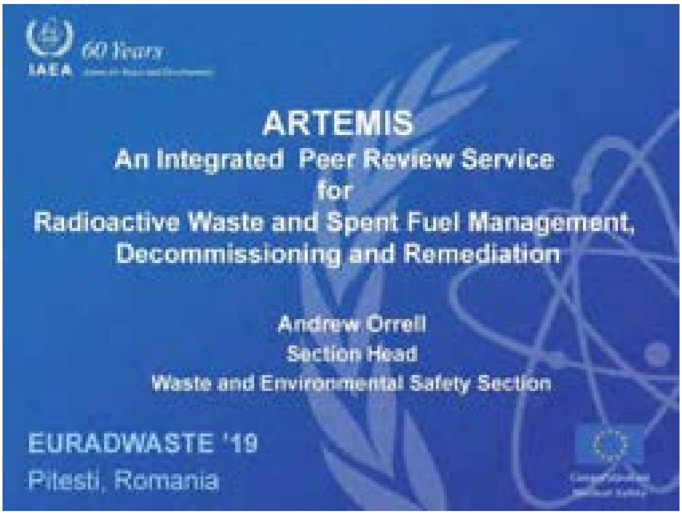
ANDREW ORRELL

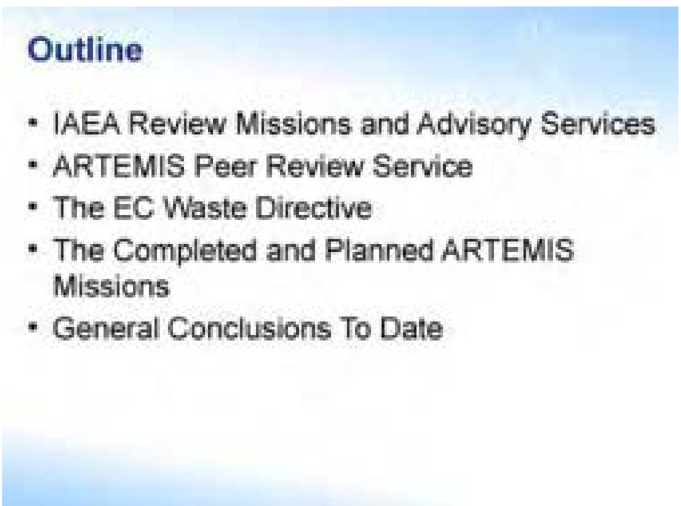
Section Head of Waste and Environmental Safety, IAEA

ARTEMIS IN EUROPE, THE INTEGRATED REVIEW SERVICE FOR RADIOACTIVE WASTE AND SPENT FUEL MANAGEMENT, DECOMMISSIONING AND REMEDIATION

ANDREW ORRELL

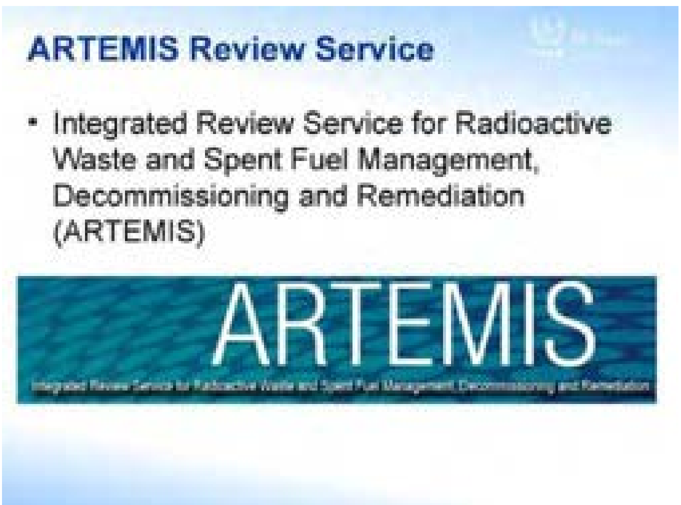
IAEA, Austria

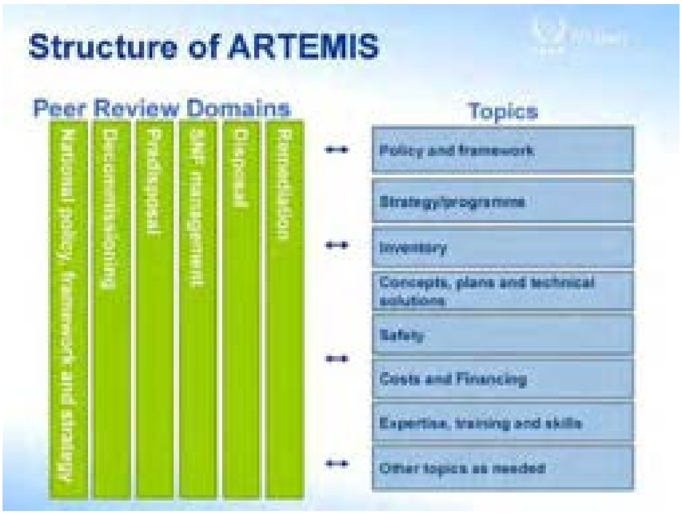


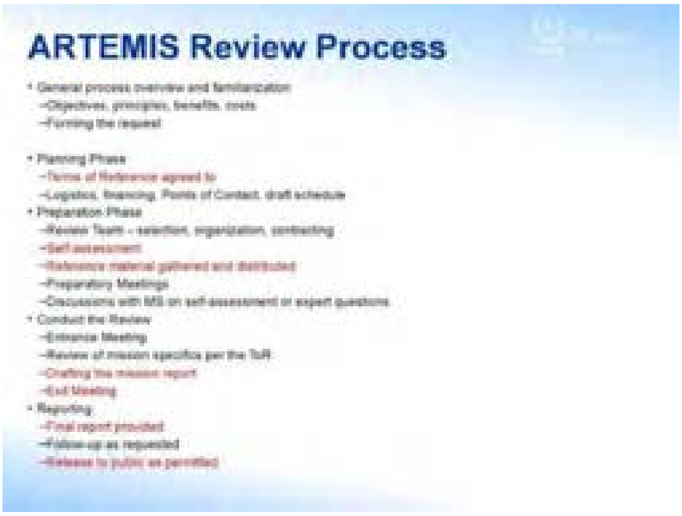



IAEA Review Missions and Advisory Services


IAEA offers Member States a wide array of review services
https://www.iaea.org/services/review-missions/calendar


ARTEMIS Review Service
• Integrated Review Service for Radioactive Waste and Spent Fuel Management, Decommissioning and Remediation (ARTEMIS)
ARTEMIS
Integrated Review Service for Radioactive Waste and Spent Fuel Management, Decommissioning and Remediation

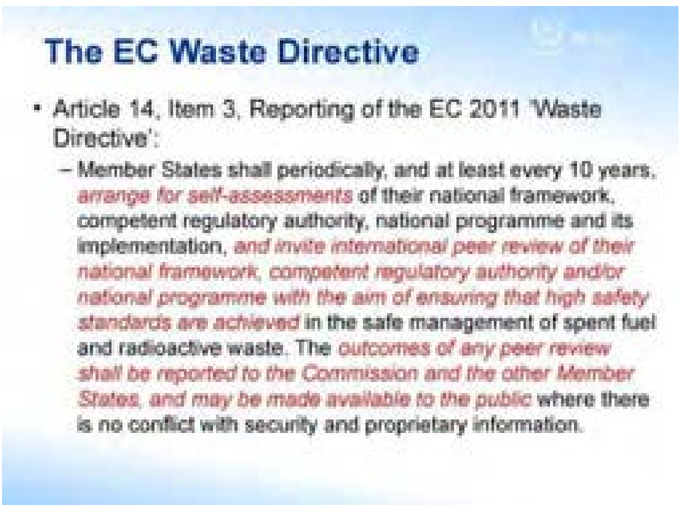

Structure of ARTEMIS
Peer Review Domains
National policy, framework and strategy
Decommissioning
Predisposal
SNF management
Disposal
Remediation
Topics
Policy and framework
Strategy/programme
Inventory
Concepts, plans and technical solutions
Safety
Costs and Financing
Expertise, training and skills
Other topics as needed

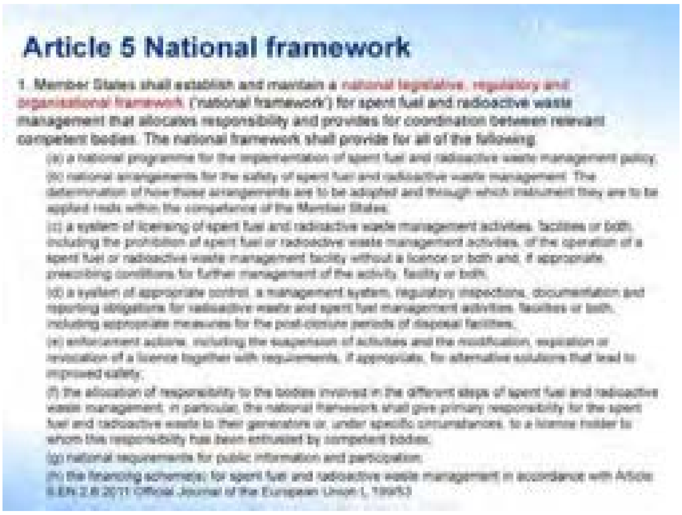

ARTEMIS Review Process
• General process overview and familiarization
–Objectives, principles, benefits, costs
–Forming the request
• Planning Phase
–Terms of Reference agreed to
–Logistics, financing, Points of Contact, draft schedule
• Preparation Phase
–Review Team – selection, organization, contracting
–Self assessment
–Reference material gathered and distributed
–Preparatory Meetings
–Discussions with MS on self-assessment or expert questions
• Conduct the Review
–Entrance Meeting
–Review of mission specifics per the ToR
–Drafting the mission report
–Exit Meeting
• Reporting
–Final report provided
–Follow-up as requested
–Release to public as permitted

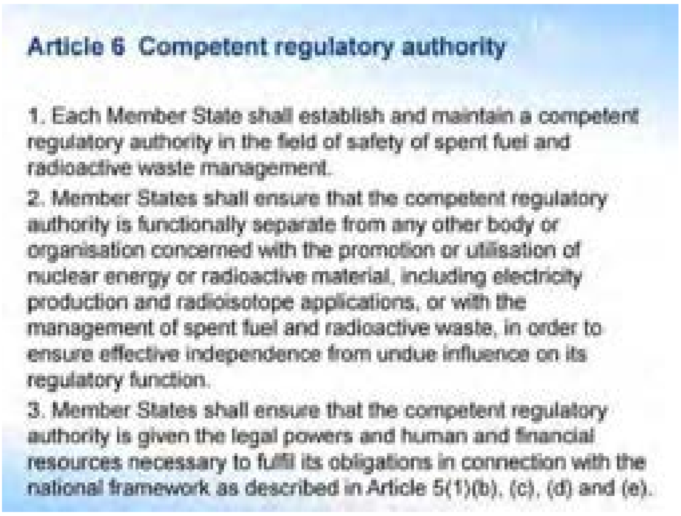

Definitions
•Recommendations
•Recommendations are proposed where aspects relative to the IAEA Safety Requirements and additional supporting documents agreed as basis for review such as other IAEA documents, Conventions, Code of Conduct or other supporting documentation are missing, incomplete, or inadequately implemented. … In the case of peer review in relation to the obligations under the European Council Directive 2011/70/EURATOM to review the national programmes and frameworks, the review and recommendations made should also be based on this Directive.
•Suggestions
•Reviewers may identify opportunities for improvement not directly related to inadequate conformance with IAEA Safety Requirements, but which should be shared with the host country (e.g. a more efficient way of utilizing staff resources). Suggestions are means of achieving improvements. … In general, suggestions should stimulate the management and staff to consider new or different approaches to technical, regulatory and policy issues that may enhance performance. … Each suggestion shall have a basis either in IAEA Safety Requirements, Safety Guides or other relevant IAEA documents or international commitments (e.g., Codes of Conduct, Conventions, etc.).
•Good Practices
•A good practice is identified in recognition of an outstanding organization, arrangement, programme or performance superior to those generally observed elsewhere. A good practice goes beyond the fulfilment of current requirements or expectations. It will be worthy of the attention of other organizations or entities as a model in the general drive for excellence.


ARTEMIS on GNSSN Platform
IAEA GNSSN
ARTEMIS
https://gnssn.iaea.org/main/ARTEMIS


The EC Waste Directive
Council Directive 2011/70/Euratom
Community approach for the Responsible and Safe Management of Spent Fuel and Radioactive Waste

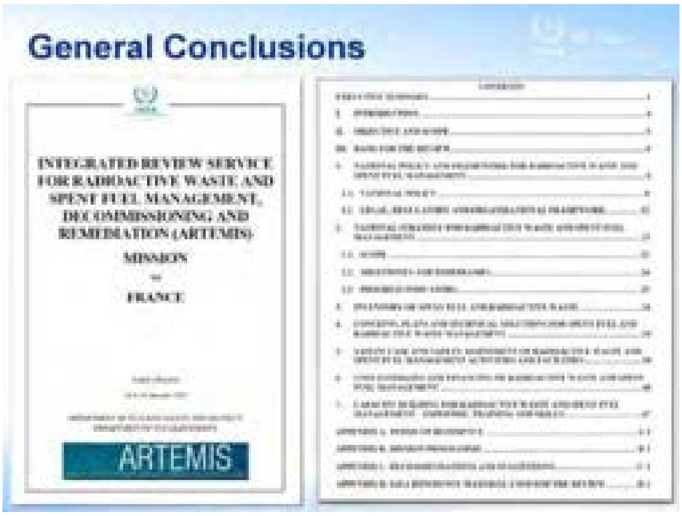

The EC Waste Directive
• Article 14, Item 3, Reporting of the EC 2011 'Waste Directive':
– Member States shall periodically, and at least every 10 years, arrange for self-assessments of their national framework, competent regulatory authority, national programme and its implementation, and invite international peer review of their national framework, competent regulatory authority and/or national programme with the aim of ensuring that high safety standards are achieved in the safe management of spent fuel and radioactive waste. The outcomes of any peer review shall be reported to the Commission and the other Member States, and may be made available to the public where there is no conflict with security and proprietary information.


Article 5 National framework
1. Member States shall establish and maintain a national legislative, regulatory and organisational framework ('national framework') for spent fuel and radioactive waste management that allocates responsibility and provides for coordination between relevant competent bodies. The national framework shall provide for all of the following:
(a) a national programme for the implementation of spent fuel and radioactive waste management policy;
(b) national arrangements for the safety of spent fuel and radioactive waste management. The determination of how those arrangements are to be adopted and through which instrument they are to be applied rests within the competence of the Member States;
(c) a system of licensing of spent fuel and radioactive waste management activities, facilities or both, including the prohibition of spent fuel or radioactive waste management activities, of the operation of a spent fuel or radioactive waste management facility without a licence or both and, if appropriate, prescribing conditions for further management of the activity, facility or both;
(d) a system of appropriate control, a management system, regulatory inspections, documentation and reporting obligations for radioactive waste and spent fuel management activities, facilities or both, including appropriate measures for the post-closure periods of disposal facilities;
(e) enforcement actions, including the suspension of activities and the modification, expiration or revocation of a licence together with requirements, if appropriate, for alternative solutions that lead to improved safety;
(f) the allocation of responsibility to the bodies involved in the different steps of spent fuel and radioactive waste management; in particular, the national framework shall give primary responsibility for the spent fuel and radioactive waste to their generators or, under specific circumstances, to a licence holder to whom this responsibility has been entrusted by competent bodies;
(g) national requirements for public information and participation;
(h) the financing scheme(s) for spent fuel and radioactive waste management in accordance with Article 9.


Article 6 Competent regulatory authority
1. Each Member State shall establish and maintain a competent regulatory authority in the field of safety of spent fuel and radioactive waste management.
2. Member States shall ensure that the competent regulatory authority is functionally separate from any other body or organisation concerned with the promotion or utilisation of nuclear energy or radioactive material, including electricity production and radioisotope applications, or with the management of spent fuel and radioactive waste, in order to ensure effective independence from undue influence on its regulatory function.
3. Member States shall ensure that the competent regulatory authority is given the legal powers and human and financial resources necessary to fulfil its obligations in connection with the national framework as described in Article 5(1)(b), (c), (d) and (e).


Article 11 & 12 National Programmes
Contents of national programmes


ARTEMIS Reviews Status
Requested combined IRRS and Artemis:
• Slovenia 2021
• Sweden 2022
• The Netherlands 2023 (tbc)


General Conclusions
INTEGRATED REVIEW SERVICE FOR RADIOACTIVE WASTE AND SPENT FUEL MANAGEMENT, DECOMMISSIONING AND REMEDIATION (ARTEMIS)
MISSION
to
FRANCE
ARTEMIS


60 Years
IAEA
Thank you!
ARTEMIS.Contact-Point@iaea.org

CHRISTOPHE DAVIES

Project & Policy Officer, DG RTD - Euratom Fission, European Commission

Euratom research and training programme in radioactive waste management: Overview status, vision and future perspectives

CHRISTOPHE DAVIES

DG RTD - Euratom Fission, European Commission

Euratom Research and Training (R&T) on radioactive waste management began in 1975. It is one of the first, European Commission research programmes. The purpose of this extended abstract is to take stock of the evolution the Euratom (R&T) programme underpinning the strategic vision and plan of the European Commission for its continued role and support in the field of radioactive waste management.

Over the nine successive programmes, Euratom went through all the R&D phases needed to manage and dispose all types and categories of radioactive waste including decommissioning, pre-disposal (characterisation, treatment, conditioning), fuel cycle (reprocessing, partitioning and transmutation-P&T) and disposal (basic science on key processes; performance assessment calculations; site, host rock and geological investigations plus natural analogues; underground research laboratory constructions and in situ testing for performance investigations, constructions and disposal concept feasibility and technology development); policy and waste management strategies; and social science and humanities (SSH) for public perception and acceptance.

R&D on dismantling was gradually stopped in the mid-2000's due to the industrial maturity of the dismantling projects. Working groups to maintain and exchange knowledge in this domain are operating at the two international organisations (OECD Nuclear Energy Agency and IAEA). At Euratom level, the need to re-open R&D on decommissioning for advanced and innovative techniques and technologies is being investigated in a Coordination & Support Actions (CSA), SHARE, to identify any need for a decommissioning R&D roadmap for activities of EU added-value.

Near-surface disposal of short-lived and intermediate level waste is being widely implemented across Europe, hence activities supported by Euratom in this field were discontinued during Framework Programme (FP7, 2007-2013). Support to characterisation and waste treatment for these wastes was reopened during the Horizon 2020 FP as part of the Work Programme 2016-17.

International/EU/EURATOM Status

R&D on P&T is conducted mostly by the research community close to reactor systems, hence in Euratom this domain of research is managed within the part of the programme on reactor safety.

In the early 2000's, after 25 years of R&D, there was still no scheduled date for start of operation of the first underground repositories in Europe and no country was still foreseeing a date of submission of an operation license application to its regulatory authority. Disposal of high-level and long-lived radioactive waste (HL&LL W) and spent fuel (SF) in deep underground repositories was and still is the most important challenge in all national programmes, which have to manage SF.

Being a priority in EU Member States (MS), Euratom gradually focussed its support on this domain and lower priority was given to R&D on pre-disposal.

Geological Disposal (GD) is a complex multidisciplinary scientific, technical, organisational and societal issue. R&D in this domain being mostly non-commercial and open science the Commission started to advocate for increase and close collaboration and joint activities within the respective research communities involved in the safety case (SC) of GD. Although the principle for EU support is competitive project proposals, this principle had to be adapted to the specific situation of radioactive waste disposal, so that even if scientific excellence is the objective in R&D, collaboration instead of competition can bring more benefits to all MSs, which face the same challenges. This approach also avoids unnecessary duplication of research. The question has been and remains to which extent and scope collaboration in all domains of the SC for GD is of EU added-value as opposed to specific requirements in each MS national programme. And it is also necessary to identify which R&D has to be done in any case in each national programme.

Only competitive projects may not be the most effective working method both for the Commission and the research actors on GD. Evidence of unfruitful competition was exemplified by the failure, in 2007, of two large competitive project proposals on gas led on the one side by Technical Support Organisations (TSO) and the other side by Waste Management Organisations (WMO): GASCONI and GASMIG. Both proposals were rejected at the evaluation stage and both communities had lost time and effort. The underlying argument leading to this competition was that TSOs considered that they need to remain independent to draw conclusions on the outcome of the project. This argument was challenged during evaluation saying that the purpose of the projects was to develop scientific knowledge and understanding on the processes of gas in underground repositories and that the interpretation of the results for the performance of the repositories remains of the responsibility of the respective communities. Fortunately, a joint project (FORGE) was developed the year after with fruitful collaboration and did set the pace for future method of work of the different research communities for disposal.

In the mid-2000's, one of the steps taken by the EC to increase collaboration and joint activities within the respective research communities was to introduce new types of project contracts: Integrated Projects, Network of excellence and European Technology Platforms (TP), to help speed up industrialisation of research outputs and to help establish the European Research Area (ERA). The first initiative in Euratom was the start of work towards integration / coordination of WMOs. A number of projects were conducted between 2002 and 2009 with the Network of excellence NET.EXCEL, then CARD, which eventually led to the establishment of IGD-TP, the Implementing Geological Disposal –Technology Platform, in 2009, between 11 WMOs.

In line with the strategy of ERA, the EC/Euratom aim is to provide EU-added value, leverage and benefit to all national programmes. Therefore, beyond collaboration within the research communities, EC policy to achieve this objective has been to gradually bring together the different research communities generating knowledge for the safety case of disposal with the end-users of the results, i.e; Waste Management Organisations (WMO), TSOs and academic and research organisations.

In the early 2010's, the context at the EU level and in the MSs continued to evolve in a way justifying, reinforcing EC strategy towards integration of the different research communities, but furthermore to develop Joint Programming activities between MSs at EU level.

In 2011 and 2012, the first two license applications for underground repositories were submitted in Sweden and Finland demonstrating maturity of knowledge for the SC in countries with advanced programmes for GD. This could have been understood that continued support from Euratom could be questioned. However, at the EC EURADWASTE '13 conference, two key conclusions provided evidence of the continued role for Euratom.

The first conclusion was that each underground repository is a first of the kind because of many different conditions including geological formations, disposal concept, etc..

The second conclusion was that knowledge underpinning the SC needs to be continuously improved in order to be in a position to update the operating license, respond to uncertainties in processes measured during operation and to regulatory questions, to optimise the repository concept and facility, to provide competence to next generations of scientists due to the long operational time of repositories (up to one hundred years), etc..

At the same time, the Council Directive 2011/70/Euratom establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste (the waste Directive) was adopted by the MSs.

The Directive requires each MS to establish and maintain national policy, and legislative, regulatory and organisational framework for managing all types of radioactive waste from generation to disposal. This includes establishing a national programme with significant milestones and clear timeframes, as well as RD&D activities needed in order to implement technical solutions. Therefore, a R&D programme is needed in each MS concerned with radioactive waste management.

The role of Euratom is considered as reinforced, when considering the different time scheduled between MSs on the start of their respective repositories. Advanced countries like Finland, Sweden and France plan operational starts in the next decade, while many other MSs have longer implementation timescales, i.e. commissioning dates of deep geological repositories planned around 2055-2065. These countries in early stage will need to go through all the research steps undertaken in advanced countries. Therefore, there is a central role for Euratom in organising cooperation between all national programmes so that all countries can benefit from joint work.

In working together, as part of a European Joint Programme, advanced countries will be able to address specific cutting-edge science on very deep scientific topics, while less-advanced programmes will be able to plan, structure and implement the necessary R&D, with guidance, training and transfer of competence and knowledge from advanced programmes and not having to redo and duplicate R&D effort for which there is state of the art knowledge.

International/EU/EURATOM Status

From a regulatory support point of view, given the on-going and forthcoming license applications Euratom began to support networking and R&D activities of TSOs for their necessary competence in the review of Safety Cases. The two SITEX projects, started in 2011, led to establishment of the SITEX Network in 2018.

Recently, the community of research entities (RE), taking into account the EURADWASTE '13 key messages, also started to structure and coordinate at European level in order to contribute to the long-term R&D challenges of, in particular, GD as part of a European Joint Programme and to be in a position to provide a flowerbed for education and training of the needed scientists for the future. In 2018, this community launched its own network called EURADSCIENCE.

In response to the evolving context described above, the Commission initiated the process of integration of MSs' national programmes in a Joint Programming at EU level via the use of the new contractual instrument: Joint Programme co-fund.

Preparatory work for a European Joint Programme was discussed intensively between IGD-TP and SITEX and eventually in effective cooperation within the JOPRAD project in the years 2015 to 2017. One important criterion for collaboration was preserving independence of the TSO. The three R&D communities took part and elaborated a common Strategic Research Agenda (SRA) for joint implementation at European level. The SRA is the basis for joint collaborative activities based on agreed prioritisation and decisions of the Joint programme governing board. The SRA structure, being built to address research on scientific technical gaps, and on acquisition of basic science allows joint work between communities. This method is considered as respecting independence between implementers and reviewers, which can use separately the results obtained, to respectively develop their safety case and implement their review process. Non-technical stakeholders were also involved to provide input on their view of the needed R&D to be performed.

Integration of the actors of the disposal communities (WMO, TSO and RE) at European level, which have an official role in their respective national programme has delivered the EURAD European Joint Programme (EJP) to be launched in mid-2019 for five years.

One of the benefits of Joint Programming should be effective close collaboration and avoid undue competition on topics of common interest. The question will be whether R&D leading to industrial and commercial activities could be included in Joint Programming, which is mostly working on open science.

Regarding the national programmes with longer GD implementation timescales and those with small radioactive waste inventories, including those from central and eastern Europe, their participation in Euratom research projects has over the years been limited. Therefore, taking into account this situation, that of advanced knowledge on GD and that their R&D priorities could be, for the time being, on pre-disposal management of radioactive waste Euratom has reopened R&D topics on other categories than HL&LL W and SF. The scope of activities includes, the development of methods, processes, technologies and demonstrators for characterisation, quality control / checking, treatment and conditioning of unconventional, legacy waste, operational wastes, waste arising from repair or maintenance and decommissioning/dismantling waste or other waste streams for which there is currently no industrial pre-disposal and or disposal mature processes.

These activities are generally carried by waste producers and owners and the projects issued from this Euratom call domain are separate from the EURAD EJP. However, EC strategy is to gradually involve and integrate this community in future Joint Programming at

EU level. The justification is that if characterisation, treatment and conditioning processes are developed together with the disposal community based on co-developed waste acceptance criteria, there will be efficiency, optimisation and benefits on both sides. The current limitation of the types of activities to be included in the EJP, considered by Euratom, is that decommissioning activities up to pre-treatment for stabilisation and packaging of dismantled waste are more of the responsibility of utilities. Also, dismantling are commercial and competitive markets, which does not seem compatible with the open-science approach in the EJP. This could be considered as an obstacle to open cooperation. Recent evidences can be found in project proposals received in the category Innovation actions (IA). A large number of technical reports were classified as confidential. Although an objective of the EC in the research programmes is to contribute to economic growth and employment, observation is made that when a project includes activities covering innovative products, processes or services and prototyping, testing, demonstrating, piloting, large-scale product validation and market replication of advanced and new technologies, the results are of direct benefit to a small number of organisations with IPR for commercial use.

The question for the EC is, whether these activities should be included in Joint Programming. In the domain of waste treatment, the current EC idea is to allow inclusion of development of new processes and technologies for waste types or streams common to several MSs or eventually for which there could be co-ownership of the process and possible common exploitation facilities. Otherwise, other research proposals based on existing technologies or new ones which are or would be property of a single company should be subject to competitive call for proposals.

Public acceptance and political decision to select a site to construct a repository or an underground research laboratory (URL) is a sensitive issue. Already early, a number of applications for site investigations and URLs had been refused due to local and public opposition. Euratom opened the domain of SSH to increase public perception and acceptance around 2000. A series of projects were supported to investigate communication, stakeholders' engagement, governance aspects and public involvement, mainly at local level: RISCOM2, TRUSTNET, COWAM series, OBRA, ARGONA, IPPA and InSOTEC. General principles and recommendations on communication and stakeholder involvement were produced by the projects.

The results are available for use in national programmes and in working groups of the OECD NEA, the Stakeholder Forum for Confidence (SFC). Therefore, the need to continue social science on its own as part of Euratom did not appear as justified. Instead the Euratom programme on radioactive waste management proposed, in some way an innovative approach for public participation by suggesting to involve public non-technical stakeholders in scientific / technical R&D projects when a clear task/contribution can be identified for them. A series of projects implement this approach: MODERN 2020, SITEX II, JOPRAD, MIND and Beacon. Lessons learnt from these projects need to be drawn and a number of questions need to be addressed to clarify which role and task could public and non-technical stakeholders play in future Euratom research activities.

The future involvement of public, non-technical stakeholders in R&D projects and Joint Programming at European level thus needs analysis. Civil Society Organisations (CSO) and Non-Governmental Organisations (NGO) have defined their role as interaction with civil society in following the research to give civil society the opportunity to follow, discuss and give feedback on the research conducted in the projects and to create the conditions for civil society local and national representatives to interpret, discuss and give feedback on the research result and other information made available by the projects. CS experts also wish to perform social science (SC) activities within scientific technical projects.

On the role of CSOs and NGOs to follow the projects to discuss and give feedback on the research conducted, trials have been tested in on-going projects. Scientific experts have been used to comment of the work performed by the projects. The content of the deliverable is similar as that requested from the external advisory boards composed of end-users (WMOs and TSOs). Therefore, the EC considers that if CSOs and NGOs wish to make scientific comments on the projects work, this should be carried jointly with the other external experts in the advisory boards.

On the role to create the conditions for civil society local and national representatives to use the project results and other information in future situations where there are consultation processes as a part of safety case reviews and licensing decisions, this could be considered as training and performed as such in the form of deliverables presenting the project results in understandable way for the public.

Social science activities are performed extensively as part of the OECD NEA SFC forum, therefore SC as individual projects in the field of RWM are not justified also because such activities on their own usually address strategic issues as nuclear energy and radioactive waste management policies, which are not part of the Euratom R&T programme scope.

Summary:

– The European Commission via the Euratom R&T programme on radioactive waste management has a role in fostering close cooperation and joint implementation of R&D on radioactive waste management,
– The criteria for supporting research are cutting-edge science on issues of common EU added-value for Member States. However, the wide gaps in the status of the national programmes towards implementation of geological repositories for high-level and long-lived radioactive waste (HL&LL W) and spent fuel implies a central role for Euratom in the management of scientific and technical knowledge on RWM for exchange between organisations across the MSs and to transfer to new generations of scientists to ensure the long-term safety of disposal,
– The European Joint Programme tool for R&D at EU level appears to be the most effective way to jointly prioritise and implement R&D at the European level between the main actors of the disposal community (WMO, TSO and RE) representing their official MS national programme,
– Public non-technical stakeholders may contribute in R&D activities at Euratom level whenever a clear and genuine task can be identified and does not diverge from the programme of their country of origin,
– The needs for R&D on pre-disposal at EU level may be justified as long as the criteria for cooperation are clear and that benefit is acknowledged for several MSs as opposed to activities leading to competitive and commercial markets of benefit to single entities.

STC Opinion on future Euratom research and traning programme, February 2017

OPINION

For more than five decades, the Euratom STC has provided broad-based technical opinions on issues within the scope of the Euratom Treaty – nuclear energy systems, nuclear safety, radiation protection, radioactive waste management, related research requirements and education & training – as part of its statutory role in advising the European Commission, Council of Ministers and European Parliament. These opinions are often coordinated with the preparation by the Commission of proposals for future Euratom research and training programmes under Art. 7 of the Euratom Treaty.

The present opinion is the latest such opinion in view of the preparation by the Commission of the proposals for the 2019-2020 Euratom research and training programme and also for the following 5-yr programme scheduled for 2021-25. The Euratom STC has developed this current opinion through the setting up of five working groups covering research infrastructures (both fission and fusion facilities), future fission systems, fission-fusion synergies, radiation protection and decommissioning. The individual working group reports (see annex) underpin the present opinion.

The Euratom STC would like to underline that many of the following principal themes and priorities have remained largely unchanged, certainly throughout the last two decades, and often are as relevant today as they were at the inception of the Euratom Community. They include:

- the significant role played by nuclear energy in certain Member States as a component of low carbon electricity supply and contributing to the competitiveness of European industry;
- the understanding that all EU Member States, even those with no nuclear power plants, have an interest in ensuring nuclear safety throughout the EU;
- the importance of a European contribution, both as regards safety culture but also technological and industrial knowhow, in ensuring appropriate attention is paid to the safety, sustainability, non-proliferation and competitiveness aspects of advanced (so-called Generation-IV) systems as progress is made internationally towards industrial scale deployment of these systems around the middle of the 21st Century;
- the need for Member States to prioritise which advanced systems and associated fuel cycles should be supported in order to ensure meaningful progress with the limited resources available;
- maintaining flexibility within current and future Euratom programmes to keep abreast of these emerging technologies, including those given high priority internationally in key third countries and paradigm shifts such as possible recourse to smaller modular reactors;
- ensuring a vibrant education & training culture, involving basic academic education as well as continuous professional development, focused on advanced technology across all nuclear topics to guarantee a new generation of experts will be available when needed, and to maintain high levels of safety throughout the sector;
- the important role played by nuclear technology, and related competence and expertise, in the fields of medicine, radiation protection and non-energy applications, and the need in general for the Euratom programme to be seen as an integral part of the broader Horizon 2020 initiative able to capitalise on synergies over a much wider range of research areas;
- the need for a strongly coordinated nuclear fusion research programme focused on the implementation of the Fusion Roadmap;
- the need for a robust, enduring and efficient infrastructure base across the EU to underpin all aspects of research and innovation throughout the sector;
- the importance of including decommissioning and dismantling R&D which reflects the need to grow capacity and capability to undertake these activities in the future and stimulates exchange of good practice and efficient and effective knowledge management.

Furthermore, in view of the findings of the working groups set up to provide detailed input in the present exercise, the Euratom STC would in particular like to emphasise:

- the urgent need for a coordinated and coherent approach to infrastructure investment that must be undertaken if the EU is to ensure value for money, appropriate leverage both between and within the 'direct actions' and 'indirect actions' components of the Euratom research and training programme, and enduring capacity and capability in facilities that underpin nuclear technology and that are vital for Member States in all related fields, including those essential for medicine and radiation protection, security and safeguards;
- the risks inherent in continued underinvestment in advanced nuclear systems, and that failure to grasp opportunities at either the European level or in support of leading Member States will mean that the EU is no longer able to fulfil its potential and occupy its rightful position in the evolving international initiatives in this field;
- that, in this regard, Europe is in danger of ceding leadership in both advanced reactor systems and fuel cycle technologies to China, India and Russia, and in so doing will fail to bring to bear its significant expertise, know-how and influence so vital in ensuring the highest standards of safety, security, waste management and non-proliferation are achieved and maintained globally;
- the need with continue the R&D efforts on waste management and geological disposal associated to the existing reactor fleet;
- the significant cross-cutting benefits that can be

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realised between fission and fusion energy research programmes as the latter evolves from one focused on basic plasma physics to one focused more on technology and nuclear-related aspects;

- the need to maintain the effort in radiation protection research where the focus remains the area of low-dose risk, which has important implications for EU citizens in view of the growing exposure from medical diagnostic and therapeutic practices and in which research actions should therefore be co-funded by the Horizon 2020 health programme, enabling the limited Euratom funding to be focused on priorities related to nuclear technology, such as the efficient production of radioisotopes for medical purposes and biological research;

- the need for the European programmes to include R&D in the field of Dismantling and Decommissioning to maintain capacity and capability to undertake these activities in the future. The report recognizes that there is presently no Euratom funding for this type of research;

- the paramount importance of guaranteeing an adequate supply of experts and trained workers in view of the increasing demand across the full scope of disciplines coupled with the ageing and imminent retirement of a generation of experts, and the role that the Euratom programme, as a research and training programme, can and should play in ensuring this supply.

9 February 2017

MARTIN MURRAY

Environment Agency, UK

EURATOM SCIENTIFIC AND TECHNICAL COMMITTEE LEGACY MESSAGES FROM THE 2013-2018 MANDATE

MARTIN MURRAY

Environment Agency, UK

How long have we existed

- The Euratom Scientific and Technical Committee (STC) is the only scientific and technical advisory body formally enshrined in the Euratom Treaty (Article 134) and active since 1957.
- For over 60 years, the STC has provided independent, authoritative advice and opinion on all aspects of nuclear technology. Its members are appointed from all Member States, for a five-year renewable term, as independent experts in nuclear medicine and radiation protection, in nuclear fission reactor systems and fuel cycles, waste management and thermonuclear fusion. The STC is also responsible for nominating the experts advising the Commission on the basic standards for radiation protection (the Article 31 Expert Group) and on the assessment of the health impact of radioactive release from nuclear facilities (the Article 37 Expert Group).

Our Work 2013 - 2018

- The 2013-2018 STC provided a detailed, multifaceted Opinion covering Future Fission Systems and Fuel Cycles, Radiological Protection, Infrastructure, Waste Management and Decommissioning and a separate stand-alone Opinion on the Fusion Roadmap.
- Recognises nuclear energy in a number of Member States is and will be a component of low carbon electricity supply
- Makes the point that all EU Member States, even those without nuclear power plants, have an interest in ensuring nuclear safety throughout the EU;

Why do we need research

- Maintain Capability – Intelligent Client role if not Leadership
- Nuclear safety security and environmental impacts cross national and international boundaries
- Need to influence and ensure high standards of safety
- Climate Change – non fossil fuelled generation – enable mixed energy economy
- Safe decommissioning and disposal of current and future wastes
- Sustainability and inter generational equity
- Future provision of medical radio-isotopes

Research Priorities

- Fusion
- Fission
- Nuclear Materials
- Medical and Industrial uses of radiation/radio isotopes
- Maintain Skills
- Develop Capability
- Enable Leadership

Future Opportunities : Limited Future Funding

- Climate Change 4, 3,2, or 1.5 degree increase in temperature
- Nuclear Power as part of the roadmap to zero carbon
- Sustainable use and supply of radio-isotopes for industrial and medical uses
- Leadership in Generation III and IV reactor Systems
- Small Modular Reactors
- Fusion
- Decommissioning

Looking forward

- Socio economic research
- Safety and Operation of Nuclear Reactors: technology, safety culture and human factors
- Fusion Roadmap Assessment
- The Joint Research Centre (JRC) Direct and Indirect actions
- A balanced view : Research in support of radiological protection, notably regarding medical and industrial applications of radiation and radioactive material

Opening up other research fields for Euratom research

- The outgoing STC has indicated for a number of years that the budget for fission research within the Euratom Framework Programme is insufficient to enable the most important topics to adequately progress. It has sought to encourage and recommend that synergy is sought from cross-cutting initiatives in other EU research fields, *inter alia* materials and medicine and from the basic research programme as well from the fusion programme.
- The Opinion also highlighted the need and appetite for funding for activities that can and should be pursued in parallel to ITER and are of critical importance at the DEMO and reactor stage for fusion energy.

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EURATOM SUCCESS STORIES IN FACILITATING PAN-EUROPEAN EDUCATION AND TRAINING COLLABORATIVE EFFORTS

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Abstract. The European Atomic Energy Community (Euratom) Research and Training framework programmes are benefitting from a consistent success in pursuing excellence in research and facilitating Pan European collaborative efforts across a broad range of nuclear science and technologies, nuclear fission and radiation protection. To fulfil Euratom R&D programmes key objectives of maintaining high levels of nuclear knowledge and building a more dynamic and competitive European industry, promotion of Pan-European mobility of researchers are implemented by co-financing transnational access to research infrastructures and joint research activities through Research and Innovation and Coordination and Support Actions' funding schemes. Establishment by the research community of European technology platforms are being capitalised. Mapping of research infrastructures and E&T capabilities is allowing a closer cooperation within the European Union and beyond, benefiting from multilateral international agreements and from closer cooperation between Euratom, OECD/NEA, IAEA and international fora. 'Euratom success stories' in facilitating Pan-European E&T collaborative efforts through Research and Training framework programmes show the benefits of research efforts in key fields, of building an effective 'critical mass' and implementing European MSc curricula, of promoting the creation of 'Centre of Excellence' with an increased support for 'Open access to key research infrastructures', exploitation of research results, manaement of knowledge, dissemination and sharing of learning outcomes.

Key Words: Education and Training, Research and Innovation, Centers of Excellence, Nuclear knowledge.

1. Introduction to the European landscape

Nuclear power plants (NPP) currently provide 30 % of the overall European electricity generated and 15 % of the primary energy consumed in the European Union. In 2016, 126

NPPs are in operation in Europe, representing a total installed electrical capacity of 137 GWe and a gross electricity generation of around 850 TWh per year. Nuclear fission is a major contributor already today as a low-carbon technology in the Energy Union's strategy to reduce its fossil fuel dependency and to fulfil its 2020/2030/2050/COP21 energy and climate policy objectives [1] however the sector is currently facing several challenges: a) one concerns the plans of most EU Member States (MS) to extend the design lifetime of their nuclear power plants; b) other countries, such as France, Finland, Czech Republic, Hungary and the UK, are planning new builds; c) while others, like Germany, are either considering or have excluded nuclear energy from their energy mix for now; d) a bigger share of renewables should be fostered at European level; and e) fierce international competition is taking place on a global level. Interest in nuclear power is boosted by the need to ensure a secure and competitive supply of energy and by concern over climate change. Finally, whether or not Member States will continue to use nuclear for their electricity production, for both energy and non-energy applications, Europe will need to keep and train highly qualified staff across the whole continent and share its knowledge worldwide.

2. Euratom Treaty and EU/Euratom legislative framework [2]

The Euratom Treaty provides the legal Framework to ensure a safe and sustainable use of peaceful nuclear energy across Europe and helps non-EU countries meet equally high standards of safety and radiation protection, safeguards and security. With legally binding Nuclear Safety Directive (2009/71/Euratom) and its latest amendment (2014/87/Euratom), EU nuclear stress tests, including safety requirements of the Western European Nuclear Regulators Association (WENRA) and the International Atomic Energy Agency (IAEA), the EU became the first major regional nuclear actor with a legally binding regulatory framework as regards to nuclear safety. Furthermore, this legal framework has been recently complemented by the Directive (2011/70/Euratom) that establishes a Community framework for the responsible and safe management of spent fuel and radioactive waste (both from fission and fusion systems), and the Directive (2013/59/Euratom) laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation. Directives on Nuclear Installations' Safety (Art.7), Nuclear Waste Management (Art.8), Basic Safety Standards (Ch.4) and IAEA Convention on Nuclear Safety, all emphasize that each MS shall take the appropriate steps to ensure that sufficient numbers of qualified staff with appropriate education, training and re-training are available for all safety-related activities in - or for each - nuclear installation throughout its life. 'Conclusions' were issued at: a) 'EU Competitiveness Council in November 2008 encouraging Member States and the EC to establish a 'review of EU professional qualifications and skills' in the nuclear field; and b) a 'Second Situation Report on EU E&T in the Nuclear Energy Field' was published in 2014 by the European Human Resources Observatory in the Nuclear Energy Sector (EHRO-N, the latest created in 2009 by the European Nuclear Energy Forum (ENEF)).

The EC promotes and facilitates through the Euratom Framework Programmes (FP) [3] nuclear research and training activities within MS and complements them through its specific Community FP. R&D activities supporting the enhancement of the highest nuclear safety standards in Europe are mainly promoted by EC DG RTD indirect actions together with JRC direct actions. JRC has also been providing for 30 years internationally recognized scientific and technical support e.g. training courses, educational modules, support to the European Safeguards R&D Association (ESARDA), and CBRN risk areas of chemical, biological, radiological and nuclear. European and International safeguards authorities such as Euratom, MS and IAEA benefitted from JRC's dedicated R&D and operational support in collaboration with other EC DGs, ENER, TRADE, DEVCO and EEAS

[4]. Beyond EU borders, DEVCO manages the ‘Instrument for Stability (IfS)’ and the ‘Instrument for Nuclear Safety Cooperation (INSC)’ where among others an initiative on Training and Tutoring (T&T) provided post graduate professional education to expert staff at Nuclear Regulatory Authorities (NRA) and Technical Support Organizations (TSO), both in terms of management and of technical means in the areas of nuclear safety and radiation protection which proved to be very successful in strengthening local organizations and regional cooperation.

3. EU/Euratom initiatives are being capitalized

The European Commission helps to stimulate joint funding from Member States and/or enterprises, and benefits are being capitalised from the increasing interaction between European Technology Platforms (ETPs) [5] launched during the 7th Framework Programme (2007-2013), namely the ‘Sustainable Nuclear Energy Technology Platform’ (SNETP incorporating NUGENIA Generation II III water cooled reactor technology, ESNII Generation IV fast reactors aiming at closing fuel cycle, and NC2I Cogeneration of electricity and heat), the ‘Implementing Geological Disposal of Radioactive Waste Technology Platform’ (IGDTP), the ‘Multidisciplinary European Low Dose Initiative’ (MELODI association), the European Energy Research Alliance (EERA) Joint Programme in Nuclear Materials (JPNM), the Strategic Energy Technology Plan (SET-Plan) [6] and other EU stakeholders (ENEF, ENSREG, WENRA, ETSON, FORATOM, etc.) [7] as well as OECD/NEA, GIF and IAEA at international level [8].

Euratom Fission Training Scheme (EFTS) coordination actions aimed at structuring Higher University Education Master of Science (MSc) training and career development benefitting from a European Credit Transfer and Accumulation System (ECTS) initiated by the Bologna Process in 1999 for higher academic education. European Credit System for Vocational Education and Training (ECVET) launched in Copenhagen in 2002 is also promoted today for lifelong learning in the field of nuclear and successfully tested across a wide range of industrial sectors. It is further promoting transparency, mutual trust, continuous professional development based on a modular course approach and recognition of learning outcomes that refer not only to knowledge but also to management of skills and competences [9].

Successful Euratom EFTS - selected on a competitive basis and promoted through the scientific community (detailed information on all projects is available on CORDIS [10]) - covered highly relevant E&T needs for industry (energy and non-energy including medical) and associated end-users: ECNET (2011-13), EU-China nuclear cooperation; ENEN-III (2009-13), Generation III and IV engineering training schemes for nuclear systems suppliers and engineering companies; TRASNUSAFE (2010-14) nuclear safety culture in health physics (e.g. ALARA principle applied to both industrial and medical fields); CORONA-II (2015-18) on the creation of a regional center of competence for VVER technology and nuclear applications; CINCH-II (2013-16) cooperation establishing a European MSc in nuclear and radiochemistry; EUTEMPE-RX (2013-16) for Medical Physics Experts in Radiology and focusing on the implementation of the BSS Directive; GENTLE (2013-16) delivering graduate and executive nuclear training and lifelong education with a focus on synergies between industry and academia; NUSHARE (2013-16) on nuclear safety culture competences for policy makers, regulatory authorities and industry; PETRUS III (2013-15) a program for a European RadWaste MSc, E&T research on underground storage addressing mainly radiation waste management agencies; ENEN-RU-II (2014-17), ETKM MSc cooperation with Russia, ROSATOM and MEPhi and VVER technology; and ENETRAP-III (2014-18) MSc in radiological protection addressing mainly nuclear regulatory authorities and TSOs. Some of the above EFTS are developing

European Passport (Europass) based on personal transcripts of records and learning outcomes modules obtained through various paths (traditional face-to-face, virtual classroom, training and tutoring, internships, workshops, webinars, on-line or blended learning tools such as e-learning or today's Massive Open Online Courses (MOOC)). IT technologies are being set to transform today the higher education system, benefitting from the huge capabilities of computer simulations and virtual reality accessible anywhere and at any time, however it will never constitute per se a license of a practice or an official authorization to operate or to supervise nuclear facilities from national nuclear regulatory authorities but complementary IT tools benefits for E&T and KSC management have to be acknowledged.

Support from Euratom to key research infrastructures has proven to be highly beneficial to the scientific community at facilitating Pan-European mobility of researchers, engineers or scientists, transnational access to large and unique infrastructures, promoting joint research activities and collaborative efforts across a broad range of nuclear science and technologies in most fields covered by Euratom is supporting today's Euratom portfolio of success stories. Increased cooperation in research in Europe is benefitting from H2020 cross-cutting support from all EU financial instruments available: ERASMUS+ education and training actions (MSC, Engineers, Bachelors, Lifelong learning funding schemes across the globe), Marie Slodowska Curie Fellowships (PhDs), European Research Council on 'Excellent Science' (ERC), Fusion and ITER, JRC ETKM support using its world class laboratories, and the European Institute of Technology Knowledge Innovation Centre (EIT KIC InnoEnergy). The latest promoted a highly successful European Master in Innovation in Nuclear Energy (EMINE) involving major industrial partners AREVA, EDF, ENDESA and VATTENFALL, but also CEA (FR) and universities KTH (SE), University of Catalonia (UPC, ES), INP (Grenoble, FR) and Paris-Saclay (FR) [11].

A publication from EHRO-N in 2012 'Putting into Perspective the Supply of and Demand for Nuclear Experts by 2020 within the EU-27 Nuclear Energy Sector' [12] also confirmed today's EU challenging gap in covering 50% of nuclear experts training needs by 2020 (estimated at around 2000 a year) due to retirement by then. Faced with the challenge of shortages of skilled professionals, the nuclear fission community has called for a steady upgrade of the level of knowledge, skills and competences while striving to attract a new generation of experts to cover the entire life cycle of new nuclear power plants from design and construction to dismantling and green field. The European Union is urged to speed up implementation of EU Directives emphasizing that each MS (governments together with professional organisations and universities ensuring any adequacy between competences needed and jobs available) shall take the appropriate steps to ensure that sufficient numbers of qualified staff with appropriate education, training and re-training are available for all safety-related activities in - or for each - nuclear installation throughout its life.

4. EU/Euratom E&T in support to sustainable Fast Reactor and closed fuel cycle technologies: from technological workshops and international schools to EU training Centers of Excellence

The OECD/NEA Generation-IV International Forum (GIF) [13] has stimulated innovation towards sustainable nuclear reactor technologies since the year 2001 such as Sodium-cooled Fast Reactor (SFR), Lead-cooled Fast Reactor (LFR), Very High-Temperature Reactor (VHTR), Gas-Cooled Fast Reactor (GFR), Supercritical Water Cooled Reactor (SCWR) and Molten Salt Reactor (MSR). On the basis of an EU Commission Decision, EU/Euratom acceded to GIF by signing in July 2003 the 'Charter of the Generation IV Forum' and the International 'Framework Agreement' existing between all Members of the

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Generation IV International Forum. The Joint Research Centre (JRC) of the European Commission is the Implementing Agent for EU/Euratom within GIF. In November 2016, EU Commissioner T. Navracsics has signed on behalf of EU/Euratom the agreement to extend for another ten years the Framework Agreement for an International Cooperation on Research and Development of Generation IV Nuclear Energy Systems. EU/Euratom contributions shall also be extended towards all respective six GIF Systems Arrangements as Fast Neutron Reactor systems are considered as key for the deployment of sustainable nuclear fission energy. EU/Euratom framework programmes constantly promote research and training, innovation and demonstration of nuclear fission technologies to achieve EU SET-Plan objectives being: by 2020, (1) to maintain the safety and competitiveness in fission technology, and (2) to provide long-term waste management solutions; and by 2050, (3) to complete the demonstration of a new generation (Gen-IV) of fission reactors with increased sustainability namely via the European Sustainable Nuclear Fission Industrial Initiative (ESNII), and (4) to enlarge nuclear fission applications beyond electricity production through the Nuclear Cogeneration Industrial Initiative (NC2I).

The European Commission has also promoted since 2007 the establishment of technology platforms such as the Sustainable Nuclear Energy Technology Platform (SNETP) gathering today around 100 key stakeholders mainly from research organisations, industry and academia. Its latest 2013 Strategic Research and Innovation Agenda (SRiA) and 2015 Deployment Strategy gave prioritization between all GIF systems to the three most advanced. Sodium Fast Reactor (SFR) is the reference technology since it already has substantial technological and operations feedback in Europe and today's French ASTRID demonstrator lead by CEA is promoted. Lead Fast Reactor (LFR) technology has significantly extended its technological base. It can be considered as the shorter-term alternative technology with support first from MYRRHA (Multi-purpose hYbrid Research Reactor at SCK CEN (BE), even the leading ESNII industrial demonstration project following the French government's decision to delay the construction of ASTRID, a Pb-Bi Accelerator Driven System) and later ALFRED projects. Gas Fast Reactor (GFR) technology is considered to be a longer-term alternative option and ALLEGRO is supported by the Visegrad 4 central European countries (CZ, SK, HU and PL). With innovative emerging technologies fostering increased efficiency, competitiveness and enhanced safety through design, one could expect: a) by 2025, a licensed SMR and/or cogeneration (V)HTR design(s) available in the EU, with operating demonstrator(s) by 2030; and b) by 2030, at least one Gen-IV demonstrator fast reactor in Europe, including associated fuel cycle facilities.

Gen-IV innovative nuclear reactors are very attractive to young students, scientists and engineers engaging in a nuclear career thanks to the related scientific challenges characterized by higher operating temperatures, studies on high temperature materials, corrosion effects, heavy liquid metal thermodynamics, innovative heat exchangers, fast neutron fluxes for both breeding and enhanced burning of long-lived wastes. Development, fabrication and testing of entirely new nuclear fuels, advanced fuel cycles, fuel recycling concepts including partitioning and transmutation are required, all promoting excellent topical opportunities for internships or PhD studies within R&D laboratories. Beyond the obvious educational merit for young engineers investing on average into additional two years' fast reactor studies, scientists and engineers would also have a broader expertise when working on enhanced LWR technology and cross-cutting safety, core physics, engineering and materials areas. Also, a successful Gen-IV design team would highly benefit from 'systemic' and 'interdisciplinary' specialists in the various scientific disciplines involved such as neutronics, thermal-hydraulics, materials science, coolant technologies together with 'assembling' engineers capable to perform optimized integrations of all topical results into 'realistic' reactor components and 'most efficient' balance of plants.

Successful EU/Euratom projects - selected on a competitive basis and promoted through the scientific community (detailed information on all projects is available on CORDIS) - covered highly relevant E&T needs for research organisations, industry and associated end-users. EU/Euratom fission work programmes supported 'GIF concept-oriented' projects, in line with the strategy implemented by the European Commission together with EU leading Member States, but also key cross-cutting fields of nuclear safety, fuel developments, thermal hydraulics, materials research, numerical simulation, design activities of future reactor technologies, partitioning and transmutation, support to infrastructures, education, training and knowledge management, and international cooperation. EU/Euratom framework programmes consistently co-funded dedicated collaborative 'Research and Innovation' (E&T evaluated at around 5% of the total budget for each projects) and 'Coordination and Support Actions' (E&T could be up to 100% of the total budget for each projects) in the area of advanced nuclear systems. All R&D projects incorporated E&T tasks, workshops focused on R&D progress but also training courses for Higher University MSc and PhD students co-organised in collaboration with industrial and research laboratories. They are usually open to participants from partner institutions outside the project and third countries. Coordination support from ENEN is systematically provided to strengthen its international visibility and ensure the highest impact of dissemination and sharing of knowledge among the European scientific community.

Some projects were 'concept-oriented' such as: CP-ESFR (2009-13) Collaborative Project on European Sodium Fast Reactor; LEADER (2010-13) Lead-cooled European Advanced Demonstration Reactor; HELIMNET (2010-12) Heavy liquid metal network; GOFASTR (2010-13) European Gas Cooled Fast Reactor; VINCO (2015-18) Visegrad Initiative for Nuclear Cooperation; ESNII+ (2013 17) Preparing ESNII for HORIZON 2020; EVOL (2010-13) Evaluation and Viability of Liquid Fuel Fast Reactor System; SAMOFAR (2015-19) A Paradigm Shift in Reactor Safety with the Molten Salt Fast Reactor, MYRTE (2015-19) MYRRHA Research and Transmutation Endeavour and ESFR-SMART (2017-21) European Sodium Fast Reactor Safety Measures Assessment and Research Tools.

Other projects addressed cross-cutting research and innovation areas such as: GETMAT (2008 13) Gen-IV and Transmutation MATerials; MATTER (2011-14) MATerials TEsting and Rules; MATISSE (2013-17) Materials' Innovations for a Safe and Sustainable nuclear in Europe; FAIRFUELS (2009-15) FAbrication, Irradiation and Reprocessing of FUELS and targets for transmutation; F BRIDGE (2008-12) Basic Research for Innovative Fuels Design for GEN IV systems; THINS (2010-15) Thermal-hydraulics of Innovative Nuclear Systems; SEARCH (2011-15) Safe ExploitAtion Related CHemistry for HLM reactors; SESAME (2015-19) Thermal hydraulics Simulations and Experiments for the Safety Assessment of MEtal cooled reactors; SACSESS (2013-16) Safety of ACtinide Separation processes; GENIORS (2017-21) GEN-IV Integrated Oxide fuels recycling strategies; CINCH-II (2-13-16) Cooperation in education and training In Nuclear Chemistry; ASGARD (2012-16) Advanced fuelS for Generation IV reActors: Reprocessing and Dissolution; TALISMAN (2013-2016) Transnational Access to Large Infrastructure for a Safe Management of ActiNide; ARCAS (2010-13) ADS and fast Reactor CompArison Study in support of Strategic Research Agenda of SNETP; JASMIN (2012-16) Joint Advanced Severe accidents Modelling and Integration for Na-cooled fast neutron reactors; and SARGEN-IV (2012-13) Towards a harmonized European methodology for the safety assessment of innovative reactors with fast neutron spectrum planned to be built in Europe.

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As an illustration of the consideration brought to E&T in the above-mentioned projects, E&T activities within FP7 CP-ESFR included five European Sessions dedicated to SFR and have been organized by the ESML (Ecole du Sodium et des Métaux Liquides) at CEA-Cadarache in France, University of 'La Sapienza' (IT), Karlsruhe Institute of Technology (KIT, DE) and the University of Madrid (ES). More than 120 trainees and PhD students were welcomed during these five Sessions. Within the following H2020 project ESNII+, a large effort dedicated to Fast Neutron Reactors cooled by Sodium, Lead and Gas has been foreseen. Eight Seminars and two Summer Schools are being organized between 2014 and 2017 and dedicated to various topics such as: a) Fuel properties and fuel transient tests; b) Core neutronic safety issues; c) Instrumentation for Fast Neutron Reactors; d) Thermal-hydraulics and thermo-mechanical issues; e) Mitigation of seismic risks; e) Coolant physico-chemistry and dosimetry, and quality control strategy; f) Safety Assessment of Fast Neutrons Reactors; g) Severe accidents in Fast Neutron Reactors; and h) Sitting and Licensing of Fast Neutron Reactors.

One should also highlight the FP7 ENEN-III project which has elaborated Training Schemes for the development and pre-conceptual design of Gen-IV nuclear reactors. All six Gen-IV reactor types were considered; however, emphasis has been given the three concepts (SFR, LFR and GFR) prioritized within the EU/Euratom framework. Gen-IV training schemes are more research oriented and they have a broader scope than Gen II III training schemes. Following basic principles and introductory courses common to all Gen-IV concepts, dedicated schemes for experts and using supporting research facilities have been identified, and learning outcomes classified accordingly.

To ensure any continuity between implementation of such FP7 ENEN-III training schemes, organizing EU/Euratom projects workshops on R&D progress and international schools could be challenging if they would be exclusively supported by Euratom due to a risk of a lack of continuity between projects selected on a competitive basis following yearly of bi-annual call for proposals. Euratom is highly recognized as a framework benefitting from a high European added value fostering increased cooperation and joint programming activities between EU and Member States, Public and Private investments involving industry, research centres, academia and technical safety organisations capitalizing international partnerships and any use of key infrastructures.

EU/Euratom Education, Training, Skills and Competences sustainable objectives are fulfilled as national and European 'Technological schools' are today evolving successfully towards 'International training platforms' (or Centers of Excellence) [14] [15] e.g. in France, Belgium, Germany, Italy, Sweden or the UK. Courses and training schemes further benefit from a consolidated pedagogical support, a database of lecturers, a management of course materials with a certified Quality Assurance process including evaluation procedures, regular updates and better harmonisation, communication and logistical organization, and an increasing mutual international recognition of certificates or diploma. The availability of attractive research infrastructures in support to Education, Training, Skills and Competences has to be underlined as they highly contribute to quality hands-on training in nuclear technology such as research reactors, critical assemblies, thermal-hydraulic facilities, fuel cycle related laboratories and hot-cells, computer based simulators and state-of-the-art computer codes.

As an illustration where EU/Euratom projects have contributed in a relevant way other the years by supporting dedicated E&T activities, France is providing an important nuclear teaching platform organized around engineering schools, universities, research laboratories, technical schools but also nuclear companies or dedicated entities for professional training. Within this context, the Institut National des Sciences et Technologies Nucléaires (INSTN), with its own Nuclear Engineering Master level (or specialization) degree and a catalogue of more than 200 vocational training courses, is a major nuclear E&T operator in Europe. The International Institute for Nuclear Energy (I2EN) launched in 2010 is federating French entities delivering high level curricula in nuclear engineering and science and is promoting the French offer for education and training in partner countries. With the objective to build ASTRID in France, an important and a rapid increase of R&D work orientated towards the design and conceptual evaluations has taken place. Two reactors are currently being dismantled namely PHENIX and SUPERPHENIX, and it was therefore necessary to further support E&T initiatives delivered at the Ecole du Sodium et des Métaux Liquides (ESML). The Ecole des Combustibles (EC) is also located in CEA Cadarache with the support of INSTN for the development of SFR technology. Trainees usually belonged to French companies such as CEA, EDF, AREVA, IRSN, or any companies involved in sodium activities and belonging (or not) to the nuclear industry. Specific training sessions were also provided to German operators (1983), Japanese operators for the first start-up of the Monju reactor (1990) or in support to PFR and DFR decommissioning projects (UK). Specific sessions were provided to the chemical industry such as UOP (USA). And more recently, ESML in association with the plant operator from PHENIX has extensively increased its offer to foreign institutes such as trainees from CIAE in China, ROSATOM in Russia on Reactor technologies, safety and operation, or IGCAR in India dedicated to Safety. The pedagogical approach consists of combining lectures, discussions and hands-on training on Sodium loops. Since 1975, more than 5000 trainees benefitted from a training at the Sodium School.

In Belgium, SCK•CEN Academy for Nuclear Science and Technology was established at the beginning of 2012 benefitting from sixty years of research into peaceful applications of nuclear science and technology, material and fuel research performed today at the BR2 reactor. With such an extensive experience and involvement in the development of an innovative Multi-purpose hYbrid Research Reactor for High-tech Applications (MYRRHA), major nuclear installations and specialist laboratories are available today on site, SCK•CEN is well placed to take on the role of an international education and training platform on Heavy Liquid Metal (Pb-Bi). In addition, IAEA and SCK•CEN Academy have agreed in 2015, CEA-INSTN and SCK•CEN have also signed in September 2016 cooperation framework agreements on E&T.

EU/Euratom Education and Training initiatives are increasingly being organized with the support of the European Commission to the European Nuclear Education Network (ENEN), and within the frame of projects co-funded through the Euratom Framework Programmes. ENEN was established in 2003 as a French non-profit association to preserve and further develop expertise in the nuclear fields through Higher Education and Training. ENEN has currently over 60 members, mainly in Europe but also from Japan, Russia, South Africa, Canada, Ukraine including strengthen cooperation with IAEA. This objective is realized through the co-operation between universities, research organizations, regulatory bodies, the industry and any other organizations involved in the application of nuclear science and radiation protection and by fostering students' mobility schemes within Europe and beyond. National and international organizations currently undertaking E&T activities in support to Fast Reactor and closed fuel cycle technologies are all very keen to cooperate and to share their resources, to open key research infrastructures in support to common challenging initiatives to the highest benefit of the entire nuclear community (IAEA initiative on the creation of International Centers of Excellence on Research Reactors (ICERR) is very welcome), supporting international mobility of young scientists or researchers and mutual recognition of competences, giving overall a new impetus, high incentives and perspectives for E&T within Europe and beyond.

5. EU/Euratom research perspectives and outreach

The 'Euratom experience' with the Framework Programmes has been one of consistent success in pursuing excellence in research and facilitating pan-European collaborative efforts across a broad range of nuclear science and technologies including nuclear safety, safeguards and security within EU and non-EU countries. Associated education and training activities are in line with Horizon 2020's key priorities, but also in the proposal of Horizon Europe (2021-27), excellent science, industrial leadership, and societal challenges, one of the latter being the secure, clean and competitive energy challenge for Europe in the context of the Energy Union.

Nuclear 'Research and Innovation and Demonstration' needs a policy-driven programmatic approach, to meet the strategic objectives of EU 2020/2030/2050/COP21 Energy and Climate policies. Lack of coordinated research leads to national or bilateral programmes in countries with large capabilities, threatening smaller countries with scientific isolation and loss of expertise. In nuclear medical applications, proliferation vigilance and waste management, non-participating countries risk to become second-class.

In contrast to earlier approaches characterised by a bottom-up projects' selection on a competitive basis and their following implementation, future nuclear R&D should be policy driven. A programmatic approach involving all relevant stakeholders and fora at an early stage - rather than a project approach - should be called for, to meet the strategic objectives of EU energy and climate policies: sustainability, security of supply and competitiveness for a future low-carbon economy. EU energy R&D should satisfy all three policy pillars simultaneously, in a coordinated and output oriented manner. This type of structured R&D organisation should nevertheless not exclude some funding being reserved for good ideas by small research groups (technology watch), since creative solutions often emerge from unexpected initiatives.

National laws and EU Directives should play a bigger role in the organisation of research and training (typically through a roadmap, deployment strategies and priorities), with national organisations (e.g. for nuclear waste management, with the launch of a European Joint Programme EURAD in June 2019) taking the lead in R&D programmes which should be coordinated at the EU level.

It seems appropriate to use different partnerships for collaboration depending on the subjects treated. Public- public partnerships between the European Commission and EU Members States remain crucial to long term R&D (especially infrastructures, demonstration and prototype plants, and basic nuclear education, training, skills and competences) and to societal R&D (such as external costs and radiation protection). In contrast, public-private partnerships are more appropriate for short-term work (design and operation of reactors and waste facilities, regulation, procedures and practical training). For management and operation of large infrastructures of common interest, legal schemes such as a joint technological initiative or European research consortiums should be considered. In addition, use of all H2020 funding instruments available should be capitalised together with the KIC InnoEnergy of the EU's European Institute of Innovation and Technology, and where needed, of EU structural funds in combination with H2020.

The attractive and challenging scientific topics associated to innovative and sustainable Fast Neutron Reactors create a new and highly incentive context for students and young scientists with high potential to embark on a nuclear career. The perspective of new build, innovative Small and Modular Reactors (SMR), construction of SFR, LFR or GFR demonstration reactors or prototypes are key drivers. EU/Euratom Education, Training, Skills and Competences sustainable objectives are fulfilled as national and European 'Technological schools' are today evolving successfully towards 'International training platforms' (or Centers of Excellence). An exemplary and precursory approach in France has allowed a preservation of knowledge on SFR and know-how gained during the past four decades. INSTN, I2EN, SCK•CEN and ENEN are among others respectively increasingly capitalising the practical and sustainable implementation of training schemes, any complementary skills and competences in addition to knowledge, for the qualification and mobility of workers, scientists and engineers. Promoting any further use of key experimental infrastructures, research reactors, irradiation facilities and hot laboratories, simulation platforms and computer codes are highly valuable, and a long-term investment supporting international cooperation.

The dynamic and fast-evolving nuclear industry and its research activities need to be supported by an up-to-date education and training system based on mutual trust, on a certified quality assurance process, on transparency and integration of pan European needs that will deliver an increased number of highly skilled and trained personnel. This updated system could be based on the combination of traditional learning paths and, innovative ones, such as virtual classrooms and MOOCs, to be most effective. All EU stakeholders, from policy-makers, academia, research organisations, regulators, and industry are unanimous in stating that 'a common pan European approach is the way forward', benefitting from EFTS, ECTS and ECVET in combination to 'Open Access to key or world class infrastructures'. For the funding of education and training, beyond the usual programmes in schools and universities, creative instruments could be envisaged. For example, should the minimal educational and training be better specified within national law or by a Euratom Directive? Also, it could maybe be reasonable to set up a common education and training fund jointly managed by the European Commission and Member States and, similarly to the funds for waste management, financed by a mandatory levy on nuclear generators based on nuclear MWh produced if we wish to ensure the meeting of all challenging targets.

References

[1] European Energy Strategy: Secure, competitive, and sustainable energy
http://ec.europa.eu/energy/en/topics/energy-strategy

[2] EU/Euratom legislative framework - http://ec.europa.eu/energy/en/topics/nuclear-energy

[3] Horizon 2020 European Research Framework Programme
http://ec.europa.eu/research/horizon2020/index_en.cfm
http://ec.europa.eu/programmes/horizon2020/h2020-sections

[4] European Commission Departments (Directorates-General) and services
http://ec.europa.eu/about/ds_en.htm

[5] European Technology Platforms (ETPs) - http://cordis.europa.eu/technology-platforms/
SNETP Sustainable Nuclear Energy Technology Platform - http://www.snetp.eu/
IGDTP Implementing Geological Disposal of Radioactive Waste - http://www.igdtp.eu/
MELODI Multi-disciplinary European Low Dose Initiative - http://www.melodi-online.eu/

[6] Strategic Energy Technology Plan (SET-Plan) -

http://ec.europa.eu/energy/technology/set_plan/set_plan_en.htm

[7] Independent authoritative expert body with regulatory backgrounds for the stress tests, ENSREG European Nuclear Safety Regulator Group
http://ec.europa.eu/energy/nuclear/ensreg/ensreg_en.htm
ENEF European Nuclear Forum Energy -
http://ec.europa.eu/energy/nuclear/forum/forum_en.htm

[8] OECD/NEA Nuclear Energy Agency - http://www.oecd-nea.org/
GIF Generation-IV International Forum - http://www.gen-4.org/
IAEA International Atomic Energy Agency - http://www.iaea.org/

[9] Bologna Process in 1999
http://ec.europa.eu/education/policies/educ/bologna/bologna_en.html
Copenhagen Declaration in 2002
http://ec.europa.eu/education/lifelong-learning-policy/ecvet_en.htm
ECVET European Credit System for Vocational Education and Training
http://www.ecvet-team.eu/

[10] CORDIS, European Community Research and Development Information Service
http://cordis.europa.eu/home_en.html
EU Participant Portal
http://ec.europa.eu/research/participants/portal/desktop/en/home.html

[11] EIT KIC InnoEnergy MSc EMINE – European Master in Nuclear Energy
http://www.innoenergy.com/education/master-school/msc-emine-european-master-in-nuclear-energy/

[12] EHRO-N, European Human Resources Observatory for the Nuclear sector, Perspective report
http://ehron.jrc.ec.europa.eu/sites/ehron/files/documents/public/ehro-n_putting_into_perspective_report_2012_05_25_0.pdf

[13] GIF Generation-IV International Forum Progress in Nuclear Energy, volume 77
http://www.sciencedirect.com/science/journal/01491970/77
GIF Annual reports https://www.gen-4.org/gif/jcms/c_44720/annual-reports

[14] INSTN, Institut National des Sciences et Technologies Nucléaires
http://www-instn.cea.fr
I2EN, the International Institute for Nuclear Energy http://www.i2en.fr
SCK•CEN Academy for Nuclear Science and Technology
http://www.sckcen.be/en/Education_training/SCKCEN_academy
ENEN European Nuclear Education Network Association http://www.enen-assoc.org

[15] FR13 Conference Proceedings held in Paris, France, from 4 to 7 March 2013 http://www-pub.iaea.org/books/IAEABooks/10682/Fast-Reactors-and-Related-Fuel-Cycles-Safe-Technologies-and-Sustainable-Scenarios-FR13-Proceedings-of-an-International-Conference-on-Fast-Reactors-and-Related-Fuel-Cycles-Paris-France-4-7-March-2013

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JRC IN EURATOM RESEARCH AND TRAINING PROGRAMME – 2014-2020

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Abstract: The Euratom Research and Training Programme 2014-2018 and its extension 2019-2020 (the Euratom Programme) is implemented through direct actions in fission – i.e. research performed by the Commission's Joint Research Centre (JRC), and through indirect actions in fission– i.e. via competitive calls for proposals, and in fusion – i.e. through a comprehensive named-beneficiary co-fund action managed by the Commission's Directorate-General for Research & Innovation (RTD). The general objective of the Programme is "to pursue nuclear research and training activities with an emphasis on the continuous improvement of nuclear safety, security and radiation protection, in particular to potentially contribute to the long-term decarbonisation of the energy system in a safe, efficient and secure way." The Programme is an integral part of Horizon 2020, the EU Framework Programme for Research and Innovation

The direct actions implemented by the JRC constitute an important part of the Euratom Programme and pursue specific objectives covering: nuclear safety, radioactive waste management, decommissioning, emergency preparedness; nuclear security, safeguards and non-proliferation; standardisation; knowledge management; education and training; and support to the policy of the Union on these fields.

The JRC multi-annual work programme for nuclear activities fully reflects the aforementioned objectives. It is structured in about 20 projects, and allocates 48 % of its resources to nuclear safety, waste management, decommissioning and emergency preparedness, 33% to nuclear security, safeguards and non-proliferation, 12% to reference standards, nuclear science and non-energy applications and 7% to education, training and knowledge management. To ensure that direct actions are in line with and complement the research and training needs of Member States, JRC is continuously interacting with the main research and scientific institutions in the EU, and actively participating in several technological platforms and associations.

JRC also participates as part of the consortia in indirect actions, which allows JRC scientist to engage in top level scientific research, and yields maintaining and further developing JRC's scientific excellence. At the same time, the members of the consortia can have access to unique research infrastructure.

The participation of JRC in indirect actions can be improved by exploiting synergies inside the Euratom Programme, and also with the future Horizon Europe Framework Programme. In preparation of the next Euratom Programme 2021-2025, two pilot projects on knowledge management and on open access to JRC research infrastructure will explore and test this improved involvement of JRC in indirect actions.

The paper highlights some of the achievements of recent JRC direct actions with a focus on the interaction with EU MS research organisations, as well as some of the most important elements of the Commission Proposal for the next (2021-2025) Euratom Programme, with a focus on the new positioning of the JRC as regards its participation in indirect actions.

Key Words: Education and Training, Research and Innovation, Nuclear Knowledge, Safety and Safeguards.

1. INTRODUCTION

Currently, fourteen Member States operate around 130 nuclear power reactors to generate over 25% of all electricity consumed in the EU, contributing to competitiveness, security of energy supply and limitation of CO_2 emissions as part of the European Union energy and climate policy objectives. Regardless of the individual decisions on continuing, phasing out or embarking in new built nuclear power plants, nuclear energy will continue to be part of the energy mix in the European Union for the next decades. Indeed, in recent Communications on the Energy Union and on the European long-term vision for a prosperous, modern competitive and climate neutral economy, the European Commission recognises nuclear energy as an important player to achieve, together with renewable sources, a carbon-free European energy system. Worldwide, about 450 nuclear power plants are in operation and around 50 more are under construction; several of them in EU neighbouring countries.

To ensure the highest levels of nuclear safety and security, the European Union needs to be at the forefront not only in the development and implementation of the most advance legislation at regional level, with the Euratom Directives on Nuclear Safety (2009 [1], amended in 2014 [2]), Safe and Responsible Management of Radioactive Waste and Spent Fuel (2011) [3], and the Basic Safety Standards (2013) [4], but also promoting nuclear research and training. Indeed, nuclear research and training is a key factor to help the European Union maintain the scientific and technological leadership in nuclear technologies, also in non-power applications.

The Euratom Treaty [5] establishes that the Commission is responsible for promoting and facilitating nuclear research in the Member States and for complementing it by carrying out a Community research and training programme. These programmes are proposed by the

European Commission, and are discussed and adopted by unanimity in the Council. The programmes are funded by the budget of the Community.

2. The EURATOM RESEARCH AND TRAINING PROGRAMME

The Euratom Research and Training Programme 2014-2018 [6] and its extension 2019-2020 [7] (the Euratom Programme) is implemented through so called indirect and direct actions. Indirect actions are research activities carried out by consortia of research institutions from EU Member States and associated countries partially funded by the research budget of the European Union. Research focuses in nuclear fission (via competitive calls for proposals), and in nuclear fusion (through a comprehensive named-beneficiary co-fund actions). Direct actions are research activities in nuclear fission carried out by the European Commission's Joint Research Centre (JRC).

The overall objective of the Programme currently in force is "to pursue nuclear research and training activities with an emphasis on the continuous improvement of nuclear safety, security and radiation protection, in particular to potentially contribute to the long-term decarbonisation of the energy system in a safe, efficient and secure way."

The Programme also sets specific objectives for both indirect and direct actions. Specific objectives of the indirect actions encompass:

(a) supporting the safety of nuclear systems;

(b) contributing to the development of safe, longer-term solutions for the management of ultimate nuclear waste, including final geological disposal as well as partitioning and transmutation;

(c) supporting the development and sustainability of nuclear expertise and excellence in the Union;

(d) supporting radiation protection and the development of medical applications of radiation, including, inter alia, the secure and safe supply and use of radioisotopes;

(e) moving towards demonstrating the feasibility of fusion as a power source by exploiting existing and future fusion facilities;

(f) laying the foundations for future fusion power plants by developing materials, technologies and conceptual design; and

(g) promoting innovation and industrial competitiveness; (h) ensuring the availability and use of research infrastructures of pan-European relevance.

The direct actions implemented by the JRC constitute an important part of the Euratom Programme and pursue specific objectives covering:

(a) improving nuclear safety, including: nuclear reactor and fuel safety, waste management, including final geological disposal as well as partitioning and transmutation; decommissioning, and emergency preparedness;

(b) improving nuclear security, including: nuclear safeguards, non-proliferation, combating illicit trafficking, and nuclear forensics;

(c) increasing excellence in the nuclear science base for standardisation;

(d) fostering knowledge management, education and training; and

(e) supporting the policy of the Union on nuclear safety and security.

The Programme is an integral part of Horizon 2020, the EU Framework Programme for Research and Innovation.

International/EU/EURATOM Status

The extension of the Euratom Research and Training Programme for 2019-2020 was adopted on 15 October, 2019. The adopted extension carry over the activities of the 2014-2018 Programme, keeping the same strategy, scope and mode of implementation, introducing as well the recommendations of the interim evaluation of the 2014-2018 Programme issued by a team of reputed international experts.

The recommendations for the JRC were to reinforce its education and training activities; improve communication and reach-out; introduce project management culture in the work programme; ensure a more efficient management or resources; proof that JRC is cost effective; integrate a coherent direct/indirect actions programme; and pursue synergies between the nuclear and the non-nuclear activities.

The implementation of the programme will therefore continue the activities in education and training, reinforce knowledge management, increase the synergies between nuclear and non-nuclear research in the field of nuclear science applications, and improve open access to scientists to JRC research infrastructure.

The budget for the extension rises up to €770.2 million, with €268.8 million for direct actions to be carried out by JRC.

It is clear that most of the challenges and research needs of the current programme will remain for the EU from 2021 onwards. Thus, the Commission proposal for the next framework programme, the Euratom Research and Training Programme 2021-2025 [8] complementing Horizon Europe will need to focus in nuclear safety, security, radioactive waste and spent fuel management, radiation protection and fusion. The programme will expand research into non-power applications of ionising radiation, and make further improvements in the areas of education, training and access to research infrastructure.

Horizon Europe is the most ambitious framework programme for research and innovation ever. The proposed budget for 2021 to 2027 is €100 billion including €2,4 billion for the Euratom Research and Training Programme. For 2021 to 2025, 619 M€ (out of the 1.6 b€ for Euratom) are for Direct Actions undertaken by JRC.

The proposal of the Commission establishes a common set of objectives for the Direct and Indirect Actions, in order to better streamline the research activities, and allow the combination of instruments and assets, such as JRC's research infrastructure and knowledge base.

The proposal has two general objectives:

(a) to pursue nuclear research and training activities to support continuous improvement of nuclear safety, security and radiation protection;

(b) to potentially contribute to the long-term decarbonisation of the energy system in a safe, efficient and secure way.

As well as four specific objectives:

(a) improve the safe and secure use of nuclear energy and non-power applications of ionizing radiation, including nuclear safety, security, safeguards, radiation protection, safe spent fuel and radioactive waste management and decommissioning;

(b) maintain and further develop expertise and competence in the Community;

(c) foster the development of fusion energy and contribute to the implementation of the fusion roadmap; and

(d) support the policy of the Community on nuclear safety, safeguards and security.

The proposal also includes a focus on non-power applications for medical and industrial use which are clear synergies with Horizon Europe and opens Marie Skłodowska-Curie Actions to nuclear researchers.

3. EUROPEAN COMMISSION'S JOINT RESEARCH CENTRE

The Joint Research Centre is the European Commission's science and knowledge service. It employs scientists to carry out research in order to provide independent scientific advice and support to EU policy in areas such as agriculture, food security, environment, climate change, innovation, growth, as well as in nuclear safety and security.

The JRC creates, manages and makes sense of knowledge and anticipates emerging issues that need to be addressed at EU level. It develops innovative tools and makes them available to policy-makers. It explores new and emerging areas of science and hosts specialist laboratories and unique research facilities. Its scientific results are highly ranked by international peer systems.

Established as a Joint Nuclear Research Centre by Article 8 of the Euratom Treaty [9], the JRC draws on 60 years of scientific experience and continually builds its expertise, sharing know-how with EU countries, the scientific community and international partners. With time, the JRC broadened its field of research to non-nuclear disciplines, which now cover around 75 % of its entire activities. It works together with over a thousand organisations worldwide in more than 150 networks whose scientists have access to JRC facilities through various collaboration agreements.

Figure 1. European Commission's Joint Research Centre sites

The JRC is organised in Directorates, one with corporate responsibilities for strategy, work programme coordination and resources; and one support services. Six scientific directorates dealing with growth and innovation; energy, transport and climate; sustainable resources; space, security and migration; health, consumers and reference materials; and nuclear safety and security. And two cross-JRC directorates dealing with knowledge management and competences. The JRC directorates are spread across six sites in five European Union Member States: Brussels and Geel in Belgium, Petten in The Netherlands, Karlsruhe in Germany, Ispra in Italy, and Sevilla in Spain.

3.1. JRC research and training in nuclear safety and security

The Directorate for Nuclear Safety and Security employs around 500 scientists, technicians and administrative staff in in Petten, Karlsruhe, Geel and Ispra.

The JRC multi-annual work programme for nuclear activities fully reflects the objectives of the Euratom Research and Training Programme. It is structured in about 20 projects, and allocates approximately 48 % of its resources to nuclear safety, waste management, decommissioning and emergency preparedness, 33% to nuclear security, safeguards and non-proliferation, 12% to reference standards, nuclear science and non-energy applications and 7% to education, training and knowledge management.

To ensure that direct actions are in line with and complement the research and training needs of Member States, JRC is continuously interacting with the main research and scientific institutions in the EU, and actively participating in several technological platforms and associations. In a few cases, JRC also participates as part of the consortia in indirect actions, which allows JRC scientist to engage in top level scientific research, maintaining and further developing JRC's scientific excellence. At the same time, the members of the consortia can have access to unique research infrastructure.

Without being exhaustive, the JRC's most relevant activities in the nuclear domain encompass, in nuclear safety, research in advanced mechanical tests methods to address creep fatigue or stress corrosion cracking at high temperatures in corrosive environments, such as supercritical water and liquid metals; research in severe accident modelling and analysis with computer codes such as the European software system ASTEC and others. The JRC operates the EU Clearinghouse on Operating Experience Feedback, a regional network constituted by the JRC, nuclear safety regulatory authorities, technical support organisations, and international organisations that aim at enhancing nuclear safety through further use of lessons learned from Operating Experience. Another key activity is the development, operation and maintenance of EURDEP, EU system for almost real-time monitoring of radioactivity in the environment, and support to ECURIE, which is the technical interface of the EU early notification and information exchange system for radiological emergencies.

JRC also carries out research in safety of the nuclear fuel cycle, at in-core, storage and disposal, and under normal, abnormal and accidental conditions. JRC developed and further improves and maintains the TRANSURANUS computer code, which is a widely used independent computer code for fuel performance analysis. JRC research is not limited to current nuclear fuels, but also to advanced and innovative designs. Complementing its European partners, JRC carries out research on safety and safeguards aspects of Generation IV reactors [10].

In the area of radioactive waste management, JRC focuses in non-destructive analyses techniques for the characterisation of waste packages; standardisation of free release measurements, development of novel techniques for mapping contamination, and for decontamination in high activity environments, methods for hard to measure nuclides, etc.

JRC activities in the field of nuclear security and safeguards focuses in four main areas: effective and efficient safeguards (through research in, e.g. nuclear material measurements, containment and surveillance, process monitoring and on-site laboratories), verification of absence of undeclared activities (through e.g. trace and particle analysis, and development of in-field tools), nuclear non-proliferation (through e.g. export control, trade analysis, and studies) and combating illicit trafficking (through, e.g. equipment development, testing, and validation, nuclear forensics, preparedness plans).

In standardisation, the JRC is very active, and is a reference entity in reference measurements and data; basic and pre-normative research; and inter-laboratory comparisons. The JRC develops materials standards, and manufactures reference materials. JRC is a major European provider of nuclear data and standards for nuclear energy applications, due to its experienced and competent staff and unique scientific infrastructure. The main repositories for these data are the databases of Nuclear Data bank of the NEA-OECD and the IAEA, which provide open access to the data to scientific and engineers.

JRC has relevant research activities in the field of nuclear science applications, such as accelerator-based nuclear measurements, basic properties of radionuclides and associated applications, including supporting the authentication and preservation of cultural heritage and archaeological studies, use of tracers for climate modelling, nuclear medicine, such as targeted alpha-immunotherapy, food fraud detection, and space applications.

Figure 2. Targeted alpha-immunotherapy

JRC activities in knowledge management, education and training include organisation and active participation in expert and scientific conferences, and the participation, preparation and implementation of education and training initiatives such as the European Nuclear Security Training Centre (EUSECTRA), European Safeguards Research and Development Association (ESARDA), education and training of Euratom and IAEA nuclear inspectors, European Learning Initiatives in Nuclear Decommissioning and Environmental Remediation (ELINDER), international summer schools in radioactive waste management and decommissioning, nuclear resonance analysis, radionuclides, as well as a number of other education and training courses in nuclear safety, security, nuclear data, etc.

3.2. JRC nuclear research infrastructure.

The nuclear research experimental facilities of the JRC are distributed in the sites of Geel (Belgium), Petten (the Netherlands), Karlsruhe (Germany) and Ispra (Italy).

JRC-Geel research infrastructure mainly focuses in nuclear data, radioactivity metrology, and nuclear reference materials:

a) The neutron time-of-flight linear accelerator (GELINA) is a pulse white spectrum neutron source with the best time resolution in the world. It is a multi-user facility serving up to 12 different experiments simultaneously. GELINA combines four specially designed and distinct units: a high-power pulsed linear electron accelerator, a post-accelerating beam compression magnet system, a mercury-cooled uranium target, and very long (up to 400 m) flight paths.
b) The tandem accelerator based fast neutron source (MONNET) is a 3.5 MV electrostatic accelerator for the production of continuous and pulsed proton-, deuteron- and helium ion beams. The combination of both facilities GELINA and MONNET makes JRC-Geel one of the few laboratories in the world which is capable of producing the required accuracy for neutron data needed for the safety assessments of present-day and innovative nuclear energy systems.
c) Radionuclide metrology laboratories: a cluster of instruments for high precision radioactivity measurements (RADMET laboratories) and the high activity disposal experimental site (HADES): Laboratory for ultra-sensitive radioactivity measurements 225 m deep underground at the premises of the Belgian nuclear institute SCK.CEN.
d) Nuclear reference materials laboratories for the preparation and provision of certified nuclear reference materials and reference measurements (METRO) and well-defined and well-characterised samples for nuclear data measurements (TARGET). The nuclear reference materials laboratories encompass mass spectrometry equipment, chemical sample preparation equipment in glove boxes, substitution weighing equipment in glove boxes, robot systems for dispensing of radioactive solutions, equipment for production of reference particles and UF6 reference measurements.

Figure 3. Accelerators for nuclear data measurements in JRC-Geel

JRC-Petten hosts and operates laboratories for the assessment of materials and components performance under thermo-mechanical loading, corrosion, and neutron irradiation:

a) The high flux reactor (HFR, owned by JRC but operated by the Dutch company NRG) is one of the most powerful multi-purpose materials testing research reactors in the world. The HFR is a tank in pool type light water-cooled and moderated and operated at 45 MW. The reactor provides a variety of irradiation facilities and possibilities in the reactor core, in the reflector region and in the poolside facility, as well as neutron beams.

b) The laboratory for the ageing of materials in light water reactor (LWR) environments (AMALIA) is a laboratory for aqueous corrosion and stress corrosion cracking investigations, a unique facility encompassing four recirculating water loops with 6 autoclave systems, all featuring full water chemistry control. The autoclaves (Tmax = 650°C, Pmax = 360 bar) are equipped with environmental mechanical testing facilities (slow strain-rate tensile tests, crack initiation and crack growth rate tests, fracture mechanics, cone-mandrel tests, small-punch tests), electrochemistry, electric impedance, DC potential drop, and acoustic emission monitoring, to assess coolant compatibility and materials degradation issues in light water reactor environments. The autoclave systems with mechanical test rigs are unique in their high temperature capabilities and in that they feature proprietary bellows-based pneumatic test control.

c) The Structural Materials Performance Assessment laboratories (SMPA) are used for the mechanical performance characterisation, life assessment and qualification of structural materials for present and next generation nuclear systems. The test installations include 3 servo-hydraulic and 3 electro-mechanical universal test machines for (thermo-)mechanical tests, low-cycle fatigue, and fracture mechanics tests, 11 uniaxial creep rigs, 5 small-punch creep rigs, 2 Charpy test rigs, a dedicated test rig for thermal fatigue tests of tubular components, and a nano-indentation hardness tester (–150°C to + 700°C). Depending on the application, temperature control ranges from cryogenic (liquid nitrogen) to high temperatures (induction heaters, radiation heaters and resistance furnaces).

d) The Microstructural Analysis Infrastructure Sharing laboratory (MAIS) is a user lab for microstructural characterisation and materials degradation studies. The facilities include scanning electron microscopy, transmission electron microscopy and atomic force microscopy (AFM), optical microscopy, metallography, 3D X-ray computed tomography with comprehensive image analysis and defect visualization capabilities for cracks, creep damage, grain boundary decohesion, dimensional analysis etc., X-ray diffraction, 3D profilometer, thermo-electric power and Barkhausen noise measurements.

Figure 4. AMALIA laboratory.

Karlsruhe mainly focuses in properties of irradiated and non-irradiated nuclear materials, as well as research in fuel, fuel cycle, radioactive waste, security and safeguards. The Karlsruhe site has two nuclear licenses, one collective for the wings A, F and G, in which glove box work with radioactive materials is performed, and one for wing B, the hot cell wing for handling irradiated materials.

a) Fuels and materials synthesis and characterisation facility (FMSC): The facility comprises 3 shielded glovebox chains for U/Th, Pu and Am bearing samples respectively for the synthesis and characterisation of actinide materials, including nuclear fuels.

b) Hot cells (HC): 24 hot cells with different capabilities for irradiated fuels, cladding and nuclear material detailed scientific investigations covering all aspects related to the safety of nuclear fuels during irradiation under normal and accident conditions, such as non-destructive examinations, destructive physical analyses: structure and microstructure, morphology, fission products and phase distribution and properties; high temperature behaviour during severe accidents; mechanical characterization. Destructive nuclear chemistry tests: dissolution, inventory/burnup determination; separation using aqueous and pyrometallurgy routes; leaching and corrosion behaviour for waste management/disposal studies.

c) Materials research laboratories (MRL): Series of unique, mostly home-built experimental installations dedicated to the study of thermodynamic and thermo-physical properties of actinides and nuclear materials.

d) Nuclear trace and analyses facility (NTA): Set of installations for the chemical, physical and spectroscopic analysis of actinide and nuclear materials. It encompasses 25 glove boxes, mass spectrometers, titration chain, element analysis, chemical separations, gamma spectrometers, alpha spectrometers, calorimeter, neutron counters and Hybrid K-edge detectors.

e) Fundamental properties of actinide materials under extreme conditions (PAMEC): State-of-the-art installations designed for basic research on behaviour and properties of actinide materials under extreme conditions of temperature, pressure, external magnetic field and chemical environment. Surface science laboratory for synthesis, structural, and spectroscopic characterisation of model nuclear materials. The facility includes devices for measurements of crystallographic, magnetic, electrical transport, and thermodynamic properties as well as facilities for Np-237 Mössbauer spectroscopy, and a modular surface science spectroscopy station allowing photoemission, atomic force microscopy, and electron scattering measurements.

f) EUSECTRA offers a unique combination of scientific expertise, specific technical infrastructure and availability of a wide range of nuclear materials, to enable unparalleled training opportunities in the field of nuclear security and safeguards. Training areas for EUSECTRA include border detection, train-the-trainers, mobile emergency response (i.e., MEST), reach-back, creation of national response plans, nuclear forensics, radiological crime scene management, nuclear security awareness and sustainability of a national nuclear security posture. It is based on the JRC facilities at the Ipsra and Karlsruhe sites.

g) The large geometry secondary ion mass spectrometry laboratory (LG-SIMS) laboratory is equipped with a highly sensitive mass spectrometer to detect trace quantities of uranium/plutonium in micron-sized particles collected for safeguards purposes.

A new laboratory building, known as wing M, which will contain laboratories involving the handling of significant amounts of radioactive materials is currently being constructed on site. Activities currently distributed among several hot laboratories of JRC Karlsruhe will be transferred into the new dedicated lab.

Figure 5. JRC hot-cells

Figure 6. Nuclear facilities verification laboratory

JRC-Ispra carries out research in safeguards and security

a) Laser laboratory for nuclear safeguards and security: Laser based systems to carry out containment and surveillance techniques for nuclear safeguards, including fingerprinting of nuclear containers, change detection, design information verification systems and outdoor verification systems.

b) Advanced safeguards, measurement, monitoring and modelling laboratory (AS3ML): Laboratory to measure nuclear material, to monitor the operation of facilities through an extensive collection of data from multiple types of sensors, and to model the plant operations in order to be able to analyse the data collected by the monitoring system. AS3ML is thus used for testing and developing innovative integrated solutions for the implementation of safeguards in the different types of nuclear installations.

c) Performance laboratory / Pulse neutron interrogation test assembly (PERLA / PUNITA): Laboratory for the assessment and evaluation of performances for all non-destructive assay (NDA) techniques applied in the safeguards of nuclear materials. PUNITA incorporates a pulsed (D-T) neutron generator.

d) Tank measurement laboratory / Solution monitoring laboratory (TAME / SML): Bulk handling facilities, which proposes challenges to the performances of inventory quantification and density characterisation.

e) Sealing and identification laboratory (SILab): Laboratory for the development, testing and commissioning of security systems used for nuclear and commercial applications.

f) Illicit Trafficking Radiation Assessment Programme (ITRAP). The facility is dedicated to perform tests on radiological performances of radiation detection equipment used in nuclear security. It is composed by two laboratories: the static test lab for handheld equipment and the dynamic test lab for portals.


Figure 7. European Nuclear Security Training Centre (EUSECTRA)

3.3. Decommissioning and Radioactive Waste Management Programme

The Commission's Joint Research Centre (JRC) owns nuclear research installations in four sites: JRC-Geel in Belgium, JRC-Karlsruhe in Germany, JRC-Ispra in Italy and JRC-Petten in the Netherlands. As nuclear operator and/or owner under Belgian, Dutch, German and Italian laws, the JRC is responsible for the decommissioning of these installations and for the responsible and safe management from generation to disposal of the resulting spent fuel and radioactive waste.

International/EU/EURATOM Status

The JRC's Decommissioning and Waste Management Programme [11] launched in 1999 details all the activities that the JRC plans and carries out for the safe decommissioning and dismantling of its obsolete facilities (historical liabilities) and the integration of the decommissioning and dismantling plans of its still operational nuclear research facilities (future liabilities). The programme also covers the management of the historical radioactive waste and the waste arising from the decommissioning and dismantling activities of the programme up to the disposal of all radioactive waste and unconditional release of the sites.

The scope of the programme includes a variety of installations, ranging from research reactors to hot cells, accelerators, laboratories and other facilities where radioactive substances were and are handled. It also aims to treat “historical” waste and waste arising from the dismantling operations as well as management of nuclear materials used for research during operation of the installation. The Commission issues a Communication to the Council and European Parliament on the progress of the D&WM Programme every four years (2004 [12], 2008 [13], and 2013 [14]).

In 2018, the Commission proposed a Council Regulation [15] to establish a common instrument to address the decommissioning of nuclear facilities of the Kozloduy nuclear power plant units 1-4 (Kozloduy, Bulgaria), the Bohunice V1 nuclear power plant (Jaslovské Bohunice, Slovakia), and the JRC nuclear facilities and the management of the arising waste, in order to to optimise synergies and bring added value through becoming a benchmark within the EU for safely managing technological issues in nuclear decommissioning and disseminating knowledge to Member States.

Figure 8. Tomography of waste drums in the characterisation/clearance stage. JRC-Ispra

3.4. International cooperation and support to EU policies

Along the years, JRC has concluded and maintained agreements of different nature (e.g. Memoranda of Understanding, Collaboration Agreements and others) with relevant research institutions within EU Member States, through which joint projects in nuclear research are being carried out. These agreements foster scientific exchanges and stimulate pursuing excellence. At the same time, regular Steering Committee meetings ensure that the research objectives of both parties are aligned and maintained relevant.

But the JRC does not limit its cooperation to within the European Union. On the contrary, the JRC engages with third countries' actors which are important in the nuclear research landscape, including large nuclear countries and specifically, international organisations such as the IAEA and OECD/NEA. Its involvement in EU and international cooperation activities allows the JRC to be kept up-to-date of the nuclear research trends and challenges, and helps shaping, within the EU framework, its own research programme, with the objective of contributing to maintaining the EU competence and leadership in nuclear safety, nuclear security, and nuclear safeguards. In the field of education and training, JRC cooperates with and hosts one of the offices of the European Nuclear Education Network, (ENEN), an international non-profit organization which main purpose is the preservation and the further development of expertise in the nuclear fields by higher education and training in Europe.

Building upon the scientific expertise and its work with the different partners, including European and third countries reputed research institutions, international organisations, and others, the JRC contributes to the development, implementation and monitoring of nuclear-related EU policy (EU Directives and Euratom Treaty obligations), and instruments (e.g. for nuclear safety and nuclear security), together with other Directorates-General of the European Commission and other Institutions. In particular, and in addition to JRC's research work on the safety and safeguards aspects of innovative Generation IV reactors, the JRC has been entrusted to be the Euratom implementing agent [16] of Generation IV International Forum, which is a co-operative international endeavour was set up to carry out the research and development needed to establish the feasibility and performance capabilities of the next generation nuclear energy systems.

4. THE WAY FORWARD

The long-term safe, secure and sustainable use of nuclear energy must be ensured by a consistent approach to safety (implementation of appropriate and commensurate common principles, rules and standards); safeguards (verification, reporting and non-proliferation commitments such as export controls) and security (prevention, detection and response), as well as international acceptance and mutual trust (transparency). This can only be achieved based on sound scientific evidence, reliable nuclear measurements and appropriate control tools, as well as on public involvement, which at the same time can only be guaranteed if competence and technology leadership are maintained within the EU (research, education, training and knowledge management).

The Commission's proposal for the next Euratom Research and Training Programme (2021-2025), which is currently being discussed at the Council aims at focusing in the same key research areas as the current programme, i.e. nuclear safety, security, radioactive waste and spent fuel management, radiation protection and fusion energy. At the same time, the programme intends to expand research into non-power applications of ionising radiation, and make improvements in the areas of education, training, knowledge management and access to research infrastructure (including in particular the infrastructure operated by JRC), as well as to better exploit the complementarity between research carried out by Member States scientific institutions, and research carried out by the Joint Research Centre.

Up to now, JRC participated in indirect actions by taking part of consortia, which would compete against national research institutions in the different calls prepared by the Commission [17]. The recommendations from STC and from the various independent experts panels (that carried out the interim and ex-post evaluations of Euratom research and training programmes) underlined the necessity of exploiting synergies inside the Euratom Programme, and also with the future Horizon Europe Framework Programme. The Commission proposal reflects the need to streamline and foster the complementarity between the nuclear research carried out by the Member States and the one carried out directly by the JRC by establishing a single set of objectives for both direct and indirect actions. It is also envisaged that projects can be drawn up by combining different instruments and assets, such as JRC's knowledge base and research infrastructure.

Starting in the next Euratom Programme, it is proposed that the JRC participates in indirect actions where the JRC has a specific competence. In this way, the JRC, through direct actions, would complement consortia's activities where the JRC has the necessary expertise or dedicated infrastructure without participating in competitive biddings against research institutions of the Member States.

In preparation for this approach, three pilot projects [18] on knowledge management in nuclear safety, open access to JRC research infrastructure, and roadmap for access to the Jules Horowitz Reactor, will explore and test this improved involvement of JRC in indirect actions.

In the project on knowledge management in nuclear safety, JRC will provide technical and scientific support for the management of the created knowledge in both indirect and direct actions of the successive Euratom Programmes. The JRC should develop methods and tools to gather and valorise that knowledge making it available to the European research Community.

The project on open access to JRC research infrastructure aims at making the JRC research infrastructure available for the use by the Euratom research community. Scientists of Member States will have the financial support of RTD to facilitate the experimental research in JRC laboratories.

In the project developing the Jules Horowitz Reactor operation plan 2040, the JRC participation is expected to ensure that the full use of the Euratom access rights is covered, while taking into account the JRC planned activities.

In all these three pilot projects, JRC personnel costs as well as the operational costs of JRC research infrastructure will be covered exclusively by the JRC direct actions budget.

5. CONCLUSIONS

Regardless of the EU Member States decisions on continuing, phasing out or embarking in new built nuclear power plants, nuclear energy will continue to be part of the energy mix in the European Union for the next decades, and also in neighbouring countries. The EU must ensure that Member States use the highest standards of safety, security, waste management and non-proliferation. The EU should also ensure that it maintains technological leadership in the nuclear domain so as not to increase energy and technology dependence. Efficient research and training at EU level are key elements to achieve these objectives.

The JRC is a very important partner in European research, which aims at complementing the nuclear research and training carried out by the research institutions of EU Member States through its scientific expertise and research infrastructure. JRC's areas of work cover ample disciplines in the field of nuclear safety, nuclear security, nuclear safeguards, and nuclear science applications ranging from basic research up to ready to use applications, as well as development of reference measurements and supply of reference materials. To this end, the JRC operates cutting-edge laboratories and research infrastructure, in many cases with unique characteristics and capabilities.

Although cooperation in nuclear research has been always a key objective in the work programme of the JRC, the Commission proposal for the next Research and Training

Programme, which is still under discussion, has taken further concrete actions towards a more efficient alignment of the research and training activities of Member States and those of the Joint Research Centre.

The JRC, together with its partners is getting ready to this new approach by proposing and new way of implementation, in which the JRC will not bid with research institutions of the Member States in competitive processes, but rather will form part of those projects for which the knowledge and capacities (including infrastructure) of the JRC are significant or relevant. This new way of implementation will be tested through three specific pilot projects on knowledge management, open access to JRC research infrastructure, and access rights to the Jules Horowitz Reactor.

For more than 60 years, the Joint Research Centre has developed a sound knowledge base and expertise in nuclear matters, continually pursuing scientific excellence. It shares its know-how and achievements with EU Member States, the scientific community, and international partners. It works together with over a thousand organisations worldwide in more than 150 networks whose scientists have access to JRC facilities through various collaboration agreements. The JRC will continue to be a relevant actor in the nuclear research arena, focusing on nuclear safety, responsible and safe management of radioactive waste and spent fuel, radiation protection, nuclear science applications, nuclear security, nuclear safeguards, and standardisation as the challenges of today will still outstand in the next years. The next Euratom Programme will, in addition, reinforce JRC education and training as well as knowledge management activities, increase synergies with non-nuclear activities, further develop nuclear science applications, and improve access of scientists to JRC research infrastructure.

REFERENCES

[1] Council Directive 2009/71/Euratom of 25 June 2009 establishing a Community framework for the nuclear safety of nuclear installations, OJ L 172, 2.7.2009, p.18-22.

[2] Council Directive 2014/87/Euratom of 8 July 2014 amending Directive 2009/71/Euratom establishing a Community framework for the nuclear safety of nuclear installations, OJ L 219, 25.7.2014. p. 42-52

[3] Council Directive 2011/70/Euratom of 19 July 2011 on establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste, OJ L199, 2.8.2011, p. 48-56.

[4] Council Directive 2013/59/Euratom of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom (OJ L13, 17.1.2014, p. 1 - 73).

[5] https://www.consilium.europa.eu/media/29775/qc0115106enn.pdf

[6] Council Regulation (Euratom) No 1314/2013 of 16 December 2013 on the Research and Training Programme of the European Atomic Energy Community (2014-2018) complementing the Horizon 2020 Framework Programme for Research and Innovation. OJ L 347, 20.12.2013, p. 948–964

[7] Council Regulation (Euratom) 2018/1563 of 15 October 2018 on the Research and Training Programme of the European Atomic Energy Community (2019–2020) complementing the Horizon 2020 Framework Programme for Research and Innovation, and repealing Regulation (Euratom) No 1314/2013. OJ L 262, 19.10.2018, p. 1–19

[8] Proposal for a COUNCIL REGULATION establishing the Research and Training Programme of the European Atomic Energy Community for the period 2021-2025

complementing Horizon Europe – the Framework Programme for Research and Innovation. COM/2018/437 final

[9] Consolidated version of the Treaty establishing the European Atomic Energy Community. OJ C 327, 26.10.2012, p. 1–107

[10] Euratom Contribution to the Generation IV International Forum Systems in the period 2005-2014 and future outlook. JRC 2017

http://publications.jrc.ec.europa.eu/repository/bitstream/JRC104056/kjna28391enn.pdf)

[11] Historical liabilities resulting from nuclear activities carried out at the JRC under the Euratom Treaty – Decommissioning of obsolete Nuclear Installations and Waste Management, COM(1999)114 final

[12] Communication from the Commission to the Council and the European Parliament – Decommissioning of nuclear installations and waste management - Nuclear liabilities arising out of the activities of the Joint Research Centre (JRC) carried out under the Euratom Treaty, SEC(2004)621 final

[13] Communication from the Commission to the Council and the European Parliament – Decommissioning of Nuclear Installations and Management of Radioactive Waste: Management of Nuclear Liabilities arising out of the Activities of the Joint Research Centre (JRC) carried out under the Euratom Treaty, COM(2008)903 final

[14] Communication from the Commission to the Council and the European Parliament – Decommissioning of Nuclear Installations and Management of Radioactive Waste: Management of Nuclear Liabilities arising out of the Activities of the Joint Research Centre (JRC) carried out under the Euratom Treaty, COM(2013)734 final

[15] Proposal for a COUNCIL REGULATION establishing a dedicated financial programme for decommissioning of nuclear facilities and management of radioactive waste, and repealing Council Regulation (Euratom) No 1368/2013

[16] Council Decision (Euratom) 2016/2116 of 12 February 2016 approving the conclusion by the European Commission, on behalf of the European Atomic Energy Community, of the Agreement extending the Framework Agreement for International Collaboration on Research and Development of Generation IV nuclear energy systems. OJ L 329, 3.12.2016, p. 1–2

[17] Council conclusions of 26 April 1994 on the role of the Joint Research Centre (JRC). OJ C 126, 7.5.1994, p. 1–4

[18] COMMISSION IMPLEMENTING DECISION of 14.12.2018 on the financing of indirect actions within the framework of Council Regulation (Euratom) No 2018/1563 and on the adoption of the work programme for 2019-2020. C(2018) 8412 final

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Session One - Predisposal and disposal technology developments

Chair: Jon Martin (RWM, UK)

Rapporteur: Wilhelm Bollingerfehr (BGE, DE), Expert

FISA 2019
EURADWASTE '19

4-7 June, 2019
Pitesti, Romania

SESSI ON ONE SUMMARY

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1. Scope

Session 1 of EURADWASTE ´19 conference is related to the "Pre-disposal and disposal technology developments’". Thus, this session is in mainly dealing with activities prior to waste emplacement (waste characterization, waste minimization and waste treatment). In addition two important activities during repository operation and closure were presented (repository monitoring and closure measures). According to EC-funding policy pre-disposal is becoming a pillar domain of EURATOM. That means that is expected that waste producers, technology developers and Research Entities (RE) will in general closely work together in this area.

Session 1 was opened by the invited keynote-speech of Mr Radek Trtílek (ÚJV Řež, a. s., CZ), Director of Radioactive Waste & Decommissioning Division, who discussed the role and contribution of REs in developing treatment processes and solutions for legacy and problematic waste, in particular from the perspective of smaller nuclear countries.

The following five presentations provided information on the one hand side of EC-projects dealing with predisposal aspects like waste minimization, thermal treatment and waste characterization. On the other hand side recently finalised EC-projects related to engineered barrier systems and monitoring were presented.

- Improved Nuclear Site Characterisation for Radioactive Waste Minimization in Decommisioning and Dismantling under Constrained EnviRonment (INSIDER)
- Characterization of Conditioned Nuclear Waste for its Safe Disposal in Europe (CHANCE)
- Thermal treatment for radioactive waste minimisation (THERAMIN)
- Tunnel plugs and shaft seals demonstrations (DOPAS)
- Monitoring strategies & technologies for geological disposal (Modern2020)

The panel eventually seeks for a wider view from the different categories of organisations from different countries on the issues they have to solve or contribute to in term of pre-disposal and disposal technologies.

2. Overview about presented projects on predisposal and disposal technology developments

The projects presented in Session 1 represent examples of the wide scope of waste management activities. Three of them are focussing on predisposal aspects (**INSIDER, CHANCE and THERAMIN**) mainly relevant for L/ILW prior to disposal; the other two are covering disposal technology developments (**DOPAS and Modern2020**) and are more relevant for HLW deep geological repositories.

T**he INSIDER project** belongs to the group of predisposal projects and is aiming at improving the knowledge of the radiological state of nuclear facilities under decommissioning operations in constrained environment prior to the start of decommissioning and dismantling. Thus, the project is focusing on the improvement of sampling strategies coupled to in-situ and in-lab available technique and methods. The four years project is a joint undertaking of 18 European partners from 10 countries coordinated by CETAMA (CEA Nuclear Energy Division). The project was started in June 2017 and provided first results.

The second project of the group of predisposal projects, **the CHANCE project,** addresses the characterization of Conditioned Radioactive Waste (CRW). The first objective was to establish, at the European level, a comprehensive understanding of current CRW characterization and quality control schemes. The second aim was to further develop, test and validate techniques already identified that will undoubtedly improve the characterization of CRW. Specifically, these technical tasks will focus on:

- Calorimetry as an innovative non-destructive technique to reduce uncertainties on the inventory of radionuclides;
- Muon Tomography to address the specific issue of non-destructive control of the content of large volume nuclear waste and heavily shielded nuclear waste casks;
- Cavity Ring-Down Spectroscopy (CRDS) as an innovative technique to characterize outgassing of radioactive waste, namely 14C and 36Cl.

The approaches applied, the tests performed and the results achieved in the project which runs from 2014-2018 were presented in detail for all three characterization methods.

The intention of **the THERAMIN project**, launched in June 2017, is to provide an EU-wide strategic review and assessment of the value of thermal waste treatment technologies applicable to a broad range of waste streams. These streams include ion exchange media, soft operational waste, sludges, organics, and liquids. The treatment technologies can provide significant improvements: volume reduction, waste passivation, organics destruction, safety demonstration facilitation, etc. THERAMIN will compile an EU-wide database of treatable wastes and document available thermal technologies. Applicability and benefits of technologies to the identified waste streams will be evaluated through full-scale demonstration tests by project partners. Safety case implications will also be assessed through the study of the disposability of thermally treated waste products. Interim results on the review of waste streams and the selected treatment technologies as well as their viability were presented.

The main objective of **the DOPAS project** (Full-scale Demonstration of Pugs and Seals) was to improve the industrial constructability of plugs and seals as main geotechnical barriers of a repository. Other objectives were the improvements of measurement of the barrier characteristics, the control of their behaviour in repository conditions, and their performance with respect to safety objectives. The DOPAS project was run from September 2012 to August 2016 and delivered improvements in the process used to develop the design basis, in the design bases for different plugs and seals, in reference designs, in strategies to demonstrate the compliance of reference designs to the design basis, in technology, in materials and in construction. Another important result was the improvement of the performance assessment of the materials and components. Five demonstration experimental programmes were implemented as part of these development activities.

- the Full-scale Seal (FSS) experiment, undertaken by Andra in a surface facility at St. Dizier, France,
- The Experimental Pressure and Sealing Plug (EPSP) experiment undertaken by SÚRAO and the Czech Technical University at the Josef underground laboratory
- The Dome Plug (DOMPLU) experiment undertaken by SKB and Posiva at the Äspö Hard Rock Laboratory in Sweden,

- The Posiva Plug (POPLU) experiment undertaken by Posiva, SKB, VTT and BTECH at the ONKALO™ Underground Rock Characterisation Facility in Finland.
- Additionally, in situ tests related to seals in vertical shafts complemented by materials research projects were conducted for the ELSA shaft seal project in Germany.

Important results were presented e.g. for defining the design basis and requirements for plugs and seals in general. And for the DOPAS project conceptual and basic designs including material development work were explained and examples for constructed and tested seals and plugs were given. The presentation included lessons learned from site characterization, material developments, construction work and measurements of sealing functions.

The Modern2020 project, launched in June 2015 and accomplished in spring 2019, aimed at providing the means for developing and implementing an effective and efficient repository operational monitoring program. This included the recognition of the requirements of specific national programs as well. The results of Modern 2020 project should enable advanced national radioactive waste disposal programs to design monitoring systems suitable for deployment when repositories start operating in the next decade. In addition the project supported less developed programs and other stakeholders by illustrating how the national context can be taken into account in designing dedicated monitoring programs tailored to their national needs. The Modern2020 program, the approaches applied in the project and the results achieved with the implementation of monitoring system inside specific demonstrators were presented in detail. Lessons learned from the operation of the demonstrators were explained as well as experiences in involving particular stakeholder interests in designing, manufacturing and performing monitor systems.

3. Observations and remarks

For each of the five presented projects observations from the presentations are discussed in some detail below.

Specific remarks about INSIDER

The INSIDER project is in the phase of implementing the planned three common case studies, which will be performed in the form of benchmarking:

- **decommissioning of a back/end of fuel cycle** and/or research facility: JRC-ISPRA tank farm by end of 2019
- **decommissioning of a nuclear reactor** (NPP or RR): BR3 reactor biological shield at SCK-CEN, already started in 2018
- **post-accident remediation of a site**: Contaminated soil from a CEA R&D soil

This approach requires different sampling strategies - matrix representative reference samples and real samples. To maintain/improve the needed reliability of the global results while decreasing the number of available samples/results, the INSIDER project is based on a metrological approach D&D specific certified reference materials and interlaboratory comparisons for both proficiency testing and method performance assessment. Eventually the project will provide a sound database on real waste from decommissioning and deliver guidance for routine operation procedures. Details of the selected sampling strategy were shown as well as the analytical approach and the performance assessments.

To my opinion the INSIDER project will widely enlarge the already existing experience and knowledge in decommissioning of nuclear facilities in particular because of the wide range of the selected case studies. Eventually the envisaged database will deliver a valuable set of information for industrial application. This will become a benefit for waste producers, for the operators of waste treatment facilities and eventually for the repository operators.

Specific remarks about CHANCE

Precise characterization of waste is of uppermost importance for deriving appropriate safety measures for waste handling, transport and disposal. In addition the knowledge about waste specifications facilitates the performance assessments of a repository. Reduction of uncertainties always serves to improve safety. Thus, the CHANCE project will improve the characterization of conditioned radioactive waste by means of new non-destructive technique.

In my opinion the selected and presented technologies (Calorimetry to estimate the overall quantity of nuclear material over a wide range of masses, Muon Tomography to address the specific issue of non-destructive control of the content of large volumes of nuclear waste and Cavity Ring-Down Spectroscopy (CRDS) as an innovative technique to characterize outgassing of radioactive waste) will provide valuable data to describe the waste package inventory more precisely as in the past. However, the design and construction of test facilities and demonstrators showed the limits of practical application of these new procedures. In particular for the CRDS the dependencies from boundary conditions like temperature became obvious and do require further studies and tests.

Specific remarks about THERAMIN

Thermal treatment of solid or liquid L/ILW waste will lead to volume reduction, waste passivation, organics destruction, safety demonstration facilitation, etc. and by that reducing the footprint and the cost for the repository accordingly.

First results showed that the application of the selected techniques provide waste products (glass or ceramics) that at least lead to an improvement in immobilisation of the nuclides. All trial tests so far –at project midterm – delivered the expected quality of waste products.

In my opinion THERAMIN is a remarkable fruitful cooperation between the industry and research organisations. According to EC funding policy "to invest in brains and not in concrete or steel" the R&D organisations themselves (VTT, NNL, USFD, CEA) and the industry (VUJE/JAVYS) provided the appropriate technical devices and facilities, and EC supported the development of the methods and procedures. This is of benefit not only for the waste producer and for the repository operator but in particular for the safety of the repository and by that for environment protection.

Specific remarks about DOPAS

Engineered Barrier Systems play an important role in all safety cases for deep geological repositories. The DOPSA-project (Full-scale Demonstration of Pugs and Seals) which was already accomplished in 2016 covered sealing systems in three different host rocks (crystalline rock, claystone and rock salt). Demonstrators in industrial scale were designed and constructed in several European countries: the Posiva Plug (POPLU) in Finland, the DOMPLU plug in Sweden, Full-scale Seal (FFS) in France, the Experimental Pressure and Sealing Plug (EPSP) in Czech Republic, and (ELSA project) in Germany. All of these demonstrators provided sound and reliable results. This facilitates the material selection, the construction and the test of the safety functions of the barriers.

In my opinion at least two very important lessons were learned. The design phase is decisive with regard to the success of barrier function. I completely agree with the project recommendation that the formulation of design criteria has to be done very precise and carefully. The safety case may provide important design data. And the second lesson learned is that the plug constructor has to be involved from the very beginning to avoid complications during seal construction underground.

Specific remarks about Modern2020

Monitoring becomes more and more an important issue in the debate with civil society about safety of repositories, in particular about long-term safety of deep geological repositories. The Modern2020 project – just accomplished in spring of this year – delivered means for developing and implementing an effective and efficient repository operational monitoring program. The answers for the three main questions with regard to monitoring were delivered. Why is monitoring necessary, what has to be monitored and who will use the gained data? There are multiple reasons why the operational period of a repository should be monitored. At least to reduce the mistrust of stakeholders form civil society.

In my opinion Modern2020is a remarkable fruitful cooperation between representatives from WMOs and research organisations -both taking care of the technical solutions for state of the art technology for long-life sensor and energy supply systems – and representatives from the civil society. Representatives from local communities hosting a repository or a nuclear facility were invited to participate and to express concerns and expectations. Both partners –the experts and the stakeholder learned a lot from each other. In particular the demonstrators implemented at URLs provided the possibility to show how the monitoring systems look like and what they are able to deliver and what not.

4. Conclusions

- Session 1 provided a very good overview about two R&D activity areas of a repository for radioactive waste. The session was dealing with activities prior to waste emplacement (waste characterization, waste minimization and waste treatment). In addition two important activities during repository operation and closure were presented (repository monitoring and closure measures). With regard to a continuing increase in decommissioning of nuclear facilities and an increase in L/ILW waste pre-disposal becomes a more important role in the Waste Management Programs in all countries at least in those who are phasing out of nuclear.
- The results achieved in the pre-disposal project are promising and should encourage WMOs as well as research organisations to seek for further improvements in characterization, minimisation and treatment of waste. This might lead to even more benefits with regard to safety and budget. This in particular could be of importance for countries with small nuclear programmes or for countries which just start their nuclear programmes.
- Specific waste streams, like bituminized waste or graphite require further investigations with regard of their disposability and long-term behaviour.
- Waste packages are important not only for long-term purposes but for transport and handling in the repository operational period as well. Few examples of real waste packages exist today. Thus, R&D should focus on the design and construction of waste packages in particular for SNF/HLW.
- Waste Acceptance Criteria range from very detailed requirements to more general ones in different countries. These criteria should be developed in dialogue between all concerned parties (WMOs, waste producers, regulatory bodies and other stakeholders). Thus, a category of unacceptable waste can be avoided.
- Engineered barrier systems (EBS) are essential in any safety case for repositories for radioactive waste. Plugs for tunnels and drifts in different host rocks have been successfully investigated in an industrial scale in the R&D-project DOPAS. Future R&D

could focus on sealing of shafts and ramps as well because there do not exist many industrial examples.

- Monitoring is not only a technical issue, as Modern2020 has clearly shown. Thus, it could be assessed if it does make sense to consider the implementation of R&D activity with regard to further and more intensive participation of stakeholders from civil society in setting up a monitoring programme. In addition it could be considered to enlarge participation of civil society in other R&D activities.
- The panel discussion at the end of session 1 reveals a few new thoughts:
    - The importance of defining waste acceptance criteria at the very beginning of repository design phase was highlighted. The expectation was expressed that this would facilitate the next design steps like waste package design and selection, repository design and safety assessments. In particular waste producers were asked to contribute to this activity from the very beginning and to deliver reasonable and reliable data of the waste.
    - With regard to waste treatment the panel agreed that the objective of treatment have to be considered carefully. Depending on the waste category different means might be appropriate. Depending on the safety concept it could for instance be of benefit to dispose of HLW/SF asap to increase closure processes of the host rock.
    - The importance of precise waste characterization was expressed as well in particular with regard to identify problematic waste and to define appropriate treatment approaches for that type of waste (e.g. bituminized waste)
    - With regard to monitoring there was a consensus that stakeholder involvement is very important issue and should happen from the very beginning of repository design phase.

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ACTIVITIES OF UJV REZ, A.S. IN THE FIELD OF RADIOACTIVE WASTE MANAGEMENT

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Abstract: The article summarises the status and competence of UJV Rez, a.s. (up to 2012, the Nuclear Research Institute Rez) in the field of radioactive waste (RAW) management. UJV Rez a. s. has been one of the Czech Republic's key research and engineering institutions in the field of nuclear energy production since 1955. The company processes and conditions prior to storage 95% of so-called institutional RAW and is the principal partner of the state with respect to the research support of the Czech deep geological repository development project. UJV Rez a. s. boasts its own accredited radiochemical analytical test laboratory, unique of its kind in the Czech Republic. Of equal importance is UJV Rez's active participation in a range of international organisations and associations and its involvement in wide range of international projects. Moreover, UJV Rez's services covering the repatriation of highly-enriched fuel from research reactors as part of the GTRI initiative for reducing global threats are recognised worldwide.

1. Introduction

UJV Rez, a. s. (formerly the Nuclear Research Institute Rez) has, for more than six decades, constituted the Czech Republic's most important research and engineering organisation in terms of the support of the peaceful use of nuclear energy and ionising radiation. From the beginning, research concerned with radiochemistry and radioactive waste management (RAW) issues have made up an integral part of the company's support activities.

1.1 Brief history

The Nuclear Physics Institute was established in 1955. This was an era that had yet to witness the deployment of satellites and space exploration and, for strategic reasons, a location in the deep valley of the Vltava River was chosen around 14 km upstream of the Prague for the construction of the facility (see Fig. 1). Today, it is hard to believe that within two years a VVR-S nuclear research reactor with a thermal output of 2 MW was designed, constructed and, in 1957, commissioned. The reactor was was completely rebuilt in 1987-1989 and transformed into the LVR-15 research reactor with a thermal output of 10 MW that is still in use today (Fig. 2). The reactor is used for the research of materials, corrosion

testing, the testing of the chemical regimes of power reactors, irradiation services, neutron activation analysis and the production of semiconductors. One of the facility’s most important activities in recent years concerns the production of radiopharmaceuticals and the irradiation of uranium targets to produce Mo-99 /Tc-99 diagnostic radionuclide generator.
A second experimental reactor, of the heavy-water TR-0 type with zero output, was commissioned in 1972 and, following reconstruction in 1982-1983, was converted to the light-water LR-0 type with a maximum thermal output of 5 kW. This reactor is used for the modelling of neutron fields and the testing of power reactor fuel and fuel batches.
Under the name Nuclear Research Institute Rez, UJV became known in 1970 when it focused on applied research and engineering support of the Czechoslovak nuclear programme.

Fig 1: View of the UJV Rez buildings in the Vltava river valley

In 1992, the Institute was transformed into the legal status of the Nuclear Research Institute Rez joint stock company (a. s.), the shareholders of which are nuclear operators ČEZ, a. s. and Slovenské elektrárne (SE, a. s.), nuclear manufacturer Skoda JS, a. s., and the municipality of Husinec. In 2012, the name of the company was changed to “UJV Rez, a. s.” (i.e. the abbreviated form of the previous name).

Two of the most significant events in the recent history of UJV Rez consisted of the acquisition in 2002 of ENERGOPROJEKT PRAHA a. s., the main designer of all the thermal and nuclear power plants constructed in the former Czechoslovakia and, in the period 2011-2017, the construction of the “Sustainable Energy” (SUSEN, see e.g. Fig. 3 and 4) infrastructure of the “Research and Development for Innovation” operational programme of the European Commission and the Ministry of Education of the Czech Republic at UJV Rez’s subsidiary company Research Centre Rez, s.r.o. (CVR).

1.2. UJV Rez today

UJV Rez has a stable and consistent history. The company has more than 750 employees, over 60% of whom are engaged in research and engineering professions. The average employee age stood at 44.3 years and 62% of the company’s workforce had received a university education.

While most of the business activities of UJV Rez are conducted in the Czech Republic, the company continues to expand its operations in Slovakia, other EU and Eastern European countries and Asia. Involvement in foreign projects currently represents almost a quarter of the company's annual turnover.

The UJV Rez and its subsidiary company Research Centre Rez, s.r.o. (CVR) boast an extensive research and technical infrastructure including nuclear research reactors, a cyclotron, hot and semi-hot chambers, gamma irradiators, experimental loops, structural material diagnostics laboratories, four accredited test laboratories for the determination of mechanical and other material properties, radiation chemistry and radiochemical analytics, three positron emission tomography (PET) medical diagnostic centres, laboratories for the research of processes underway and conditions within deep geological repositories, the Radioactive Waste (RAW) Management Centre, etc.

Fig. 2 The LVR-15 nuclear research reactor, Research Centre Rez (CVR)

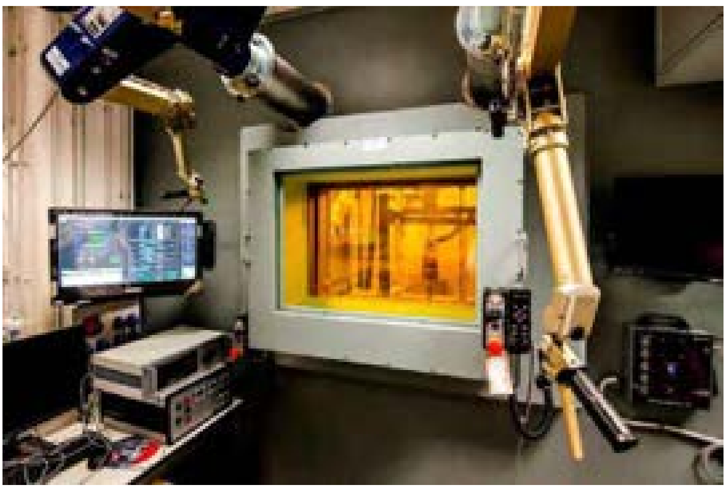

Fig. 3 The SUSEN infrastructure project – hot chamber at the CVR

UJV Rez also utilises the latest available software tools for the 3D-database design as well as for modelling purposes and the determination of complex calculations (concerning, for example, thermomechanical, thermohydraulic and strength processes, rapid process dynamics, the design and optimisation of nuclear fuel batches, deterministic and probabilistic safety analysis, shielding design and related calculations, the dissemination of radionuclides in the environment, etc.).

UJV Rez is closely involved in international cooperation both through its membership of a number of major organisations (e.g. SNETP and NUGENIA), on the basis of bilateral or multilateral agreements (e.g. CEA, GRS, EPRI, SSTC NRS, US-DOE) and through its participation in various international projects (e.g. IAEA, OECD-NEA, EURATOM, Horizon 2020). Through international cooperation and research as well as commercial projects UJV Rez currently enjoys links with 33 countries worldwide.

Fig. 4 The SUSEN infrastructure project - LOCA experimental setup at the CVR

1.3. UJV Rez products and services

Currently, UJV Rez provides engineering and research services in the following areas:
Technical and engineering support for the safe operation of nuclear power plants (safety, reliability, fuel cycle, operational and maintenance support, ageing management and life-time assessment)

Project and related energy services (design and license documentation, supervision, conceptual analysis and expert assessment)

- Development and production of PET radiopharmaceuticals and the operation of PET centres
- Radioactive waste management and related engineering services
- Research and development related to the above areas and further focusing on:
    - Construction and sorption materials
    - Hydrogen technology and hydrogen mobility
    - Networks and systems employing renewable energy sources
    - Generation IV reactors.

1.4. Research and Development

As an important institution in terms of both domestic and European research, UJV Rez focuses on projects commissioned by operators and producers of equipment used in the energy sector and nuclear and conventional power plants as well as projects concerned with the processing and disposal of radioactive waste and diagnostic radiopharmaceuticals for positron emission tomography (PET) use. UJV Rez is today involved in a total of fifty-six grant programmes and projects.

1.4.1 International projects

UJV Rez is the Czech Republic's most important participant organisation in EU-commissioned nuclear fission projects (EURATOM) and, in 2017, the company enjoyed active participation in three projects conducted under the EU's 7th Framework Programme, i.e. Severe Accident Facilities for European Safety Targets (SAFEST), CArbon-14 Source Term (CAST) and Preparation for the ESNII programme of the Horizon 2020 programme (ESNII plus).

As part of the Horizon 2020 programme, UJV Rez participated in sixteen individual projects in 2017. Research continued into cement materials and their function in engineered barriers (CEBAMA), strategies for reactor melt-down retention in the case of a severe accident (IVMR) and the development of the heat removal of supercritical CO_2 (sCO_2 HeRo) as well as issues concerning the tools and methodology for the management of the ageing of cables in power plants (TaM Cables) and the European Joint Radiation Protection Integration Programme (CONCERT). Moreover, UJV Rez is also actively involved in the Visegrad Initiative for Nuclear Cooperation (VINCO) and a range of other programmes.

In addition, UJV Rez also participated in IAEA and OECD/NEA projects focused on enhancing the safety of nuclear power plants employing VVER-type reactors.

1.4.2 Domestic projects

In 2017, UJV Rez was involved in thirty-seven projects and grant programmes supported by the Technology Agency of the Czech Republic (TACR), the Ministry of Industry and Trade and the Ministry of the Interior as well as a number of commercial projects.

2. Radioactive waste (RAW) management

Radiochemistry and issues surrounding radioactive waste management have formed an integral part of UJV Rez's activities since its establishment as a research institute. Today, the company's Radioactive Waste & Decommissioning division is responsible for both the business and technical issues involved in this area.

The original field of research upon which today's division continues to build was radiochemistry. The foundations were laid in 1952, i.e. prior to the establishment of the institute that is today known as UJV Rez. It was the third most important field (in addition to nuclear physics and nuclear power) to be developed at the Rez facility. Naturally, the nature and content of the various related activities have changed over time with the advent of new technologies, the development of nuclear power and, above all, the construction and operation of nuclear power plants.

In accordance with the applicable legislation and authorisation, UJV Rez is currently the only company in the Czech Republic able to cover the complete chain of RAW management from its detection to its safe storage/disposal (except the nuclear power plant fuel cycle).

The services offered by the RAW & Decommissioning division with respect to the management of RAW include:

- the detection, identification and characterisation of RAW, including methods for the detection of abandoned or orphan sources of ionising radiation,
- the collection, classification, storage, transport, treatment and conditioning of institutional RAW, transport to the repository for disposal)
- support for RAW processing and treatment technologies,
- the development and support of the operation of RAW repositories,
- the accredited measurement of the content of radionuclide and nuclear material.

UJV Rez also provides services concerning the decommissioning of workplaces with sources of ionising radiation and support for the decommissioning of nuclear facilities.

Since 2007, UJV Rez specialists have been providing engineering and maintenance services for the transport of spent nuclear fuel from research reactors in the international context.

2.1. Institutional RAW management

Currently, UJV Rez processes for safe disposal almost 95% of the so-called institutional RAW (solid and liquid) generated in the Czech Republic in the industry, medical and other sectors. However, it is perhaps only fair to add that around 60% of such waste is produced by UJV Rez itself (see Tab. 1).

Tab. 1: Volume of RAW accepted for processing and transferred for storage

Producer	RAW form	unit	2014	2015	2016	2017
UJV Rez	solid	m^3	25.2	20.3	24.4	41.4
	liquid		60.3	9.9	8.0	9.2
External producers	solid		16.3	9.7	9.7	21.0
	liquid		4.23	14.4	23.9	14.0
Remediation of environmental damage	solid		55.8	63.9	98.1	36.2
	liquid		2.95	4.3	9.2	3.0
Total RAW accepted for processing			**164.8**	**122.5**	**173.3**	**124.8**
Storage containers *)	solidified	package	639	479	547	418

*) Usually 200 l drums, but in some cases non-standard waste packages

Typical examples of institutional waste consist of old fire alarms (that contain Am-241), diagnostic medicine waste contaminated with Tc-99 (solid, biological) and various iodine isotopes, i.e. I-123, I-131, and I-125 (liquid), irradiators that employ the H-3 radionuclide for the excitation of phosphorescence and various closed radionuclide sources that are used as sensors and detectors or as calibration standards, etc. UJV Rez processes waste for around 45 regular customers, i.e. RAW producers.

Waste generated by the ÚJV Group of companies originates mainly from the operation of its research reactors and consists of e.g. refrigerant cleaning materials, discarded waste following repairs and maintenance and contaminated protective equipment. Historical RAW created via the remediation of the ecological liabilities of the former nuclear research institute makes up a special waste group.

The acceptance of RAW from its producers and its processing and handover for storage or disposal is provided for by the RAW Management Centre, which is equipped with the technology that enables the fragmentation, decontamination, processing and treatment of the waste. For example, it has a two-stage evaporation station for the thickening of liquid RAW, a solid waste press, an ultrasonic decontamination vessel, high-pressure blasting chambers for fragmentation and abrasive blasting, cementation lines, etc. The Centre also has the full range of handling and transport equipment along with waste transport containers. The Centre was completely reconstructed in 2011-2014.

2.2. Seizure of orphan or abandoned sources

The division is also responsible for the detection of orphan and abandoned sources of ionising radiation (so-called seizures) based on long-term contracts with SURAO (waste management organisation) and operators of communal damps and scrap yards. The usual scenario for this service is the removal of the seizure and the tracing and identification of the source, the securing of the capture pending the decision to trace the originator (or not), its processing and handing over for storage/disposal. Around twenty such procedures are conducted annually. Typical captures include waste from medical facilities, usually originating from the patient, or discarded instruments in which Ra-226 containing paint has been used for luminescence.

2.3. Development and engineering support in the field of RAW

UJV Rez also addresses minor projects, though no less important in terms of maintaining and expanding overall knowledge, and contracts for research and engineering services concerned with radioactive waste management issues. The company has a permanent contract for the testing of the “liquid waste - bitumen matrix” system in order to verify compliance with waste acceptance conditions prior to the processing of the radioactive concentrate batches at nuclear power plants, in connection with which the company’s Frobit experimental line (completely modernised in 2017, see Fig. 5) serves to simulate the conditions of the processing facilities of both of the Czech Republic’s nuclear power plants.

Further contracts include the laboratory optimisation of the formula for the solidification of liquid and semi-liquid RAW (sludges, ion exchangers, concentrates) based on geopolymers, cement or mixed geo-cement matrices. The optimisation process is conducted in cooperation with Chemcomex a. s. (ref.: Š. Svoboda et al: An Innovative Method for the Solidification of Radioactive Sludge, in Waste Forum, 10/2014). The Mochovce nuclear power plant waste matrix was optimised in 2011-2012, followed by that of the Dukovany nuclear power plant from 2013-2014 and that of the Paks NPP (Hungary) in 2016-2017. Together with Chemcomex a. s. and based on previous optimisation and licencing verification experience, two contracts were awarded to UJV Rez for the consolidation of ion exchangers and sludges in ALUSIL matrices at the Dukovany nuclear power plant.

Fig. 5: Frobit experimental facility, UJV Rez

Concerning R&D, the most complex challenge addressed by the company in recent years consisted of the "R&D of the RAW technology and management system of new nuclear sources" project (Ministry of Industry and Trade project no. FR-TI3/245) that was addressed in 2011-2015. The project included the development of a filling simulator for the Dukovany RAW repository, technology for the processing and treatment of RAW (the optimisation of existing matrices - the so-called pure bitumen matrix, and the development of new matrices – geo-cement and polysiloxane matrices), the design of a system for management very low-level waste (VLLW), the development of advanced decontamination methods and new methodologies for the characterisation of radioactive materials.

Two of the most important projects currently underway are the "Knowledge Base for the Decommissioning of Nuclear Energy Facilities" project (Ministry of Industry and Trade application no. CZ.01.1.02/0.0/0.0/15_019/0004507 in co-operation with the Technical University of Liberec) and "A Recyclable Decontamination Medium for the Decommissioning of Nuclear Facilities" project (Ministry of Industry and Trade no. FV10023, in cooperation with the Czech Technical University - Faculty of Nuclear Sciences and Physical Engineering and Chemcomex a.s.). The main objectives of the first project are: the development of a sampling probe for the collection of primary circuit piping material for the analysis, and design of a technological procedure for the processing of sorption materials from the cleaning of decontamination media during the decontamination of the primary circuits of nuclear power plants. The main aim of the second project involves the development of an original (patentable) decontamination medium designed specifically for WWER (VVER) nuclear power plant primary circuit materials.

Engineering support also includes the provision of expert consultation services, examples of which include input for a background study for the updating of the Czech National SNF and RAW Management Concept (2011-2012 for SURAO) and cost analyses for the back-end of the fuel cycle for SE, a.s. (Slovakia) (2010, 2014 - 2015).

2.4 Support for RAW disposal and the development of a deep geological repository (DGR)

UJV Rez is the main institution with respect to the provision of research and development support for the Czech deep geological repository project which is managed by the Czech Radioactive Waste Repository Authority (SURAO, waste management organisation). The activities of the RAW & Decommissioning division concern primarily:

–The research of DGR engineered barriers,

–The testing and evaluation of the migration characteristics of the environment

–The assessment of long-term safety.

All the above form part of the provision of research support for the DGR safety assessment.

In addition to the research and development of the safety aspects of the future DGR, UJV Rez is also concerned with DGR technical feasibility issues, the optimisation of the project and the cost analysis of the development, construction and operation of the facility.

UJV Rez is also involved in the preparation of the Slovak DGR both at the conceptual level (conceptual project, cost analysis, development schedule) and with respect to the selection and evaluation of potential sites (contracts for JAVYS a.s. 2013 - 2016 and 2017 - 2018).

As part of the development of the Czech DGR, UJV Rez has been involved in a wide range of European projects conducted under EURATOM framework programmes, e.g. the LTD, CAST, DOPAS, CEBAMA, BELBAR, SAFEST, CROCK and other projects.

Except DGR, UJV is also involved in services for operation of LLW/ILW repositories. UJV Rez was leading safety assessment of Bratrství LLW/ILW repository. Moreover, UJV Rez is responsible for the environmental and discharge monitoring of the Bratrství RAW repository and is currently involved in the preparation of a project for the closure of this repository and the modernisation of the Richard RAW repository.

2.5 Radiological measurement and radiochemical analysis

The basis for the provision of radiological measurement and radiochemical analysis services consists of the company's accredited Central Analytical Testing Laboratory (CAL-ZL) which is the only accredited laboratory in the Czech Republic concerned with non-waterworks radiochemical analysis. The work of the CAL-TL mainly consists of the determination and monitoring of those radionuclides present in various liquid and solid materials that are important in terms of the safe operation of nuclear facilities, the determination and monitoring of radioactive, toxic and other elements (isotopes) important from the point of view of environmental protection, the investigation of samples of natural materials, RAW characterisation and the analysis of gas and biomass samples. The laboratory also provides for the radiation monitoring of workplaces and the environment, the measurement of the efficiency of air-conditioning aerosol and iodine filters and the non-destructive analysis of RAW (gamma scanning and radiography).

Whereas the primary responsibilities of the CAL-ZL in the past were to monitor discharges from and the surroundings of UJV Rez, the development of analytical methods and the provision of internal analytical support for other projects, today the CAL-ZL contracts for and conducts its own projects, the most important of which include sampling and analytical support for the decommissioning of the Ispra European Joint Research Centre in Italy and for the decommissioning survey of a V-1 power plant in Slovakia. Standard contracts include the measurement of the efficiency of air-conditioning system filters at the Temelín and Dukovany nuclear power plants and the determination of the biomass fraction in energy combustion processes as required by legislation.

The CAL-ZL is a member of the IAEA Nuclear Materials Laboratory Network and participates in the regular EQ-RAIN inter-laboratory comparison organised by the French Atomic Energy Commission (CEA). In the 2007–2009 comparison, the CAL-ZL ranked second of 26 laboratories in terms of measurement accuracy and in the 2013–2015 comparison it ranked in the top one-third of laboratories.

2.6 The transport of spent nuclear fuel

The transport of spent nuclear fuel from research reactors is one of the most interesting responsibilities of the Radioactive Waste and Decommissioning division and, indeed, one of the most interesting projects conducted by UJV Rez in recent decades.

The programme was launched almost 15 years ago when the Czech Republic joined the Russian Research Reactor Fuel Return (RRRFR) project which forms a part of the NNSA (National Nuclear Security Administration) Global Nuclear Threat Reduction Initiative (GTRI), the purpose of which is to provide for the return of highly-enriched (so-called HEU) fuel from research reactors from the country of use to the country of origin (in this case Russia) and its replacement with low-enriched (so-called LEU) fuel. The boundary between HEU and LEU was determined based on an agreement between the superpowers on the risks associated with the misuse of HEU materials. The Czech Republic (represented by UJV Rez) was the first country from the former Soviet bloc able to conduct the removal of HEU and to convert it, via an LVR-15 reactor, to LEU. Practically all the work of UJV Rez and most of the technical equipment required was financed by the US Department of Energy (US-DOE).

The first transport of HEU from the Czech Republic took place in December 2007. Subsequently, the results of the work conducted by UJV Rez in terms of reliability, safety and quality convinced the US-DOE that the company should be hired to carry out the technical and engineering work involved in most of the subsequent transports to the Russian Federation, an arrangement that lasted for nine years. Involvement in the RRRFR project was followed by the awarding of a contract for the transport of spent nuclear fuel from Africa and Asia to China (from reactors that had been supplied by China - the MNSR project). The first transport of core fuel under the MNSR project was from Ghana (see Fig. 6), with the arrival of the material in China in October 2017. The training programme organised at the training centre in Ghana also covered the operation of the same type of reactor in Nigeria, from where the next transport operation will be organised. Thus, since 2007, the RAW & Decommissioning division has been involved in the preparation and technical organisation of the delivery of 110 research reactor spent fuel containers in 17 separate transport operations from 12 countries, an overview of which is provided in Tab. 2.

Fig. 6: The loading the MNSR core into a container in Ghana, UJV Rez

Tab. 2: Overview of the transport of SNF by UJV Rez

Date	Country	Reactor	Notes
12/2007	Czech Rep.	LVR-15	
7/2008	Bulgaria	IRT-2000	
10/2008	Hungary	BRR	
9/2009	Poland	EWA	
2/2010	Poland	EWA	
5/2010	Ukraine	VVR-M	
10/2010	Belarus	Pamir-630D, IRT-M	
11/2010	Serbia	RA	
3/2012	Ukraine	VVR-M	
10/2012	Poland	EWA	LEU fuel
3/2013	Czech Rep.	LVR-15	First shipment by sea
7/2013	Vietnam	DNRR	First air shipment
11/2013	Hungary	BRR	
9/2015	Uzbekistan	Photon	Liquid fuel
12/2015	Georgia	Breeder-1	Neutron source

10/2017	Ghana	MNSR	First Chinese reactor
04/2019	Nigeria	MNSR	

2.7 Decommissioning issues (remediation of radiological liabilities)

The decommissioning of nuclear facilities with ionising radiation sources makes up a special area in terms of radioactive waste management. The objective of the decommissioning process is to remove the facility or site from the scope of the Atomic Act.

The provided services include: the drafting of the documentation required to launch the decommissioning process, the development and design of decontamination and fragmentation techniques and procedures, special manipulators and other equipment, the processing and treatment of primary and secondary origin RAW and radiation protection management. With respect to the international environment, UJV Rez specialises in the collection and characterisation of materials, radiochemical analysis and radiation monitoring.

The practical application of the decommissioning process is illustrated by the long-term ongoing Remediation of Ecological Liabilities incurred at UJV Rez prior to Privatisation project. Further examples are provided by the remediation of a needle production line containing Ra-226 at the Richard repository (2004) and the remediation of nuclear medicine facilities. The Radioactive Waste and Decommissioning division has accumulated considerable experience of such work at UJV Rez itself through the dismantling of the reactor vessel (see Fig. 7) and other parts of the original VVR-S reactor (modernised in 1988-1990), the removal and treatment of liquid and various types of solid RAW from underground storage tanks, the remediation of a closed facility for working with alpha nuclides, and the just finished removal and processing of around 50 m3 of waste contaminated with Pu-239 and Am-241.

Fig. 7: Dismantling of the reactor vessel from the original VVR-S research reactor at Řež

Moreover, specialists from UJV Rez gained valuable experience via the decontamination of metal parts (pipes, tanks, fittings, etc.) by means of abrasive blasting with iron pellets in a special blasting chamber. Official monitoring by the specialist company Nuvia a.s.suggests that around 95% of the resulting material can be released directly into the environment.

3. Conclusion

UJV Rez a. s. is a stable and reliable company that provides unique research, application and engineering services in the field of the support of the use of nuclear energy and ionising radiation sources. The company’s technical infrastructure, knowledge base and experience as well as the skills of its employees are unique in comparison to many much larger countries than the Czech Republic and, in certain areas, the level of knowledge and skills and the technical infrastructure are comparable to similar companies in superpower countries.

UJV Rez forms one of the fundamental pillars that provide the Czech Republic with both a significant degree of independence with respect to the safe use of nuclear energy and a guarantee of its further development as the core element of a balanced energy mix. This also applies to the field of radioactive waste management. Much of the experience gained by UJV Rez has been successfully transferred to foreign markets and international cooperation, an example of which is provided by the development of a deep geological repository in the Czech Republic.

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NUCLEAR SITE INTEGRATED CHARACTERIZATION FOR RADIOACTIVE WASTE MINIMIZATION: THE INSIDER PROJECT

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Abstract. The H2020 EURATOM project INSIDER (Improved Nuclear Site Characterization for waste minimization in Decommissioning and Dismantling under Constrained EnviRonment) was launched in June 2017. This 4 year project has 18 partners, and aims at improving the management of contaminated materials arising from Decommissioning and Dismantling (D&D) operations by proposing an integrated methodology for radiological characterization. This methodology is based on advanced statistical processing and modelling, coupled with adapted and innovative analytical and measurement methods, with respect to sustainability and economic objectives. In order to achieve these objectives, the approaches will be then applied to common case studies. To assess the analytical method performance, interlaboratory or inter-team comparisons on matrix representative reference samples and on real samples are organized. Assessment of the outcomes will be used for providing recommendations and guidance resulting in pre-standardization texts.

1. Introduction

Decommissioning and Dismantling (D&D) operations are strongly dependent on the facilities history and on the inventory of present radionuclides. These D&D projects produce large volumes of materials with different radioactivity concentration levels. The material management is a major technical and societal challenge, strongly being subject to economical optimization. Under constrained environments, new methodologies are necessary for a more accurate initial estimation of the contaminated materials, resulting waste volumes and timely planning [1].

The radiological characterization of a facility prior to performing any D&D and remediation operations is a crucial step in the definition of a viable decommissioning scenario [2]. This scenario must be robust and optimized not only with regards to technical issues, produced waste amount and workers dosimetry, but also with regards to costs, deadlines and safety. Today, information can be gained from the reconstitution of a 3D vision of a facility or of the components to be characterized.

The European project called INSIDER has been accepted by the European Commission and launched the 1st of June 2017. INSIDER is coordinated by CETAMA (CEA Nuclear Energy Division) and includes 18 European partners from 10 member states. An End User Group (EUG) will provide user requirements and feedback from the beginning of the project.

The project will focus on radiological characterization, including the sampling strategy and sampling design, through waste-led integrated approaches. Its objectives are thus to improve the management of waste coming from nuclear sites or facilities under D&D with medium (MA) and high radioactivity (HA) levels and/or other constrained environments with respect to operational decommissioning efficiency, safety and costs. It will increase confidence in the quantities and characteristics of resulting radioactive waste in particular concerning subsequent storage and disposal end points.

2. Objectives and ambitions

2.1. Technical objectives and general approaches

The project aims at improving knowledge of the radiological state of nuclear facilities under decommissioning operations in constrained environment, i.e. with limited data set.

The heart of the technical innovative part of the project is to improve the sampling strategy coupled to in-situ and in-lab available techniques and methods, to take into account different types of measurement data, with different but known levels of accuracy [2],[3].

To face the problem of radiological characterization in constrained environments, where very limited amount of available data is particularly challenging, and specific statistical strategy needs to be implemented in order to limit the variability and sensibility to outliers.

In-situ analysis techniques are of paramount importance for initial cartography. In constrained environment they must be complemented by more detailed off–site measurements. Realistic knowledge of their performance is important, without systematic optimization.

An essential consideration for the INSIDER project is that it must be possible to demonstrate that any measurements carried out to characterize the waste materials are traceable to the international measurement system. Such traceability enables nuclear sites to demonstrate that measurements are accurate, fit for purpose and scientifically rigorous, to give regulators and the general public confidence in any results. The INSIDER project involves the characterization representativity problematics of nuclear decommissioning sites.

The main characterization challenges are thus:

- Choosing suitable measurement techniques, well adapted to sampling requirements or expectations
- Adapting to constrained environments of corresponding in-situ and remote laboratory analysis techniques in a cost effective perspective

- Increasing the reliability of characterization data and of interpretation models.

It applies on three main specific use cases, fuel cycle facility, nuclear power plant and post accidental remediation. Each one is representative for different kind of constraints and analytical challenges.

To illustrate and qualify the project-integrated approaches, the methodologies will be applied to the use cases in the form of three different benchmarking exercises. An interlaboratory comparison (ILC), both proficiency testing [4] and possibly method validation [5] on synthetic similar samples will be organized at the same time to assess the performance of the laboratories and their analytical methods in representative but ideal configurations, namely analyzing fit for purpose certified reference materials.

The benchmark will deal directly on real, past or present, D&D selected worksites.

INSIDER has the ambition to develop a common applicable methodology, for hostile environments and to provide guidelines in support to D&D industrial, stakeholders and R&D community, and to future standardization studies.

2.2. Expected impact and ambitions

Recent international reports and standards [8][9][10] highlight the key role of the characterization step in decommissioning operation, planning and cost evaluation. It is central to the optimisation plans. The INSIDER project can contribute to great extent to the international scheme and further identified needs [8].

Currently, real improvement of some analytical or measurement methods is difficult due to the lack in suitable reference materials. INSIDER will support the process development and validation of specific common reference materials and associated fabrication process.

Analytical microsystems or mobile laboratories will take part in different ILC and benchmarking exercises, with increasing representability to D&D operations. They will likely benefit of an increase in TRL level for future R&D and industrial applications.

Through this radiological modelling integrated concept, the project should also contribute to 3D modelling and virtual reality approaches, which are essential areas considered for decommissioning and dismantling task improvement in constraint environments.

3. Organization of the project and status of the workpackages

Five specific technical axes are addressed by the five work packages (WP) of the project, in accordance with the organization described in figure 1. The WP7 is devoted to result exploitation and dissemination to facilitate and emphasize the developments.

The validation of the integrated approach using benchmarking practices activates multiple interfaces between the various work packages. Precise synchronisation and a rigorous scheduling monitoring are indispensable to achieve the common project ambition.

FIG. 1. INSIDER Project organization.

3.1. WP2: User requirements and validationWP2 places itself at the front-end of the INSIDER project, but it extends practically till the end.

Four tasks are devoted to actual practices and requirement reviews. The WP started with the identification of the needs of end-users and requirements imposed by boundary conditions with particular emphasis on the legislative framework. Then a state-of-the-art and associated gap analysis has followed with the purpose to identify topics for R&D; this task, led and composed by research organisation, provides an input to the three technical Work Packages of the project (WP3, WP4 and WP5). Aligned with the global project objective to improve decommissioning of nuclear facilities, different methodologies and practices applied to structure and site characterization connected with the intent of optimizing the management of wastes resulting from the associated operations (decontamination, dismantling and site-clean-up) are investigated. Regarding waste management particular emphasis is devoted to estimation and documentation of volume and characteristics of radioactively contaminated material to be produced. Strategies for waste minimization include volume reduction, segregation, in terms of material composition activity levels and half-lives of the relevant radionuclides and eventually the use of the clearance concept.

Globally, WP2 deals with setting the main requirements and objectives of INSIDER, with defining a benchmark exercise of the methodology developed during the project and evaluating the results.

The backbone of the WP is task 2.4 aiming to identify, design and organise the experimental benchmarks on the selected usage cases:

- UC1: decommissioning of a back/end of fuel cycle and/or research facility: JRC-ISPRA tank farm;
- UC2: decommissioning of a nuclear reactor (NPP or RR): BR3 reactor biological shield at SCK-CEN;
- UC3: post-accident remediation of a site: Contaminated soil from a CEA R&D soil.

3.2. WP3: Sampling & strategy

The main objective of WP3 is to draft a strategy for data analysis and sampling design for initial nuclear site characterization in constraint environments before decommissioning, based on a statistical approach. The process followed consists of four main steps: status, development, implementation and guidance.

The first step resulted in a report that provides an overview on sampling design methods and state-of-the-art statistical techniques for preliminary analyses and data processing. Many of the currently available standards and guides in the specific field of decommissioning focus on the back end of decommissioning (e.g. waste acceptance or release from regulatory control). Within the INSIDER project we aim to anticipate by concentrating at the front end (pre-decommissioning characterization), already applying a waste-led approach. Today, many of the generic currently applied sampling design techniques and state-of-the-art statistical techniques used in preliminary analyses and data processing are often considered as stand-alone methods.

3.3. WP4: Reference materials and radiochemistry

The first aim of this work package is to produce a set of reference materials, to be used in WP 6 for the interlaboratory comparison exercise. This WP involves expert laboratories from the nuclear industry working in collaboration with national measurement institutes to develop and characterize the materials; particular attention will be paid to the uncertainty budget. Two reference materials, characterised for radionuclide content (fission products and activation products) will be provided.

The second aim is to assess radiochemical measurement techniques and identify those most suited for use on D&D samples. The review will concentrate on existing measurement techniques, but in general analysis of specific radionuclides in samples requires several sample preparation steps to purify and/or isolate the target radionuclides. Some of these steps would benefit from reducing the sample and reagent volume by using miniaturized devices in order to considerably reduce the harmfulness of the analytical operations, the sample shipment constraints and the environmental impact due to analytical wastes or chemical reactants.

One novel technique to overcome this problem will therefore be validated and taken into account in the assessment.

3.4. WP5: On site measurements

This WP5 dealing with “In situ measurements techniques” mainly for constrained environments started its task in the early moment of the project but they will continue until the end of it.

In line with the general objectives of the INSIDER project, this WP5 is devoted to the definition and implementation of practical considerations about “in situ” radiological characterization. It works closely with WP2, WP3, WP4 and WP6. In addition, the results of the in situ intercomparison exercises carried out under this WP5 will be processed and perform by WP6.

The partners of the WP5 will participate in the interlaboratory comparison campaign for analytical methods of different radionuclides in real samples that are being prepared by WP4.

The main objectives of WP5 are:

- The identification and revision of the available in situ measurement techniques to be applied to constrained environments;
- The classification and categorization of these constrained environments, taken into account the impacts they generated,
- The application of the suitable techniques to real situations according to the results of the intercomparison campaigns in the three UC identified, and of “in lab” intercomparisons exercises on real samples.
- Finally, the elaboration of guidelines containing the requirements for method implementation and validation.

The first activities belonging to the inventory of radiological characterization methodologies, and of European companies involved in characterization of nuclear facilities undergoing decomminissioning have already been accomplished.

3.5. WP6: performance assessment and uncertainty evaluation

The objective of WP6 is to evaluate the performance of methods/ laboratories/ teams to measure and to try to establish a complete uncertainty budget.

Performance is assessed through interlaboratory/interteam-comparisons on site or in laboratories. For each of the UC site, WP6 will organize a comparison on on-site measurements in collaboration with WP5. For interlaboratory comparisons organized in collaboration with WP4, measurements shall be made either on real samples from UCs whose homogeneity and stability have been characterized or on synthetic Certified Reference Materials. CRMs will be produced for this purpose by WP4, one is a solution, the other is a concrete. Comparisons on real samples are called “benchmark” and comparison on synthetic materials are called “Interlaboratory comparisons ILC”.

For each comparison, measurands are defined by teams involved in WP5, for measurement on site and by WP4 for in laboratory measurements.

3.6. WP7: dissemination and exploitation

The INSIDER Project is making use of new and innovative dissemination and communication approaches. Beyond the classical dissemination & communication (i.e. web page and newsletters), a new approach to Knowledge Management is implemented, used as the basis for disseminating and communicating the achievements of the project.

In INSIDER the management and dissemination of knowledge of the State-of-Knowledge for the key topics dealt with in the project will be enabled in the JRC open-access Integrated Knowledge Management System (IKMS) under the EU Science Hub. IKMS will allow the presentation of the knowledge ensuring the knowledge transfer to future trainees, students, and workers. In addition, transfer of competence in this field will be implemented through the European Learning Initiatives for Nuclear Decommissioning and Environmental Remediation (ELINDER) training programme in nuclear decommissioning.

The IAEA CONNECT platform, available to all IAEA professional networks or communities of practice and its members, is intended to promote capacity building, facilitate collaboration and share information and experience both within and among the several networks and their members. E-Learning, nuclear education and training, discussion forums, on-line interactions, are some of the features explored in INSIDER WP7.

The overall objectives of the WP7 are to manage the outcome of the project, including documentation, generation of guidelines, pre-standards and recommendations, and assessment, dissemination and communication. The objectives thus cover different aspects to ensure that (i) the work meets the end-user expectations, (ii) the State-of-Knowledge is open-access documented and updated along the Project, (iii) Guidance and Pre-Standards are generated based on the State-of-Knowledge, (iv) Recommendations are established, (v) the outcome is disseminated to the concerned expert and user community, and finally (vi) that the project outcome is communicated also to a broader interested community.

4. INSIDER major developments and short term outlook

4.1. Integrated approach set up

The INSIDER strategy promotes an integrated and overall approach of pre-decommissioning characterization which notably consists in evaluating historical data, making on-site measurement campaigns, sampling and analysing, developing scaling factors and applying numerical codes. Therefore, we developed a strategy for sampling in the field of initial nuclear site characterization in view of decommissioning, with the most important goal to guide the end user to appropriate statistical methods and approaches to use for data analysis and sampling design. The proposed strategy has been structured by using different diagrams. All the different steps to take are described in a way that should be sufficient for the end user to make well-founded decisions.

To aid the end user in applying the proposed strategy, an application presenting the strategy in a user-friendly way has been developed (Fig. 2).

The strategy, making use of the user-friendly application, is currently being implemented on the three use cases.

The ILC and benchmark aim at a realistic assessment of the measurement uncertainties and so at an improvement of the cartography sensitivity without affecting the number of samples and analyses [11],[12].

The return of experience, supplemented with global uncertainty calculations and sensitivity analysis, will allow to refine the strategy and result in a comprehensive data analysis and sampling design strategy guide.

A classification and categorization of the constrained environments regarding impacts generated on in situ measurement techniques will complete and support this process.

4.2. Experimental benchmark status

4.2.1. Global approach

The benchmark will help the project to meet some of the INSIDER project main objectives [13], in particular:

- Definition of an improved sampling strategy for waste production optimization by demonstrating the feasibility in realistic cases.
- Validation of rapid / cost effective analytical methods (in lab and in-situ) in realistic conditions

– Performance assessment of available measurement techniques (methods & tools) to establish a science base for decision-making.

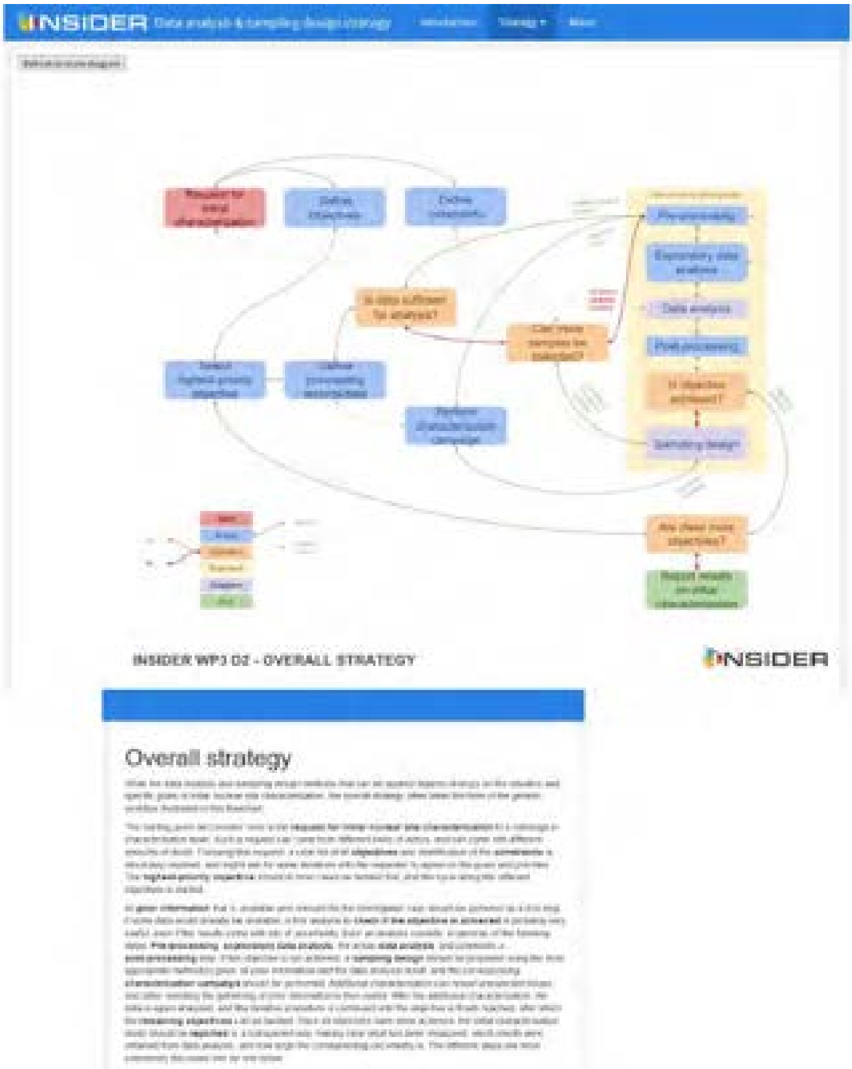

FIG. 2. Screenshot of the user-friendly application for the INSIDER data analysis and sampling design strategy.

The criteria of selection, for each use cases were discussed in relation with the presentation of the sites under decommissioning. They concern:

– Availability of the worksite for sampling and on-site measurements
– Availability of historical and/or characterization data
– Matrix and radionuclides types
– Radioactive activity level

– Shipment feasibility

Interlaboratory comparisons approaches are powerful tools used in the project to assess the performance of the analysis methods and to compare the performances of the different methods and teams. ANOVA approaches are used to prove the ability of methods used and to assess different uncertainty components.

Matrix certified reference materials are essential for a realistic evaluation of measurement uncertainties and for methods calibration.

Real samples are then paramount to compare the performance reached by the on-site teams and by the analytical labs.

4.2.2. UC1: ISPRA worksite description and benchmarking preparation

The facility selected for the case study UC1 is the liquid waste storage facility at the JRC site of Ispra (Italy), generally denominated "Tank Farm". This is a building (Fig. 3 - Left), commissioned in 2010, designed to collect all remaining liquid waste present on site, mostly stored in tanks in the old liquid effluent treatment station (STRRL), to be routed for cementation or other solidification treatment. Most of the liquid waste is contained in two double walled tanks.

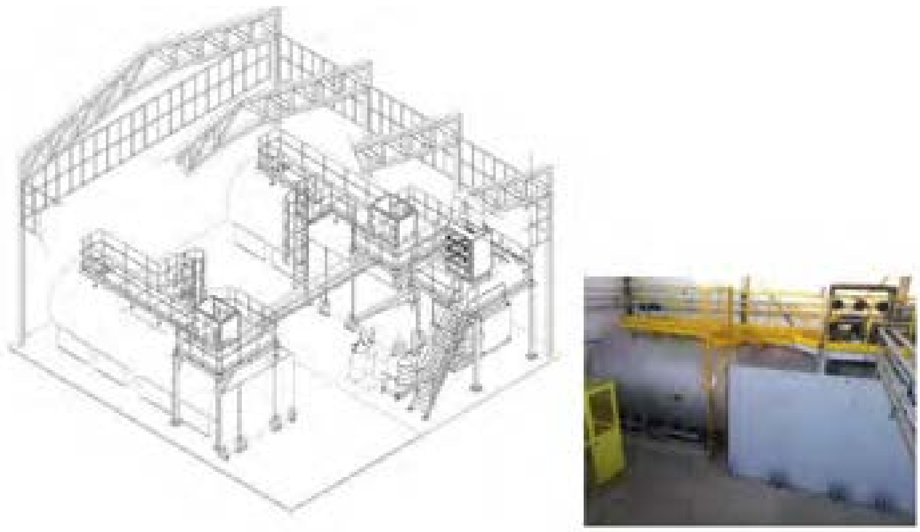

FIG. 3. (Left) "Tank farm" building at JRC Ispra. (Right) Photograph of the effluent tank for liquid effluents.

The building is easily accessible, and it is possible to perform in-situ measurements around the large tanks, even though accessibility is convenient only for half of their length or from the top, due to the presence of shielding walls (Fig. 3 - Right). The large tanks are provided with a system for sampling. Stirrers are present to ensure homogeneity of samples.

The liquid waste in the tanks has been already characterised and available information cover physical, chemical and radiological parameters.

Objective of the experimental benchmark will be to reproduce the complete radiological characterisation of at least one tank, through both in-situ measurements from WP5 partners and samples shipped to analytical laboratories of WP4.

For the in-situ benchmark, the teams will be asked to measure dose rates and gamma spectrometry in locations to be defined in the sampling strategy, developed within WP3. The measurements before and after effluent homogenization is essential in this case in terms of sampling strategy.

For the analytical laboratory inter-comparison, the measurements will include gamma spectrometry and different alpha and beta emitters among those already present.

4.2.3. UC2 worksite and benchmarking status

UC2 is dedicated to a pre-decommissioning characterization within a nuclear power plant. The worksite selected is the Belgian Reactor 3 (BR3), located at the SCK•CEN (Belgian Nuclear Research Centre) site in Mol. Today, the focus of this PWR decommissioning project lies on the building structure, since all the main installations including the complete primary circuit have already been dismantled. The high density concrete of the reactor pool is activated, except for the part surrounded by a neutron shield tank. The main goal of the radiological characterization program is to economically optimize the bioshield dismantling strategy, using a waste-led approach. Radiological measurements performed in the past on drill core samples, gave a first idea on the most important radionuclides present, namely Ba-133, Eu-152, Co-60 and Eu-154 (figure 4).

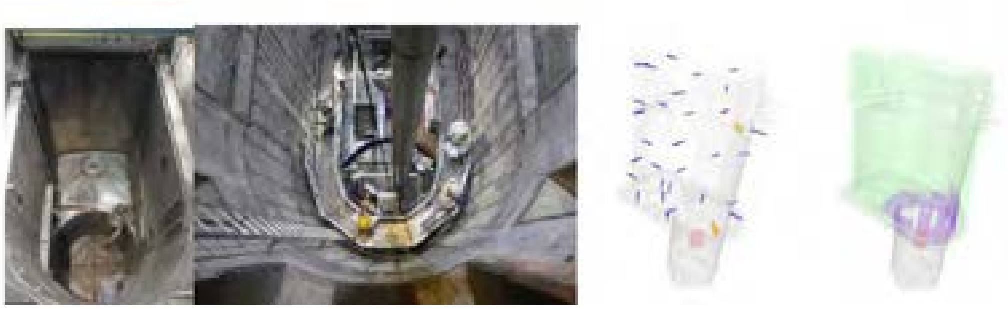

FIG. 4. Pictures from the inside of the reactor pool before and after the removal of the pool liner (left). 3D models of the biological shield indicating the sampling locations (blue = 30 samples; orange = additional samples WP4/WP5) and the preliminary activity concentration distribution map: green: 0.1 to 10 Bq/g Ba-133; purple > 10 Bq/g Ba-133 (right).

We implemented the strategy developed in WP3. Original plans, operational history, neutron activation calculations and former characterization programs were used for designing a preliminary 3D activity concentration distribution map, still showing considerable uncertainties. The subsequent sampling plan, mainly based on a systematic approach, exploited the expected symmetry and was supplemented by a few samples targeting expected trend extremes and a few judgmental samples. The 30 samples were taken by wet core drilling and sliced. Radiological measurements of the slices are ongoing [7].

Within WP5, six EU measurement teams (MTA EK, UPV/EHU, PSI & KIT, Tecnatom, Mirion and SCK•CEN) performed an in-situ measurements comparison exercise in the BR3 reactor pool consisting of dose rate, total gamma and gamma spectrometry measurements at different locations. The results are being processed by WP6.

The various measurement results enlarge the existing dataset, which will be again analyzed and checked against the objectives.

For the in-situ benchmark, the teams were asked to measure in at least three same locations (corresponding to different levels of radioactivity). Gamma-spec will be carry out in only one position.

For total gamma measurements all the teams should perform a calibration "in situ" using a Cs-137 point source and results will be expected to be provided in Bq equivalent to such a Cs-137 point source.

Results from Gamma-spec measurements are expected in Bq/kg of the main radionuclides present in the pool walls. Each team should calibrate their own equipment.

For the analytical laboratory inter-comparison the measurements will cover gamma spectrometry and some long live β emitters determination.

Additionally, drill core samples at two different activated locations and blank samples were provided to NPL (WP4) in view of their homogenization, the benchmarking exercise and the production of reference samples for the organization of an interlaboratory comparison (WP6).

4.2.4. UC3 Contaminated soil site description

Since it was not possible to identify an ideal site with all the characteristics for a meaningful post incidental site remediation exercise, it was decided to execute anyway a limited UC3 benchmark with the best available conditions.

The exercise proposed apply on nuclear site devoted to R&D activities. The historical analysis showed that leaks of active solution occurred in the tank room. Several contamination pathways to reach the soil were consider.

The soil appears to be contaminated with actinides and fission products.

A preliminary initial characterization campaign has been conducted, based on:

- non-destructive measurements, (total gamma and X doses), on drills at different depth;
- radiochemistry and chemistry analysis on extracted cores, in the most active zone of the core.

The soil samples present a large inhomogeneity. Radioactivity should be concentrated in small particles.

The contamination level is generally very low, typically below 0.1 Bq/g, but with hotspots up to hundreds of Bq/g. The main radionuclides to be consider are: Sr-90, Np-237, Pa-233 and Cs-137.There is no chemical pollution in these samples.

Seven drills are available for the INSIDER project in a horizontal plan. Samples can be derived for laboratory analysis. The drills could be also subject to NDA measurements.The sampling strategy and sampling plan will be defined by WP3, depending on the cartography optimisation objectives, knowing that new re-sampling operation will not be possible.

4.3. Next validation steps and needs

A data evaluation methodology on real cases will be performed under WP6.

The inter-comparison exercise has two different goals:

- Proficiency test (task T6.2)
- Uncertainty budget estimation (task T6.3)

To date, measurements concerning the first in situ comparison of UC2, i.e. in situ measurements made at BR3, have been made. The analysis of the teams' results is in progress.

In 2019 the ILC on the 2 CRMs (concrete and liquid) will be organized as well as the in-lab intercomparisons on BR3 concrete samples.

The practical organization of the measurement campaign at the UC1 worksite is planned for June-September of 2019. Different groups belonging to European companies/institutions will realize on site dose rate and gamma-spectrometry measurements.

Based on the comparisons results, the analysis methods will be graded and a most effective method will probably emerge, taking into account all the constraints encountered.

In order to quantify confidence in the measurement result for the initial batch, it is important to establish a complete uncertainty budget that also includes the sampling step. This will be done in collaboration with WP4, WP5 and WP3. It could be done, for example, on concrete cases proposed by WP3.

Within WP6, we also foresee to perform a global uncertainty calculation and sensitivity analysis of the entire process from initial characterization towards the assessment against objectives. Return of experience from the UC2 case will, together with the other two use cases, lead to a guide on the data analysis and sampling design strategy that has been developed within WP3 of the INSIDER project.

5. Conclusions

“Statistical modelling to optimise sampling” is one of the highest priority identified by the NI (Nuclear Innovation) 2050 expert group of the Organization for Economic Cooperation and Development (OECD) and the Nuclear Energy Agency (NEA). The novelty and originality of the INSIDER project is represented by the development of a site radiological modelling integrated concept. It is based on the coupling between advanced statistical processing approaches, measurement/analysis results obtained by existing techniques adapted for hostile or severe environment. Maximum and optimal use of existing techniques will be favored. Applicability and effectiveness of the methodologies, after implementation, will be given by the different validation step, from laboratory scale to representative environment. Performance assessment and uncertainty budget estimation at each step of the concept are crucial in constrained environments to perform a reliable characterization. They necessitate analytical and metrological specific developments shared by different laboratories joining their competences: statistics and metrology expertise, reference samples fabrication process, characterization means, adaptation and qualification of novel methods.

The second and third year of the project is devoted to benchmarking and interlaboratory comparison organizations, including two reference material fabrication and certification, and homogenization of collected real samples.

The fourth year will focussed on performance assessments and uncertainty budget evaluations, thanks to analysis results statistical processing.

The practical project implementation includes documenting, testing, verifying and assessing characterization methodologies for the selected test cases. The INSIDER project is working towards recommendations and guidelines for improving decision making of the industrial implementation for decommissioning and remediation activities Thereby, a key contributor is effective knowledge sharing within the scientific community.

Final assessment of the outcome will strengthen the recommendations and guidance, and promoting and sharing European expertise through guide and pre-normative texts.

Acknowledgment

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References

[1] OCDE NEA (2014), R&D and innovation needs for decommissioning nuclear facilities

[2] S. Boden et al, «concrete waste reduction during PWR decommissioning», CETAMA seminar Sampling and characterization III, 2015

[3] Y. Desnoyers, D. Dubot, Data analysis and sampling optimization for radiological characterization, DD&R conference, 2010

[4] NF ISO 13528 :2015, Méthodes statistiques utilisées dans les essais d'aptitude par comparaison interlaboratoires

[5] NF ISO 5725, Exactitude (justesse et fidélité) des résultats et méthodes de mesure

[6] NF ISO guide 35 :2017-Refrence materials –Guidance for characterization and assessment of homogeneity and stability

[7] S. Boden et al., R&D within the BR3 PWR decommissioning project, DEM 2018 international conference, Avignon (France)

[8] OECD –NEA (2018), Radiological characterisation from a waste and materials end-state perspective: Practice and experience

[9] ISO 18557:2017 standard: characterization principles of soils, buildings and infrastructures contaminated by radionuclides for remediation purposes

[10] IAEA Analytical Quality in Nuclear Application series n° 49. In situ analytical characterization of contaminated sites using nuclear spectrometry techniques- Review of methodologies and measurements. ISSN 2074-7659

[11] D. Roudil et al. "The European R&D project INSIDER", DEM 2018 international conference, Avignon (France)

[12] D. Roudil et al "The European R&D project INSIDER: acting on the upstream stage" RadWorkshop 2018, Roskilde (Danemark)

[13] INSIDER project internet site: http://insider-h2020.eu/

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THE CHANCE PROJECT "CHARACTERIZATION OF CONDITIONED NUCLEAR WASTE FOR ITS SAFE DISPOSAL IN EUROPE"

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Abstract. The CHANCE project aims to address the specific issue of the characterization of conditioned radioactive waste (CRW). The first objective of CHANCE is to establish, at the European level, a comprehensive understanding of current CRW characterization and quality control schemes. The second objective of CHANCE is to further develop, test and validate techniques already identified that will undoubtedly improve the characterization of CRW. Specifically, these technical tasks will focus on calorimetry as an innovative non-destructive technique to reduce uncertainties on the inventory of radionuclides; Muon Tomography to address the specific issue of non-destructive control of the content of large volume nuclear waste; Cavity Ring-Down Spectroscopy (CRDS) as an innovative technique to characterize outgassing of radioactive waste. An overview of the project and the current results are presented and discussed.

1. Context and objectives of the project

The CHANCE project aims to address the specific issue of the characterization of conditioned radioactive waste (CRW). The characterization of fully or partly conditioned radioactive waste is a specific issue because, unlike for raw waste, its characterization is more complex and needs specific non-destructive techniques and methodologies. There are different and varying reasons for this: 1) conditioned waste may no longer be in its initial form (e.g., due to incineration), 2) conditioned waste is typically embedded or surrounded by a matrix, 3) conditioned waste may contain wastes coming from different primary sources and therefore the radiological spectrum might become more complex.

CHANCE focus on these categories of waste as described in [1]:

- Very Low Level Waste (VLLW);
- Low Level Waste (LLW);
- Intermediate Level Waste (ILW);

The first objective of CHANCE is to establish at the European level a comprehensive understanding of current conditioned radioactive waste characterization and quality control schemes across the variety of different national radioactive waste management programmes, based on inputs from end-users such as Waste Management Organizations and storage operators.

The second objective of CHANCE is to further develop, test and validate techniques already identified that will improve the characterization of conditioned radioactive waste, namely those that cannot easily be dealt with using conventional methods.

To address these specific issues, the CHANCE project proposes R&D actions to develop three innovative technologies for conditioned radioactive waste packages, namely:

- Calorimetry as an innovative non-destructive technique to reduce uncertainties on the inventory of radionuclides;
- Muon Tomography to address the specific issue of non-destructive control of the content of large volume nuclear waste;
- Cavity Ring-Down Spectroscopy (CRDS) as an innovative technique to characterize outgassing of radioactive waste.

The activities performed and the results obtained within the project CHANCE are integrated, communicated and disseminated both between the project partners as well as with the broader European community involved in radioactive waste disposal. Dissemination of results and progress is an integral part of the CHANCE project. Generally stated, the goal of communication is to raise awareness concerning the CHANCE research topics and developments, and to inform the CHANCE stakeholders about the project's progress and achievements. The main communication tool to reach this goal is CHANCE website http://www.chance-h2020.eu/ .

The final ambition of CHANCE is to improve the efficiency of the characterization of conditioned radioactive waste and therefore to improve the safety of the global radioactive waste management process throughout the full storage cycle, including transport, interim storage and final disposal operational and long-term stability.

2. Project overview

CHANCE is structured into six work packages (Fig.1):

- Management and coordination (WP1)
- Methodology for conditioned radioactive waste characterization: Problematic wastes and R&D proposal (WP2)

- Calorimetry associated with non-destructive assay techniques and uncertainties study (WP3)
- Muon imaging for innovative tomography of large volume and heterogeneous cemented waste packages (WP4)
- Innovative gas and outgassing analysis and monitoring (WP5)
- Dissemination activities (WP6)

Activities related to these WP are detailed in following paragraphs.

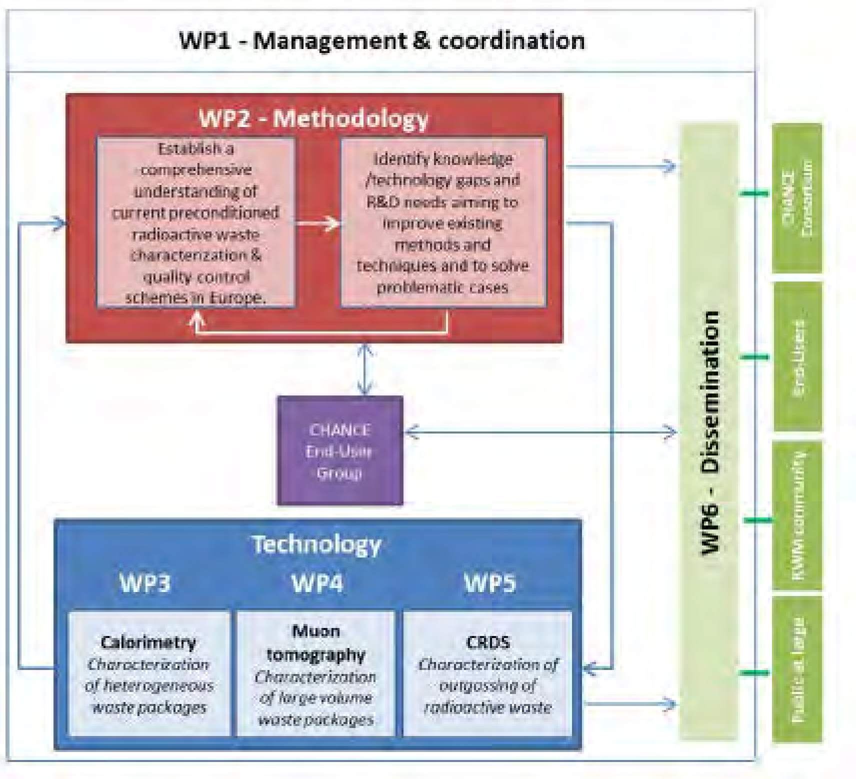

FIG. 1. CHANCE structure.

2.1. Methodology for CRW characterization: Problematic waste and R&D proposal (WP2)

End-users requirements concerning CRW characterization are driven by radioactive waste properties (VLLW, LLW, ILW or HLW) and specific waste acceptance criteria (WAC) for each disposal concept (surface, sub-surface or geological).

One of the tasks is dedicated to the identification of links and overlaps between WAC and actual waste characterization technologies available in order to allow CHANCE to identify specific methodology issues. In order to enhance the efficiency of conditioned radioactive waste characterization methodology, CHANCE proposes to identify:

- key parameters that need characterization;
- technologies commonly used for conditioned waste characterization;

- specific problematic issues for the characterization of conditioned radioactive waste;
- knowledge and technology gaps for radioactive waste package characterization methodologies.

This will be based on a survey of characterization methodologies currently used by European waste producers, disposal operators and waste management organisations, and by coupling these methodologies to the available waste conformity criteria for the different disposal solutions present in EU countries.

Based on the identified gaps, R&D will be proposed aiming to improve existing or introduce novel methods and techniques and to solve problematic cases. These R&D proposals will fuel future common research calls on waste characterization concerns.

2.2. Calorimetry associated with non-destructive assay techniques and uncertainties study (WP3)

An exhaustive study of uncertainties related to the use of existing and widely used techniques for the characterization of waste packages (gamma spectrometry and passive neutron measurement) in conjunction with calorimetry will be carried out.

Calorimetry provides a most powerful way to estimate the overall quantity of nuclear material over a wide range of masses, from a few milligrams up to kilograms of radionuclides, and volumes from one up to 385 litres, by measuring the overall thermal power (or heat flux) from radioactive decay inside the waste contained in metallic drums or various matrices (concrete, bitumen,...). It has many advantages: it is a non-destructive method, adapted to heterogeneous waste packages because it is independent of both the matrix effect and chemical composition, though chemical reaction heating must be ruled out from the preconditioning process. Calorimetry is sensitive to alpha and beta emitters, possibly hidden inside the material matrix or shielded, which cannot be addressed otherwise by gamma or neutron scanning and dose rate measurements.

In this WP, development, manufacturing and tests of a new 200 litres calorimeter with lowered detection limit will be performed. Development means radiological, thermal and mechanical modelling to optimize the performance of the instrument.

2.3. Muon imaging for innovative tomography of large volume and heterogeneous cemented waste packages (WP4)

A mobile muon tomography system will be developed to address the as-yet unsolved problem of the non-destructive assay of large volume nuclear waste packages, such as large spent fuel casks and large concrete waste packages with heterogeneous waste.

Muons are natural occurring particles with a flux at ground level of around 1 cm-2min-1; they are capable of passing through several hundred metres of rock. When they interact with matter, they scatter depending on the atomic number, Z, of the material. Hence, if muon trajectories are measured before and after traversing a volume, an image of the different materials in that volume can be produced. This mature and well-established technique is known as 'muon tomography' (MT). It has been successfully utilised in e.g. cargo screening for nuclear contraband. MT is fully passive and works for heavily-shielded volumes; it is also highly complementary to gamma and neutron tomography. The technique is particularly useful to detect heavy elements like lanthanides and actinides, but can also be applied to detect density gradients or differences within a matrix. In order to fully exploit the power of the tomography technique excellent position resolution and timing resolution is required.

A large-area demonstrator system will be developed which will utilize two different technologies, namely plastic scintillator (providing timing resolution) and resistive plate chambers (providing position resolution). The system will initially be operated at a dedicated test facility using test volumes comprising materials of different Z (e.g. metal pieces, U rods, cellulose, air enclosures), encased in concrete or bitumen (simulated inactive waste drums). The performance of the system in identifying the composition and placement of the different materials will be evaluated.

2.4. Innovative gas and outgassing analysis and monitoring (WP5)

An extremely sensitive technique, called cavity ring-down spectroscopy (CRDS), will be used to determine the outgassing amount and rate of selected radioactive molecules from nuclear waste. This isotopically selective laser spectroscopic technique provides the highest sensitivity, allowing for the detection of extremely small amounts of radioactive gases, and thus detection of the smallest leaks.

CHANCE will explore the potential of CRDS for waste package monitoring, since this technique has not been used in this context before and has several advantages over conventional techniques. Gaseous emissions from waste usually mostly consist of tritium and radiocarbon, mainly emitted in the form of water vapour (HTO), carbon dioxide ($^{14}CO_2$) and methane ($^{14}CH_4$). $H^{36}Cl$ is also of interest in the particular case of graphite waste. Even though tritium detection is important, it was decided in CHANCE to focus on radiocarbon and 36Cl isotopes, as the participants had most expertise and interest in detecting those isotopes.

The work package consists of two main parts. First, a novel instrument for the detection of $H^{36}Cl$ based on CRDS will be developed. This will be the first time that CRDS is used to detect this molecule, which is highly relevant in the case of outgassing from graphite waste. Secondly, an already-developed CRDS instrument for the detection of radiocarbon compounds will be used to study in detail their outgassing rate on various types of waste. The instrument was developed within the Euramet funded MetroDecom project and its predecessor, and for the first time will be used to provide valuable information about the radiocarbon release kinetics using this novel technique. The speciation will include methane and carbon dioxide, with reference to the outcomes of the ongoing European project Carbon-14 Source Term (CaST).

This work will therefore result in a major step forward in the development of the use of CRDS to detect radioactive gas emissions as well as demonstrate a direct application of CRDS to the characterization of the outgassing from radioactive waste.

3. Results and discussion

Main results are presented by WP in the following paragraphs.

Methodology for CRW characterization: Problematic waste and R&D proposal (WP2)

A questionnaire has been produced to obtain a broad overview on the end-users needs for the characterisation of conditioned radioactive waste. It also includes questions pertaining to Work Package 6, related to underlying socio-technical and ethical frameworks of radioactive waste characterisation practices and policies.

List of questions include the following subjects:

- Existing and planned disposal solutions for radioactive waste.
- Waste acceptance specification for each solution (including potential free-release).
- Technologies used for conditioned radioactive waste characterization.
- Potential ongoing R&D programme on the topic of conditioned radioactive waste characterization.
- Interest on R&D actions included in CHANCE (WP3, WP4 & WP5).

The questionnaire is available in the Website of Chance (http://www.chance-h2020.eu/en/Deliverables), deliverable D2.1 [2].

This questionnaire was distributed to operators of radioactive waste disposal in Europe, notably through the End-User Group. Questionnaire answer has been received and analysis are in progress. A synthesis of commonly used methodologies for conditioned radioactive waste characterization is expected for first quarter of 2019.

Calorimetry associated with non-destructive assay techniques and uncertainties study (WP3)

An overview of the existing calorimeter was carried out; the main designs of calorimeters and specific parts of the calorimetric system were detailed with their advantages and drawbacks. Their performances were evaluated depending on their mode of operation.

A review of the main characteristics concerning mature NDA techniques has also been produced. The following techniques has been considered:

- Gamma methods: Gamma spectrometry, Segmented Gamma Scanning, Tomographic Gamma Scanning;
- Neutron methods: Passive Neutron Coincidence Counting, Active Neutron Interrogation.

The performances of the different techniques were evaluated through a study of the neutron and gamma ray signal that can escape various 200 L waste drum matrices and through a comparison of the published plutonium and uranium Minimum Detectable Masses (MDM) of existing systems. The results suggest that the most interesting cases would be polyethylene, bitumen and concrete matrices. Due to the limitations of the experimental program, however, only the latter will probably be available to perform experiments. While escaping radiation can be largely hampered with these matrices, the heat flux is unaffected, thus demonstrating the usefulness and complementarity of calorimetry in these cases and in general.

Further simulations with heterogeneous and homogeneous distribution of activities within the drums showed that the neutron and gamma measurements are very sensitive to the source distribution, leading to uncertainties that can reach two orders of magnitude, depending on the matrix composition. In case of gamma emission, the two orders of magnitude are obtained for concrete, while for neutron emission it is only a factor of two, leading to a factor four in the neutron coincidence rate measurement. The first Monte Carlo simulations of the calorimeter suggest that the uncertainty related to the energy deposition, based on uncertainty on the distribution of activities within a drum, is much smaller than the two orders of magnitude. Therefore, we also demonstrated the usefulness of calorimetry in cases with unknown distribution of activities within drum.

These overviews and simulations results are presented in the CHANCE deliverable 3.1 [3] that is available in the Website of Chance (http://www.chance-h2020.eu/en/Deliverables).

A large volume calorimeter with one measurement cell opening in two half shell has been developed (Fig. 2). The manufacturing is under progress and almost completed (Fig. 3).

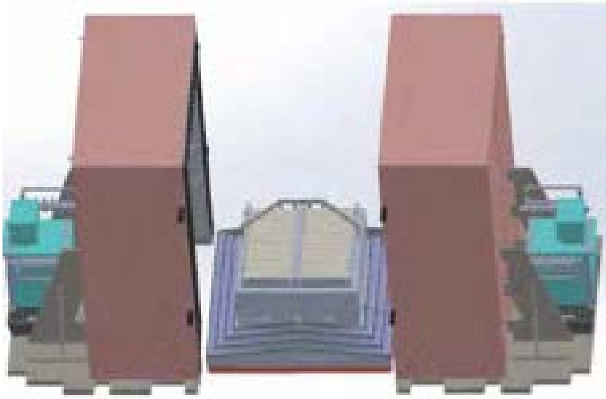

FIG. 2. 3D view of the CHANCE Calorimeter.

FIG. 3. CHANCE Calorimeter manufacturing.

Muon imaging for innovative tomography of large volume and heterogeneous cemented waste packages (WP4)

The muon system consists of a drift chamber system combined with additional Resistive Plate Chamber (RPC) layers. The two detector systems have been merged into one system. The detector system is currently being commissioned (Fig. 4) with first data expected soon.

Monte Carlo simulation has been done. This includes studies about modelling the hybrid system, how to optimally combine the data of the two subsystems, comparison studies of the

FIG. 4. Commissioning of Muon detector system.

performance of different reconstruction algorithms to determine the contents of the waste drums focusing both of high-Z materials and gas bubbles, studies of the smallest structures we can distinguish.

This has led to the development of a unique approach using figures of merit to enable performance comparisons between different algorithms and/or instrumentation techniques.

The Fig. 5 show a comparison of different algorithm outputs when imaging a 10 cm long Uranium cube for 25 days of muon exposure. The inclusion of momentum information and metric distances in the BC algorithm leads to an image with higher contrast and clarity than a simple PoCA approach.

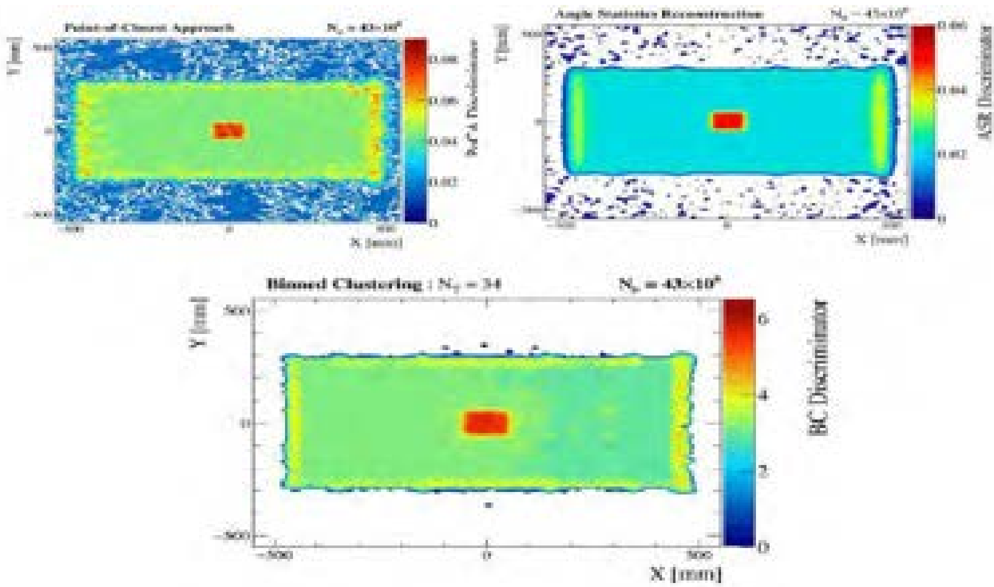

FIG. 5. Comparison of different algorithm outputs when imaging a 10 cm long Uranium cube for 25 days of muon exposure.

Innovative gas and outgassing analysis and monitoring (WP5)

The construction of a prototype of CRDS instrument dedicated to $H^{36}Cl$ measurement is under progress. $H^{36}Cl$ isotope rotation-vibration frequencies has been calculated. The optimum transition for detection by laser spectroscopy is located between the $H^{35}Cl$ and $H^{37}Cl$ transitions, with a line position of 5737.15 ± 0.1 cm-1 (Fig.6). In parallel, studies about chemical transformation of $Na^{36}Cl$ into $H^{36}Cl$ has been performed. This is an important step since CRDS can only measure ^{36}Cl in form of $H^{36}Cl$ gas, but ^{36}Cl standards are only available as $Na^{36}Cl$ solutions.

Development of a new sampling line to be used in connection with a C-14 CRDS prototype has been carried out to study C-14 outgassing from irradiated waste. As a first step CO_2 outgassing from non-radioactive graphite has been carried out. Graphite outgassing at room temperature is very small, and by heating to a few hundred's degrees the amount of released CO_2 was increased (Fig. 7) which will improve the feasibility of future studies. Measurement of C-14 from irradiatied graphite will be carried out soon.

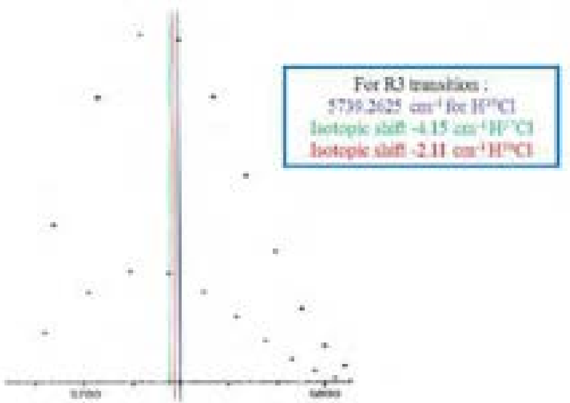

FIG. 6. Positions of the main transitions of HCl isotopes.

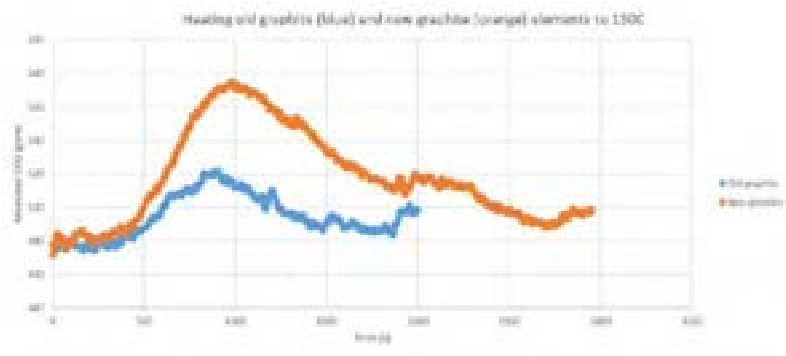

FIG. 7. Heating of graphite (blue) and new graphite (orange) elements to 150°C. The "new" graphite exhibits more outgassing due to CO_2 present on the surface.

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References

[1] IAEA General Safety Guide No. GSG-1

[2] CHANCE project (2017): End-User-Group Questionnaire, DELIVERABLE (D2.1), (http://www.chance-h2020.eu/en/Deliverables)

[3] CHANCE project (2018): CHANCE WP3 Applicability of Calorimetry, DELIVERABLE (D3.1) (http://www.chance-h2020.eu/en/Deliverables)

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THERMAL TREATMENT FOR RADIOACTIVE WASTE MINIMISATION

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Abstract. Safe management of radioactive waste is challenging to waste producers and waste management organizations. Deployment of thermal treatment technologies can provide significant improvements: volume reduction, waste passivation, organics destruction, safety demonstration facilitation, etc. The EC funded THERAMIN project will provide an EU-wide strategic review and assessment of the value of thermal technologies applicable to a broad range of (Low and Intermediate Level) waste streams (ion exchange media, soft operational waste, sludges, organics, and liquids). THERAMIN will compile an EU-wide database of treatable wastes and document available thermal technologies. Applicability and benefits of technologies to the identified waste streams will be evaluated through full-scale demonstration tests by project partners. Safety case implications will also be assessed through the study of the disposability of thermally treated waste products. This paper will communicate the strategic aims of the ongoing project and highlight some key findings and results achieved to date.

1. Introduction

The waste hierarchy sets out guidelines for waste managing in order to minimise environmental impact. Priority is on waste prevention and the lowest priority is on disposal. Disposal should be applied when no other alternatives are available and, in this case, the amount of waste to be disposed should be minimised. The principles of the waste hierarchy should also be applied for radioactive waste, though with due regard to safety standards and regulation.

Especially in the case of Low and Intermediate Level Waste (LILW), materials are typically contaminated by a very small amount of radioactive isotopes, while the majority of the waste material is not radioactive. For example, in the case typical operational Low Level Waste (LLW) the actual volume of radioactive isotopes is very low but the total volume of waste is usually large; this is also true for many LILW fractions. The guidelines of the waste hierarchy could be followed to minimise the waste volume to be disposed by thermal treatment of these LILW fractions.

Numerous technologies for thermal treatment of radioactive waste are available or in development worldwide, and more especially in the European Union. These technologies may be applied to a wide range of different radioactive waste streams, including non-standard waste types that present specific waste management challenges. Thermal treatment can result in significant volume and hazard reduction, both of which are beneficial for safe storage and disposal. Thermal treatment further removes organic material, which can form complexing agents and make radionuclides more mobile in a repository.

The European Commission funded THERAMIN project was established in order to improve awareness and understanding of capability of thermal treatment technologies to treat radioactive waste prior disposal. The overall objective of THERAMIN is to provide improved long-term safe storage and disposal of both ILW and LLW streams suitable for thermal processing. The work programme provides a vehicle for coordinated EU-wide research and technology demonstration designed to provide improved understanding and optimisation of the application of thermal treatment in radioactive waste management programmes across Europe and will move technologies higher up the Technology Readiness Level (TRL) scale. The Consortium assembles a European-wide community of experts on thermal treatment technologies and radioactive waste management and disposal, who will work together with the aim of identifying efficiencies in national waste management and decommissioning programmes across Europe.

2. THERAMIN project

The THERAMIN project will achieve an EU-wide strategic review and assessment of the value of thermal technologies applicable to a broad range of waste streams (ion exchange media, soft operational wastes, sludge, organics and liquids) and compile an EU-wide database of thermally treatable wastes, document the strategic benefits of thermal treatment, and identify the opportunities, synergies, challenges, timescales and cost implications to improve radioactive waste management. The most essential activity of the project is to evaluate the applicability and achievable volume reduction of the technologies through ‘first-of-a-kind’ active and non-active full-scale demonstration tests. Finally, the disposability of the product materials and residues will be assessed.

The project benefits from the large financial and resource investments made by partners in thermal treatment R&D facilities, which will be used to maximize the benefit across member states. THERAMIN also benefits from close engagement with an End User Group (EUG) consisting of waste producers and waste management organisations.

The THERAMIN project comprises the following core strands of research (1) strategic review of radioactive waste streams, (2) demonstration of selected thermal treatment technologies in order to evaluate viability of treatment routes for selected waste stream/technology combinations and (3) assessment of disposability of treated waste products by characterising the products and residues from demonstration trials against various Waste Acceptance Criteria, which are not harmonised in EU. In addition to these technical topics the project is also actively disseminating the results including a training program in order to enhance knowledge on thermal treatment technologies and on their benefits.

The project was started in June 2017 and has just passed the halfway point thus a substantial fraction of experimental demonstration program has not yet completed and thus the final results of the project are not yet available.

2.1. Strategic review of radioactive waste streams and potential thermal technologies

One of the first activities of the project was to identify wastes that could potentially be treated using thermal techniques, or where thermal techniques could offer strategic benefits. As a result of this evaluation the following waste categories were identified:

- Ion exchange resins, organic and inorganic, where there is significant volume and organics reduction potential.
- Soft operational waste including plutonium contaminated material (PCM), where there is also significant volume reduction potential.
- Wet wastes such as sludges and liquid wastes.
- Wastes with a significant organic content (could include bituminised waste in some countries such as Belgium or Lithuania) with the potential to be chemically reactive and/or give rise to significant gas generation, and which may contribute uncertainty to the post-closure safety case for geological disposal.
- Certain types of metallic wastes (e.g., reactor internals, cladding) that are known to cause significant gas generation by corrosion and may contribute uncertainty to the post-closure safety case for geological disposal.
- Some types of packaged waste that may have become unacceptable for geological disposal owing to package degradation.

In addition to suitability for thermal treatment, the volume of waste has an essential impact on the assessment of the potential and importance of thermal treatment techniques. The review and assessment of waste volumes turned out more challenging than was expected. Data on low and intermediate radioactive wastes is not easily available in all EU counties and thus the results from the survey are not fully comprehensive. Nevertheless, the survey demonstrated that the need and market potential for thermal treatment technologies is already significant in those countries from which the data were available.

Once the wastes of interest had been identified, an assessment on the thermal facilities available across Europe that could potentially treat these wastes was done. Following a thorough survey, the identified European thermal technologies were grouped into three high level processes: thermal treatment for volume reduction and passivation, conditioning by immobilisation in glass, and conditioning by immobilisation in ceramic or glass-ceramic matrices. For each facility information on its technical capabilities and availability to treat waste streams were summarised.

- Treatment for volume reduction and passivation included incineration (with burner and refractory walls), Rotary kiln incineration, pyrolysis, gasification, calcination, underwater plasma incineration, hydrothermal oxidation and induction metal melter.
- Conditioning by immobilisation in glass included Joule-Heated In-Can Vitrification, Joule-Heated Ceramic Melter (JHCM), Cold crucible induction melter (CCIM), Advanced CCIM (A-CCIM), Indirect induction (metallic wall - hot metal pot), Coupled cold wall direct metal induction melting and plasma burner, Coupled cold wall

direct glass induction melting and plasma burner and Refractory wall plasma burning and melting.

- Conditioning by immobilisation in ceramic, glass or glass-ceramic included Hot Isostatic Pressing (HIP).

Once the technologies and facilities were identified, and the technical details of the thermal processes were assessed, this information was utilised to establish the advantages and limitations of each of the treatment facilities. From this it was possible to map the identified waste groups to the most suitable or promising technologies. During this mapping exercise each technology was assessed as either being a viable method for treating the given waste, having some potential (either untested, or only with modification) or not being applicable. From this exercise it was clear that there are a wide range of facilities spread across Europe that could potentially treat the identified wastes.

2.2. Viability of treatment routes for selected waste stream/technology combinations

The most essential and largest activity of the THERAMIN project is the assessment of the viability of different thermal treatment routes for selected waste stream/technology combinations. This activity is based on experimental demonstrations with six different technologies. The waste materials to be used in the demonstration test trials were selected based on the results from strategic review of radioactive waste streams (presented above) and assessment of suitability of the technologies for certain wastes. In addition, one selection criterion was to cover several different waste streams, which are suitable for thermal treatment. The selected waste streams and demonstration technologies are presented in Table 1.

TABLE 1. Demonstration technologies and waste materials of the THERAMIN project.

Technology	Demonstrator	Waste stream	Waste category	Product
Shiva	CEA/Orano, France	Organic ion exchange resin	Unconditioned wastes	Vitrified
In Can	CEA/Orano, France	Ashes	Unconditioned wastes	Vitrified
Geomelt 1	NNL,United Kingdom	Cementitous wastes	Conditioned wastes	Vitrified
GeoMelt 2	NNL, United Kingdom	Heterogeneous sludges	Unconditioned wastes	Vitrified
Thermal gasification	VTT, Finland	Organic ion exchange resin	Unconditioned wastes	Solid residue
VICHR	Vuje/Javys, Slovakia	Chrompik	Liquid wastes	Vitrified
HIP	USFD, United Kingdom	Uranium containing sludges	Unconditioned wastes	Vitrified/Ceramics

Until now the first test trials have been completed. All thermal treatment facilities to be used in the project have been have been installed already before the THERAMIN project and financed by other sources but made accessible for the project. The first demonstrations in the autumn 2018 were carried out using following technologies:

- The SHIVA process: cold wall direct glass induction melting and plasma burner (CEA/Orano);
- In-Can Melting process: metallic crucible melter heated in a simple refractory furnace using electrical resistors (CEA/Orano);
- GeoMelt: In Container Vitrification (NNL);
- Thermal treatment process based on thermal gasification (VTT);
- HIP: Hot Isotopic Pressing (NNL and UFSD).

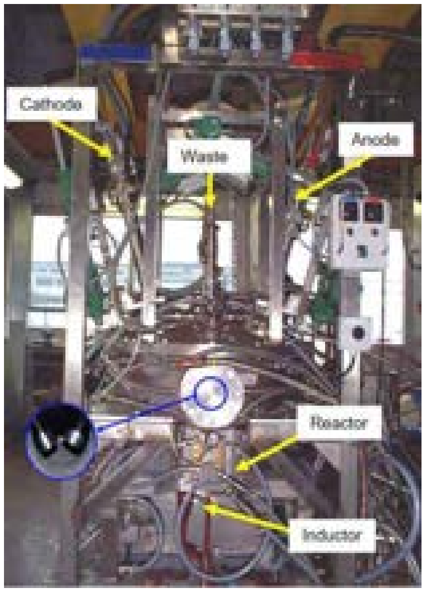

FIG. 1. SHIVA process.

The SHIVA process (CEA/Orano)

SHIVA is an incineration-vitrification process (Fig. 1) well suited for the treatment of organic and mineral waste with high alpha contamination and potentially high chloride or sulfur content. This technology is specifically designed to operate in a hot cell for high or intermediate level waste. It allows, in a single reactor, waste incineration by plasma burner and ashes vitrification. SHIVA consists of a water-cooled, stainless steel cylindrical reactor, equipped with a flat inductor at the bottom and a transferred arc plasma system in the reactor chamber (Figure 2). The gas treatment consists of an electrostatic tubular filter and a gas scrubber. The waste can be in solid or liquid form but must not contain metals. The SHIVA process has a technology readiness level (TRL) of 5-6 as a full-scale inactive pilot which has been tested by the CEA since 1998 for various wastes. TRL 5-6 means a technology validated/demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies).

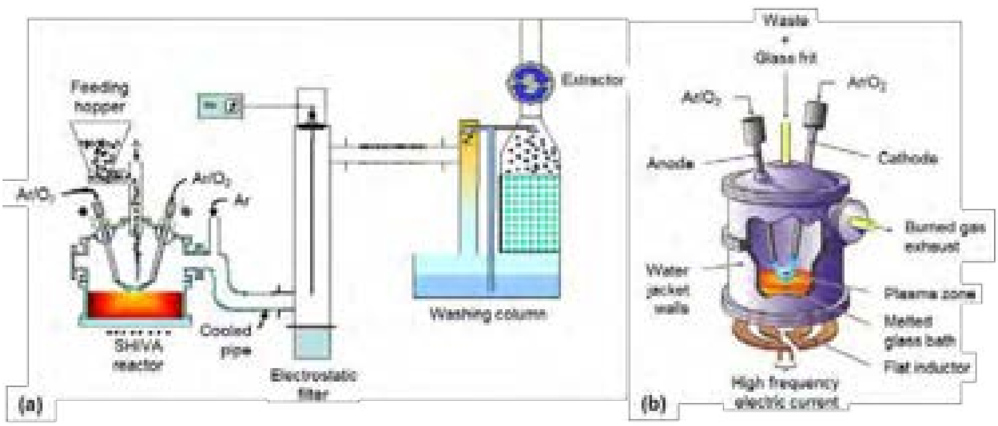

FIG. 2. (a) Simplified diagram of the SHIVA process and (b) artist's view of the reactor.

The waste selected for the THERAMIN trial is a 25 kg mixture of inorganic and organic ion exchange media composed of zeolites, diatoms, strong acid IXR, and strong base IXR. Inputs of SHIVA process composed of 38.5 wt-% of waste and 61.5 wt-% of glass frit.

The end-product of the process is an alumino-borosilicate glass which is macroscopically (millimetre scale: visual inspection) homogeneous (Figure 3).

Thus, the SHIVA trial conducted in the framework of the THERAMIN project showed the success of this process for the thermal treatment of a mixture of organic and mineral waste composed of zeolites, diatoms and ion exchange resins. The waste load of 38.5 % is high and could probably be increased in the future. Indeed, during this feasibility trial, it was not sought to maximize the waste load and the processing capacity. The waste product is a alumino-borosilicate glass, macroscopically homogeneous, whose long term behaviour could be characterized according to proven methodologies, which makes it possible to consider with confidence its disposability.

FIG. 3. Waste glass sample from the SHIVA trial

In Can (CEA/Orano)

The In-Can Melter is a metallic crucible melter heated in a simple refractory furnace using electrical resistors (Fig. 4). The can is renewed after each filling.

The process can support either liquid or solid waste feeds. With the current gas treatment process, it can only tolerate small amounts of organics. It can also accept a small fraction of metal in the waste. The design ensures that the process can operate remotely for high-activity waste. The design can also be adapted for dealing with plutonium containing material in gloveboxes. The end product can be glass, glass ceramic or simply a high-density waste product.

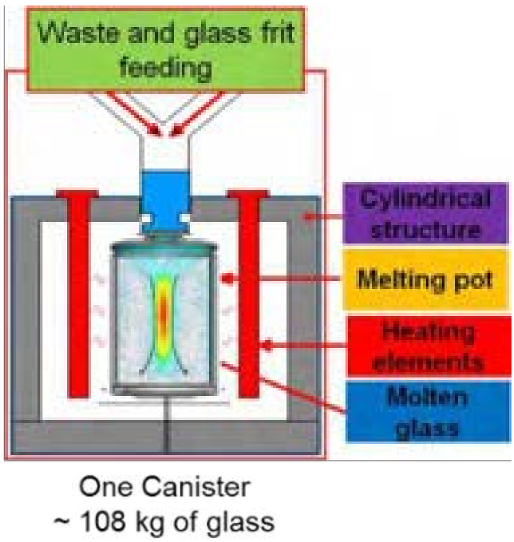

FIG. 4. Simplified diagram of the In-Can Melter process.

To prepare the THERAMIN trial preliminary tests were conducted at the laboratory-scale to select the best operating conditions in order to obtain an optimized waste load and a good quality end-product. These tests aim to demonstrate the feasibility of the confinement in a vitreous matrix of by-products coming from existing incineration processes. The preliminary tests consist of bringing into contact - at 1100 °C during 2 hours - different amounts of ashes and glass frit, in the presence or absence of an adjuvant. These tests are carried out using a few grams of materials. At the end of the tests, the crucibles are cut after immobilization in epoxy resin and the products obtained are observed under a binocular magnifier. The criteria for the choice of the optimum conditions are the obtaining of a homogeneous glass and the limitation of the expansion during the elaboration.

The preliminary tests at the laboratory-scale showed the feasibility of ashes vitrification with a high load of 50 wt.% in the end-product. They also showed the interest of adding a sugar-based or a bentonite-based adjuvant up to 10 wt.% to avoid volatile dust and ensure the best reactivity.

Thermal treatment process based on thermal gasification (VTT)

VTT has developed, constructed and tested a thermal gasification based treatment method, especially for organic IXR. Technically the method can also be used for reduction of volume of low level operational waste containing organic matter but the waste has to be crushed before treatment. The technology has been designed for compact process, which can be operated at nuclear power plant site. The process has been designed primarily for reduction of volume of high organic matter containing radioactive waste.

The primary product from thermal gasification is fine dust collected by high temperature filter In addition to the filter dust the process produces some bottom ash, which consists mainly of bed material. Both filter dust and bottom ash are powders and thus the final residues have to be immobilised (cementation, vitrification, etc.) after waste processing before final disposal.

The development of thermal gasification based treatment of LILW has been based on so called bubbling fluidised-bed (BFB) gasification. In BFB gasifier bed material is fluidised by blowing gasification air or other gas from the bottom through the air distributor. The other type of fluidised-bed reactor is so called circulating fluidised-bed (CFB) reactor, which uses significantly higher fluidising velocity enabling thermal capacity per cross-sectional area. Both reactor types can be applied for thermal gasification of LILW and are used in THERAMIN demonstration test trials. A schematic diagram of the VTT's pilot-scale Circulating Fluidised-Bed (CFB) gasifier is shown in Fig. 5.

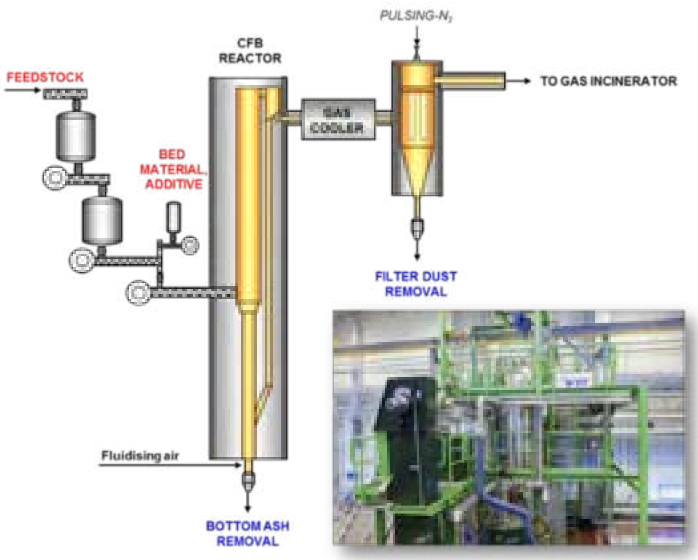

FIG. 5. Pilot-scale Circulating Fluidised-Bed (CFB) gasification test rig.

The first test trial was carried out with the pilot scale CFB gasification test facility. Organic IXR was treated in total of 325 kg during three test trial days. Total duration of the operation was 26.5 hours of which a steady-state period was measured during 12.5 hours.

Carbon conversion was calculated after the test trials. Calculation is based on the carbon mass balances and it describes how efficiently input carbon is converted to gas. The carbon conversion to gas and tars was 92-96 wt-%, which means that the removal of the organic material from the IXR succeeded very well.

Test trials with Circulating Fluidised-Bed (CFB) gasification pilot plant proved that CFB reactor is very efficient in removal of organic matter from ion exchange resin and thus reduce significantly volume of the organic ion exchange resin. The advantages of CFB compared to bubbling fluidised-bed (BFB) reactor are related to treatment capacity per cross-sectional area of the reactor. In addition, the heat and mass transfer are also better in CFB.

GeoMelt (NNL)

NNL and Veolia Nuclear Solutions have formed a collaboration to establish an active GeoMelt In-Container Vitrification (ICV) system at Sellafield. This facility is currently used to demonstrate the treatment of a wide range of UK based waste streams. The GeoMelt system installed at the NNL Central Laboratory is shown in Fig. 6.

FIG. 6. The GeoMelt system installed at the NNL Central Laboratory. (1. ICV melter, 2. feed chute, 3. feed hopper, 4. connection to off-gas, 5. sintered metal filter, 6. scrubber column, 7. demister, 8. scrubber tank, 9. off-gas heater, 10. HEPA filtration, 11. cooler, 12. off-gas blower, 13. back-up blower and 14. vent discharge).

The melter consists of a steel container lined with refractory materials containing the melt. The refractory lining consists of a 200-L cast refractory box (CRB) surrounded by refractory silica sand.

As part of the THERAMIN project, two appropriate waste streams were selected for thermal treatment demonstration using the GeoMelt system. The streams selected for demonstration using were:

- TH01- A cementitious stream representative of sea dump drums or failing cement wastes packages
- TH02- A sludge stream made up of a naturally occurring zeolite (clinoptilolite), sand, Magnox storage pond sludge and miscellaneous contaminants known to arise in a range of UK feed streams.

Thermal treatment of 279 kg of representative cementitious waste stream (TH-01) with a pre-treatment waste loading of 49% has been successfully demonstrated using the GeoMelt ICV system (Figure. 7). Macroscopic observation of the product indicated that a glassy monolith with broad homogeneity has been produced. Visual inspection of the product suggests it should be disposable against all key disposability criteria. Observations made during product sampling indicate that at least some of the original metallic objects present in the simulated waste remained on completion of processing. All plant operating parameters observed during this melt were within expected norms.

FIG. 7. GeoMelt container

Similarly thermal treatment of 238kg of a sludge stream consisting of clinoptilolite, sand and Magnox sludge (TH-02) with a pre-treatment waste loading of 72% has also been successfully demonstrated. The product manufactured from this experiment also had a glassy appearance which appeared to be homogenous.

Hot Isostatic Pressing (NNL and USFD)

The HIP is used to consolidate a pre-prepared waste feed sealed in a HIP can resulting in a monolithic waste form produced through the application of pressure and temperature while in the HIP vessel. The product will then be in a form suitable for ongoing storage and ultimate disposal. A schematic is shown in Figure 8. The HIP assembly consists of a monolithic steel pressure vessel surrounded by a water jacket for cooling. Inside the vessel is a molybdenum furnace surrounded by a thermal barrier/heat shield to protect the vessel from the high temperatures required. The work piece (e.g. canister) is placed inside the furnace and the vessel closed before applying pressure through the use of compressed argon and temperature through power to the molybdenum furnace.

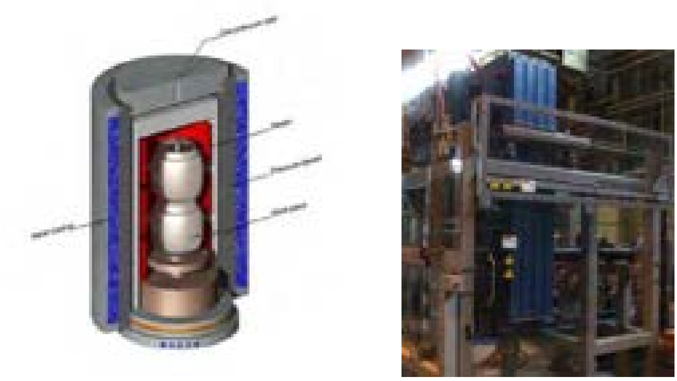

FIG. 8. Schematic of HIP (left: courtesy of ANSTO) and HIP installed at NNL Workington (right).

In the THERAMIN project NNL and USFD are focusing on HIP technology. USFD in 30 g scale and NNL in 8 l scale. USFD are currently the only facility in the UK with capabilities to fabricate and process radioactive HIP waste forms. At USFD the waste forms were based on the immobilisation of magnesium hydroxide sludges, where five waste forms used triuranium octoxide (U_3O_8) to simulate waste streams present on the Sellafield Ltd site. At NNL Workington two HIP runs have been carried out on sludge feeds.

Prior to any characterisation and analysis, some conclusions can be drawn from the observation of the trial at NNL. The primary aim was to consolidate the waste feeds into a form that may be suitable for ongoing storage and disposal. From a visual observation the cans consolidated as expected. From this it can be concluded that the pressure temperature cycle was appropriate. The visual observation of the product would suggest that the product of the trials, THERAMIN HIP 1 and HIP 2, would both be suitable for disposal.

Seven conceptual waste forms were successfully prepared and HIPed at USFD. The primary aim was to utilise a unique active furnace isolation chamber (AFIC) system that allows processing of radioactive waste simulants in the HIP without risk of contamination to the processing equipment. This target was achieved with five of the waste forms produced using U3O8 to simulate Magnox sludges located at the Sellafield Ltd site. The pre-calcination, canister packing and bake-out steps were completed with no operational issues. However, the HIP processing of waste forms MBS-U low, NNL-U and NNL-Ce had difficulty achieving and maintaining the target pressure of 100 MPa. Once the HIP repairs were completed, the target pressure for the remaining waste forms was reduced to 75 MPa in order to have a comparable suite of samples.

2.3. Development of generic disposability criteria

Samples from each demonstration, but also samples from thermal treatment processes not tested in the project, will be characterised in order to evaluate the impacts of thermal treatment on the disposability of radioactive waste. The first step of this evaluation was the identification of the relevant criteria, also called Waste Acceptance Criteria (WAC). Each participating country provided data through a questionnaire. Then, some generic disposability criteria were developed based on examination of these data. These generic disposability criteria can be used to evaluate any products from any form of thermal treatment for disposal at any type of facility, and regardless of the political, regulatory or socio-economic context. They reflect typical characteristics of thermally treated waste products. The characterisation of thermally treated waste products are currently ongoing.

3. Dissemination

Dissemination and training are also an essential activity of the THERAMIN project. For example all public deliverables can be found and downloaded from the web site http://www.theramin-h2020.eu/. In 2020 the project will also organise an international conference focusing on thermal waste treatment technologies.

In addition, a training replacement program is a way to promote thermal treatment technologies. The first round of training replacements has been completed and the second will be implemented in 2019.

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TUNNEL PLUGS AND SHAFT SEALS DEMONSTRATIONS – DOPAS

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Abstract. The goal of the Full-scale Demonstration of Pugs and Seals (DOPAS) project was to improve the industrial feasibility of plugs and seals, the measurement of their characteristics, the control of their behaviour in repository conditions, and their performance with respect to safety objectives. The DOPAS project delivered improvements in the process used to develop the design basis, in the design bases for different plugs and seals, in reference designs, in strategies to demonstrate the compliance of reference designs to the design basis, in technology, in materials, in construction; and on performance assessment of the materials and components. Five demonstration experimental programmes were implemented as part of these development activities.

1. Introduction

The Full-scale Demonstration of Pugs and Seals (DOPAS) project was undertaken in the period September 2012 – August 2016. Fourteen European waste management organisations (WMOs), and research and consultancy institutions from eight European countries participated in the project. A set of five full-scale experiments, materials research projects, and performance assessment studies of plugs and seals for geological repositories were undertaken in the course of DOPAS. The plugs and seals demonstrated in DOPAS were the Full-scale Seal (FSS) experiment, undertaken by Andra in a surface facility at St. Dizier, France [1], the Experimental Pressure and Sealing Plug (EPSP) experiment undertaken by SÚRAO and the Czech Technical University at the Josef underground research centre an underground laboratory in the Czech Republic [2], the Dome Plug (DOMPLU) experiment undertaken by SKB and Posiva at the Äspö Hard Rock Laboratory in Sweden [3], and the Posiva Plug (POPLU) experiment undertaken by Posiva, SKB, VTT and BTECH at the ONKALO® Underground Rock Characterisation Facility in Finland [4]. Additionally, in situ tests related to seals in vertical shafts complemented by materials research projects were conducted for the ELSA shaft seal project in Germany [5]. The DOPAS work was implemented in seven Work Packages (WPs). WP1 included project management and coordination. WP2, WP3, WP4 and WP5 addressed, respectively, the design basis, construction, compliance testing, and performance assessment modelling of the full-scale experiments and materials research projects. WP6 and WP7 addressed cross-cutting activities common to the whole of DOPAS through review and integration of results [6, 7, 8, 9, 10], and their dissemination to other interested organisations in Europe and beyond.

2. DOPAS project's main objectives

The work in the DOPAS project provided an updated European-level state-of-the-art for the plugs and seals studied in the project, through consideration of the following issues:

- Design basis processes: How are requirements on plugs and seals structured, and how can compliance with requirements be demonstrated? Can the learning from development of design bases for plugs and seals be applied to other repository elements? [6]
- Conceptual designs of plugs and seals: What conceptual designs exist for plugs and seals and what are their roles within the overall safety concept? [6]
- Plug and seal materials, and detailed design: What materials can be practically used to deliver the required functions of plugs and seal components as part of the detailed experimental designs? [7]
- Siting and excavation of plug/seal locations: How are the locations of plugs and seals selected? Further development of methods for the excavation of plug and seal locations. What operational safety issues are posed by the excavation of plug and seal locations and how can one overcome these? [7]
- Installation of plugs and seals: Further developments in the technology for emplacing plug and seal materials. What are the operational safety and logistical issues posed by the installation of plugs and seals? [7]
- Monitoring of plugs and seals: Does suitable technology for monitoring the performance of plugs and seals exist. What are the issues with monitoring of plugs and seals? [8]
- Performance of plugs and seals: How do plugs and seals perform with respect to detailed requirements on their performance? [8, 9]
- Compliance of plug and seal designs with their functions: To what extent can the current designs of plugs and seals be considered to meet their overall and safety functions? [9]
- Project management during plug and seal construction and full-scale testing: What learning has the DOPAS project provided with respect to the management of plug and seal implementation, conducting of full-scale tests and repository operations? [10]
- Dissemination about and integration of learning on plugs and seals: Have the dissemination activities in the DOPAS project been successful, and can the approaches adopted in the DOPAS project be applied elsewhere? [10, 14, 15]
- Technical readiness level of plugs and seals and remaining issues: What further development including testing of plugs and seals is required before designs are

ready for implementation in operating repositories, and how can the plugs be implemented efficiently during the operational period in an industrial manner? [8, 10]

3. Design basis processes for plugs and seals

Work on the design basis in the DOPAS project has allowed assessment of current practice with regard to both the process used to develop and describe the design basis and the content of the design basis of plugs and seals.

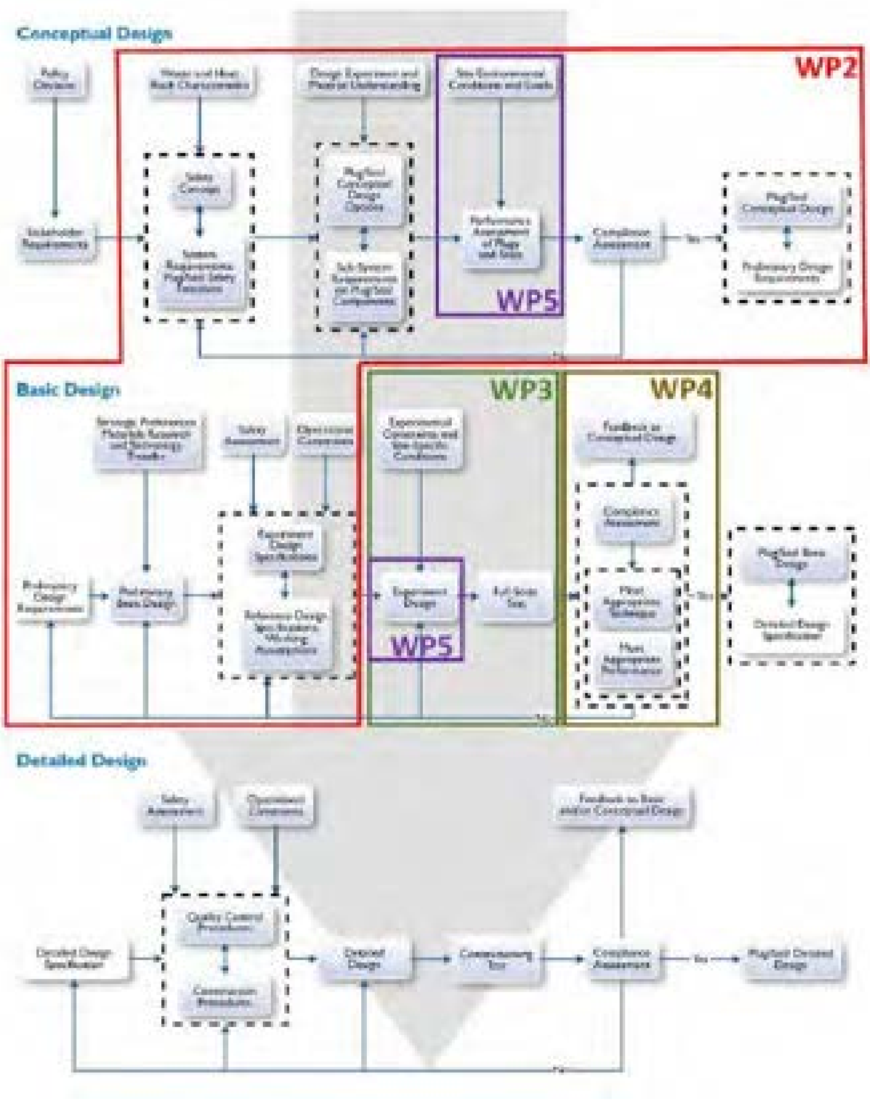

FIG. 1. The DOPAS Design Basis Workflow illustrating the iterative development of the design basis [6].

The design basis is developed in an iterative fashion with inputs from regulations, technology transfer, tests and full-scale demonstrations, and performance and safety assessments.

The learning provided by design basis compilation has been used to describe a generic process for development of the design basis for plugs and seals called the “DOPAS Design Basis Workflow” (Fig. 1).

The workflow integrates the project work package content related to construction, compliance testing, and performance assessment modelling of the full-scale experiments and material research projects. [6]

4. Implementation of plugs and seals in DOPAS project

4.1. FSS Experiment (Full-Scale seal demonstrating the Cigéo design plug)

The main objective of the experiment was to demonstrate the industrial feasibility of the construction of a large-scale swelling clay core seal (internal diameter 7.6 m), which forms part of drift and intermediate-level waste (ILW) disposal vault seal for the Cigéo repository design. Work on the FSS experiment within the DOPAS project included the design, construction and monitoring and dismantling of the experiment [1, 6, 7, 8, 9]. The components of the FSS experiment are illustrated in Figure 2.

For FSS, design work was undertaken in the period August 2012-April 2014, the upstream containment wall was cast in July 2013, the swelling clay core was emplaced in August 2014 and the downstream shotcrete plug was emplaced in September 2014. Investigations of FSS were undertaken in the period October 2014 to July 2015, and the dismantling and rehabilitation of the experimental surface facility was completed in December 2015.

The FSS experiment was not hydraulically pressurised. Instead the FSS experiment was dismantled during the duration of the DOPAS project. The dismantling of the FSS experiment included the collection of observations about the success of the construction and materials and additional information related to the properties of the installed components.

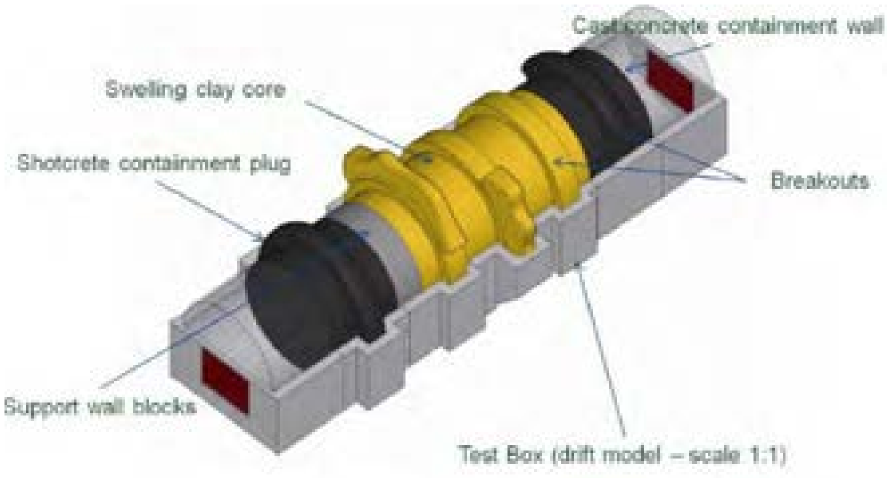

FIG. 2. FSS schematic design.

4.2. EPSP Experimental pressure and seal plug in Josef Gallery

The key objectives of the EPSP experiment were to test materials and technology, extending laboratory experience to the underground environment and to full scale, and to build the practical expertise of the SÚRAO personnel and other partners. In addition, the experiment demonstrated the successful use of shotcreting method in constructing a small-diameter experimental plug (the cross-section of the tunnel was approximately 15 m2. Work on the EPSP experiment within the DOPAS project included the design, construction and initial monitoring of the experiment [2, 6, 7, 8, 9]. The components of the EPSP experiment are illustrated in Fig. 3.

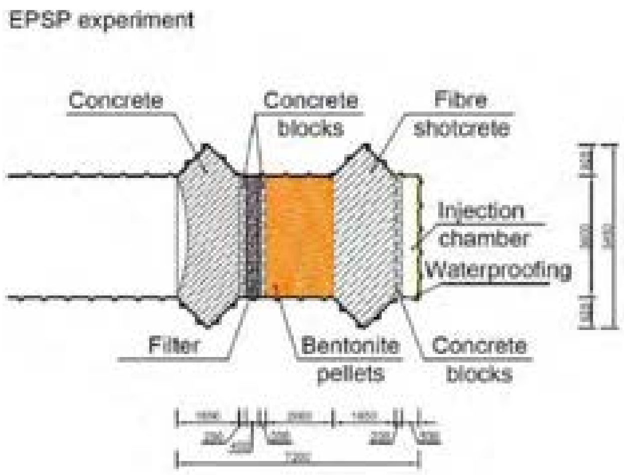

FIG. 3. EPSP plug design

The location of the EPSP plug was selected in the period September 2012 - December 2012, and ground works were undertaken in the period January 2013 - August 2014. The EPSP's inner plug was shotcreted in November 2014, the bentonite core was emplaced in June 2015 and the outer plug was shotcreted in June 2015.

Experimental testing and pressurisation of EPSP started during the construction process. The inner plug was pressurised to check the water tightness of the concrete and to determine if grouting was needed through injection of water and air into the injection chamber up to 0.5 MPa. A series of short water injection tests followed by long-term tests at various pressure levels (starting at 0.1 MPa going gradually to up to 1 MPa) were undertaken once the outer plug had cured. The testing sequence was then interrupted and the bentonite sealing section was saturated by injection of water into both the filter and the pressurisation chamber to allow swelling pressure to develop. A short pressure test was then undertaken involving injection of bentonite slurry into the pressurisation chamber at pressures up to 3 MPa (2.5 MPa being the original target value). The pressurisation chamber was then cleaned up, and water pressurisation of the experiment through the pressurisation chamber was resumed. Further pressurisation and monitoring of the EPSP experiment, and evaluation of the results are still on-going in Josef Gallery.

4.3. DOMPLU Experiment (Dome shaped plug in crystalline host rock)

The DOMPLU experiment was a full-scale test of the reference KBS-3®V deposition tunnel plug in Sweden and Finland at the time of the DOPAS project. The DOMPLU experiment was part of an on-going SKB testing and demonstration programme. The cross-section of the experiment is approximately 18 m2. The overall objective of the test was to reduce uncertainties in the performance and description of the initial state of deposition tunnel plugs. The components of the DOMPLU experiment are illustrated in Fig. 4.

Work on the DOMPLU experiment within the DOPAS project included the management, final installation and monitoring of the DOMPLU experiment up to 30 September 2014, and its evaluation and technical reporting [3, 6, 7, 8, 9]. The main part of the design and construction work for the DOMPLU experiment was not part of the DOPAS project. Excavation work for the DOMPLU experiment was undertaken between February and October 2012. The DOMPLU experiment's concrete dome was cast in March 2013 and the contact grouting was undertaken in June 2013. Monitoring was undertaken from March 2013.

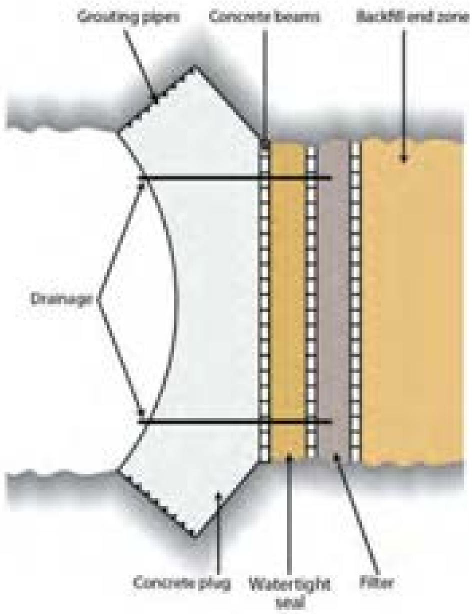

FIG. 4. DOMPLU schematic design.

Pressurisation of the system was started in December 2013 by injection of water into the filter and backfill, followed by saturation and development of swelling pressure in the watertight seal and backfill transition zone. The water pressure was artificially increased in steps inside the plug until it reached 4 MPa in February 2014. The water pressure was kept at this level for the remainder of the testing reported here. Further monitoring of the DOMPLU experiment, dismantling of the experiment, and evaluation of the results were carried out after the completion of the DOPAS project.

4.4. POPLU Experiment (wedge shaped plug in crystalline host rock)

The goal of the POPLU experiment's goal was to implement an alternative plug design for the KBS-3V disposal concept reference plug and the work on both DOMPLU and POPLU has led to further development of Posiva's plug in the current demonstration of full-scale in-situ test in ONKALO®. The cross-section of the experiment is approximately 14.5 m^2. Work on the POPLU experiment within the DOPAS project included the concrete recipe design and performance evaluation, bentonite tape and filter system planning, slot excavation planning and implementations, monitoring and pressurisation systems' design and implementation, modelling of water tightness and mechanical integrity, pressurisation of the experiment plug and its performance assessment [4, 6, 7, 8, 9]. Some aspects of the plug design, tunnel excavation and construction of the experiment were not part of the DOPAS project. The components of the POPLU experiment are illustrated in Fig. 5.

The design of the POPLU experiment was undertaken between November 2012 and September 2013. Excavation of the demonstration tunnels (one for the plug experiment and one for its monitoring data collection) and then the slot were undertaken in the period September 2013-February 2015. The first section of the POPLU concrete wedge was cast in July 2015 and the second section was cast in September 2015. Grouting of the plug-rock interface was undertaken in December 2015. Pressurisation of the plug commenced in mid-January 2016.

Once the filter section was filled with water, pressurisation of the plug could commence. In the early stage of pressurisation, the water pressure in the filter was increased to 1.4 MPa over a one-month period, and a shorter duration higher pressure test. Based on the results achieved to date, it was decided to re-grout the plug interface with an improved grout mix and methodology. It is expected that the pressurisation and performance evaluation will be undertaken again with pressures up to 4.2 MPa after the re-grouting is completed. The POPLU experiment is available for further monitoring and for potential future dismantling in ONKALO®.

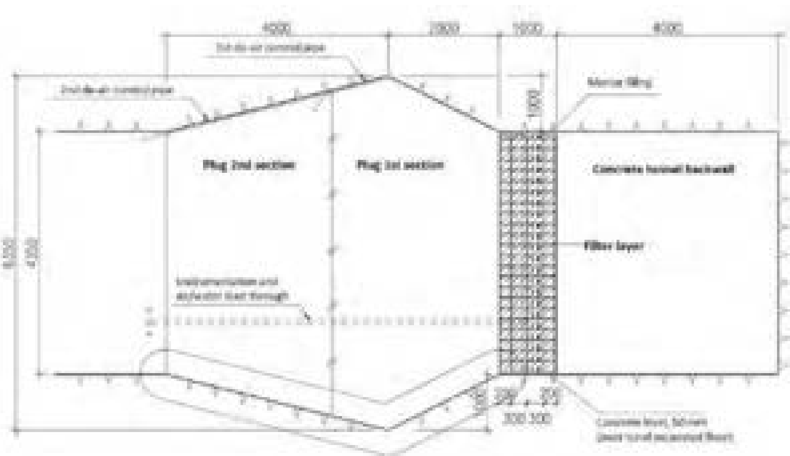

FIG. 5. POPLU plug design.

4.5. ELSA Programme for shaft seal design with related material studies

No full-scale test as part of the German ELSA project has been carried out within the DOPAS project. However, the work consisted of several smaller comparative experiments carried out at different sites. The aims of the experiments were to develop generic design concepts for sealing elements to be used in shaft seals in both salt and clay host rocks that comply with the requirements for a repository for high-level waste, and to carry out the preparatory work in shaft seal design. [11, 12].

4.6. Expert evaluation of outcomes and the dissemination of DOPAS results

The DOPAS project deliverables went through an extensive expert elicitation [13, 10] to ensure the soundness of the different work package reports and their results. A total of 16 geological disposal experts with various areas of expertise in the field, and who were not directly involved in the DOPAS work, contributed to this expert evaluation in four different elicitation processes. The outcomes of the process included external experts' review of drafts of the main WP2 - WP5 summary reports (DOPAS Deliverables D2.4, D3.30, D4.4 and D5.10) [6, 7, 8, 9].

FIG. 6. DOPAS seminar participants in Turku, Finland, May 2016. Photo: Elina Heikkilä, TVO.

In addition, the DOPAS project results were shared on tens of technical and research forums and articles, in the regular DOPAS newsletters, and in a dedicated training workshop for young professionals and students in geological disposal carried out in the Czech Republic [15]. Additionally, the DOPAS project organised three staff exchanges for competence exchange between the experiments and the participating organisations' staff. However, the main dissemination highlight was the final DOPAS seminar [14] where the project's results were disseminated to a wide audience of over 110 participants from 50 different organisations and 16 different countries, including participants from the European Union, Russia, Japan, and Australia (Fig. 6).

5. Assessment of plugs and seals

The DOPAS project contributed significantly to the further development of plugging and sealing material recipes and design, to the practical industrial installation work of the plugs and seals and finally to the safety cases for radioactive waste repositories by bringing forward the plug and sealing concepts in the three main host rock types considered in Europe: crystalline rock, clay rock and salt rock. Process modelling work performed in DOPAS contributed to the preparation and execution of the experiments and helped in interpreting the results [9]. The full-scale experiments have contributed to the safety assessment and development of safety case in following ways (see also Fig. 7):

- **Gain in process understanding and improvement of models for safety assessment by evaluation process modelling of laboratory experiments**: Process modelling of laboratory experiments in the DOPAS project was able to predict and interpret the results enhancing the confidence in the suitability of the models used to describe the observed processes. The process models were partly converted into abstract models that could be included in integrated safety assessment models to achieve a better process representation in the future total system performance assessments. Future comparison of the performed predictive modelling on mid-scale experiments with experimental results contributed in the confidence of the validity of the up-scaling of process modelling results from the small scale to the metric scale.

- **Advancement of the sealing concept**: The process modelling of laboratory and mid-scale in situ experiments contributed to the updating of sealing concepts and to the choice of sealing materials. The predictive process modelling of the in situ experiment directly supported and influenced the layout and construction of the experiment.
- **Confidence in concepts and models**: Future comparison of the predictive modelling with experimental results will further contribute to the confidence of the validity of the up-scaling of process modelling results from the small scale to the large scale.
- **Proof of constructability**: All aspects described before are jointly contributing to the confidence that plugs and seals can be constructed as planned, and will be able to meet their designed function in the overall repository concept.

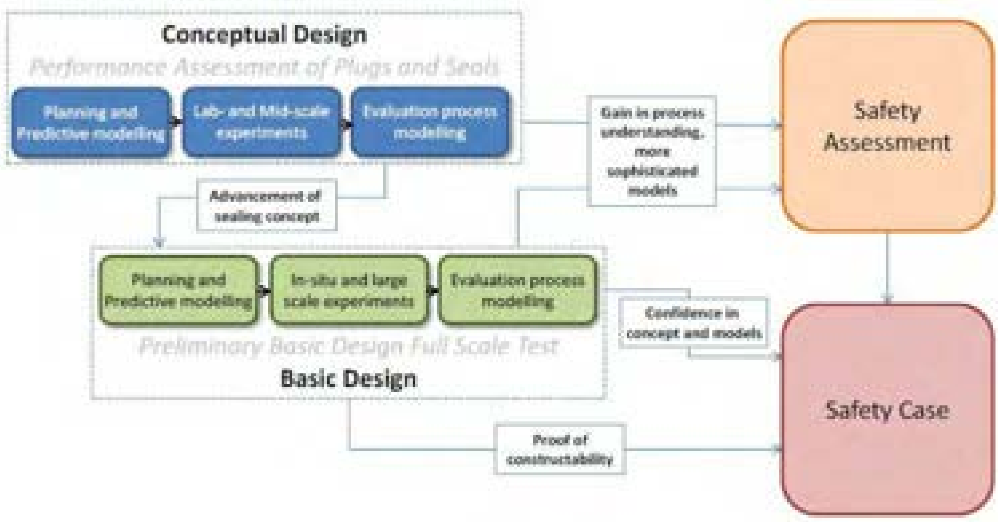

FIG. 7. Safety assessment and the development of the safety case as part of the full scale testing of plugs and seals [9].

6. Outcomes of the DOPAS project

The main outcome for defining the design basis and requirements for plugs and seals were the requirements on plugs and seals considered in the DOPAS project, conceptual and basic designs including material development work, and the strategy adopted in programmes for demonstrating compliance with the design basis. The design basis is presented for both the repository reference design, i.e., the design used to underpin the safety case or licence application, and for the full-scale experiment design, i.e., the design of the plug or seal that is being tested in the DOPAS project. The strategy is presented in

Workflow outlining how the design basis and designs of plugs and seals are developed throughout a programme at an increasing level of detail (Fig. 1).

The main outcome from design and construction feasibility for plugs and seals are the lessons learned from the detailed design, site selection and characterisation, and construction of the experiments. These include the four full-scale demonstrators, materials research and its up-scaling, and the learning provided by the practical experience in constructing the experiments. Appraisal of plug and seal systems' function considers what can be concluded from the experiments conducted in the DOPAS project with respect to the technical feasibility of installing the reference designs, the performance of the reference designs with respect to the safety functions listed in the design basis, and identifies and summarises achievements from starting the conceptual design and leading to the full-scale demonstrator. It is essential to collect the feedback from the implemented structures back to the design basis, while development is usually an iterative process and it is important to consider the aspects on the way for industrialisation and implementing the structures in repository. In the DOPAS project, performance assessment was taken to cover the performance of plugs and seals following the installation of the plug/seal materials in the experiment/repository. This included, therefore, the saturation of the materials following installation, their long-term thermal, hydraulic, mechanical and chemical (THMC) behaviour, and their representation in safety assessments.

Integrating analysis including cross-review of each other's work also included the use of an applied Expert Elicitation (EE) process to integrate critical analyses of the achievements and results from the implementation and monitoring of the DOPAS project's plugs and seals. Concluding the integration the DOPAS project, a final public technical summary report (Deliverable D6.4) [10] was published at the end of the project and the DOPAS seminar was held in May 2016 bringing together WMOs and research organisations to widely discuss about the role of plugs and seal in repository context [14].

Acknowledgements

The DOPAS project with full-scale experiments provides the basis for future needs related to plug and seal technologies for nuclear waste management. The research leading to these results received funding from the European Union's European Atomic Energy Community's (Euratom) Seventh Framework Programme FP7/2007-2013 under Grant agreement no 323273, the DOPAS project".

References

[1] Noiret, A., Bethmont, S., Bosgiraud J-M. and Foin R. (2016). DOPAS Work Package 4, Deliverable D4.8. FSS Experiment Summary Report.

[2] Svoboda, J., Hausmannová, L., Vašíček, R., Smutek, J., Stastka, J., Nádherná, D., Pacovská, D., Dvorakova, M., Hanusová, I., Belickova, L., Havlová, V., Večerník, P. and Trpkošová, D. (2016). DOPAS Work Package 4, Deliverable D4.7. EPSP Experiment Summary Report.

[3] Grahm, P.; Malm, R.; Eriksson, D. (2015). DOPAS Work Package 4, Deliverable D4.3: DOMPLU Summary Report, Version 1, December 2015 (content identical to SKB publication SKB TR-14-23).

[4] Holt, E. and Koho. P. (2016). DOPAS Work Package 4, Deliverable D4.5. POPLU Experiment Summary Report.

[5] Glaubach, U., Hofmann, M., Gruner, M., Königer, F., Emmerich, K., Schuhmann, R., Grafe, F. & Wils-nack, T. (2016). Teilbericht zum Arbeitspaket 4: Halbtechnische Versuche zu den Arbeitsschritten 2.1 bis 2.6 Im Rahmen des Vorhabens „Schachtverschlüsse für Endlager für hochradioaktive Abfälle", ELSA-Phase 2: Konzeptentwicklung für Schachtverschlüsse und Test von Funktionselementen von Schachtverschlüssen, Technische Universität Bergakademie Freiberg, Institut für Bergbau und Spezialtiefbau (in German).

[6] DOPAS (2016a). DOPAS Work Package 2, Deliverable D2.4. WP2 Final Report: Design Basis for DOPAS Plugs and Seals.

[7] DOPAS (2016b). DOPAS Work Package 3, Deliverable D3.30. WP3 Final Summary Report: Summary of, and Lessons Learned from, Design and Construction of the DOPAS Experiments.

[8] DOPAS (2016c). DOPAS Work Package 4 Deliverable D4.4. WP4 Integrated Report. Summary of Progress on Design, Construction and Monitoring of Plugs and Seals.

[9] DOPAS (2016d). DOPAS Work Package 5, Deliverable D5.10. WP5 Final Integrated Report. DOPAS Project Deliverable D5.10.

[10] DOPAS (2016e) DOPAS Final technical summary report. DOPAS Project Deliverable D6.4

[11] Jobmann, M. (2013). Requirements for Shaft Seals for HLW Repositories in Germany – Technical Report, DBE TECHNOLOGY GmbH, Peine, Germany.

[12a] Zhang, C-L. (2016). DOPAS Work Package 3, Deliverable D3.32. Final report on the sealing behaviour of fractured claystone and seal materials (THM-Ton).

[12b] Jantschik, K. and Moog, H. (2016). DOPAS Work Package 3, Deliverable D3.29. Final technical report on ELSA related testing on chemical-hydraulical behaviour – LAVA.

[13] Hukki, K. (2008). A Formal Process for Elicitation and Validation of Expert Judgments for Safety Case in the Context of Spent Nuclear Fuel Management. Posiva Working Report 2008-60.

[14] DOPAS (2016f) DOPAS 2016 proceedings DOPAS Project Deliverable D7.3

[15] Palmu, M. and Vašíček, R. (2016). Plug and seal training workshop planning and implementation report. DOPAS Project Deliverable D7.2.

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DEVELOPMENT AND DEMONSTRATION OF MONITORING STRATEGIES AND TECHNOLOGIES (MODERN2020)

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Abstract: The Modern2020 Project was undertaken with the aim to support and document a move from hypothetical repository monitoring programmes to actual, implementable monitoring programmes by providing tools and methodologies at a generic level which may be adapted by each national programme. The generic level is founded on work by different national programmes on the geological disposal of radioactive waste. Modern2020 is focus on monitoring of the near-field during repository operations with consideration of closure and post closure. Early involvement of public stakeholders may improve their confidence in the monitoring program, as well as make clear what their concerns and expectations regarding such a program are. In the Modern2020 project, we focused specifically on the challenge of involving local public stakeholders, people in concerned communities (either potential repository host communities, or communities hosting an underground research laboratory (URL)). They represent the most directly concerned, and the closest representatives of the general public with regard to the future deployment of this monitoring technology.

Status of Monitoring for geological disposal for Long-lived Radioactive Waste before the Modern2020

The geological disposal of radioactive waste is envisaged as a staged process that will take many decades to implement. During the long period over which a repository will be sited, constructed, operated and closed, future operators and future generations will need to make decisions about how, when and if to implement various steps in the development of the repository system. Decisions at each stage of repository implementation will be supported by information provided by monitoring results (IAEA, 2001[4.]; EC, 2004[7.]). In fact, a key objective of a monitoring programme is to provide information to support the post-closure safety case. During the early stages of repository implementation, monitoring can strengthen understanding of system behaviour used in developing the post-closure safety case and to allow further testing of models of long-term behaviour (IAEA, 2001, [4.]). During the operation of the repository, monitoring can be undertaken to demonstrate that the assumptions in the safety case are valid. In the United States (US), monitoring is considered a part of the performance confirmation programme, which also includes laboratory and field testing, and in situ experiments (USNRC, 2013 10 CFR Part 63 Part F, paragraph 131). The post-closure safety of a geological repository is demonstrated in a safety case (IAEA, 2012, [9.]). This is defined as a set of arguments and analyses used to justify the conclusion that a specific repository system is safe. It includes a description of the system design and safety functions, illustrates the performance of engineered and natural safety barriers, and presents the evidence that supports the arguments and analyses and discusses the significance of any uncertainty or open questions. The safety case also presents the evidence that all relevant regulatory safety criteria can be met.

Monitoring is a means to assist in checking or confirming that key assumptions regarding the post-closure safety-related features of the disposal system are valid (EC, 2004, [7.]). However, post-closure safety is ensured by passive means inherent in the characteristics of the site and the facility, and those of the waste package, and does not depend on monitoring and monitoring the should not compromise the passively safe design (IAEA, 2011,[8.]). In addition to supporting the post-closure safety case, monitoring can support other aspects of repository implementation, including demonstration of operational (industrial) safety, environmental impact assessment, and safeguards. Information will be obtained through monitoring to confirm the conditions necessary for the safety of workers and members of the public and protection of the environment during the period of operation of the facility (IAEA, 2011[8.]). Much of the monitoring that could be undertaken for operational safety, environmental impact assessment (EIA) and safeguards could overlap with monitoring undertaken in support of the post-closure safety case.

Monitoring provides information to give society at large the confidence to take decisions on the major stages of the repository development programme and to strengthen confidence - for as long as society requires - that the repository is having no undesirable impacts on human health and the environment (EC, 2004, [7.]). Therefore, monitoring can have an important role in stakeholder engagement throughout a repository implementation programme. The use of monitoring as a method for building stakeholder confidence requires consideration of particular approaches to monitoring, and consideration of monitoring of specific events and processes.

Objectives and Scope of Work

The task of monitoring may, in principle, be addressed by answering the following questions:

- Why to monitor (purpose and process identification)?
- What to monitor (parameter and/or human activities)?

- How to monitor (measurement and observation procedures and corresponding equipment)?
- When to monitor (timing, frequency and duration)?
- How to use/interpret the results (modelling, synthesis of the inputs, records)?

The overall objective of the Modern2020 project [1.] is to provide the means for developing and implementing an effective and efficient repository operational monitoring programme. Monitoring programme should be driven by safety case needs, and that will take into account the requirements of specific national contexts (including inventory, host rocks, repository concepts and regulations, all of which differ between Member States) and public stakeholder expectations (particularly those of local public stakeholders at (potential) disposal sites). The modern2020 project comes from after the Modern-fp7 project [2.]

The work in the Modern2020 Project addresses the following issues[1]:

i. WP2: Strategy: development of detailed methodologies for screening safety cases to identify needs-driven repository monitoring strategies and to develop operational approaches for responding to monitoring information;
ii. WP3: Technology: carry out research and development (R&D) to solve outstanding technical issues in repository monitoring, which are related with wireless data transmission technologies, alternative long term power supplies, new sensors, geophysics, reliability and qualification of components.;
iii. WP4: Demonstration and Practical Implementation: enhance the knowledge on the operational implementation and demonstrate the performance of state-of-the-art and innovative techniques by running full-scale and in-situ experiments;
iv. WP5 Societal Concerns and Stakeholder Involvement: Develop and evaluate ways for integrating public stakeholders concerns and societal expectations into repository monitoring programme.

The Modern2020 consortium brings together 29 organizations (details in [1.]) from Europe Union and Japan that are committed to the common goal of promoting a targeted and innovative cooperation and synergy in the field of monitoring and to respond in an efficient way to major issues and challenges of developing and implementing a monitoring system.

- 9 (Nine) radioactive waste management organisations : Andra (France), ENRESA(Spain), NAGRA(Switzerland) , ONDRAF/NIRAS (Belgium), Posiva(Finland), RWM(United Kingdom), SKB (Sweden), SURAO (Czech republic);BGE (Germany)
- 5 (five) organizations undertaking research in their respective country for the radioactive waste management: ENEA (Italy), NRG (Netherlands), RWMC(Japan), EURIDICE EIG (Belgium) and VTT (Finland)
- 1 (one) technical support organization: IRSN (France)
- 4 (four) private companies with monitoring expertise : Amberg Infraestructuras (Spain), ORANO (France), EDF-DTG (France), Arquimea (Spain)
- 8 (Eight) academic research units: CTU (Czech republic), TUL (Czech republic); UStratclyde((United Kingdom),, XLIM/CNRS (France), , UMONS (Belgium), ETH

[1] Note that WP1 is dedicated to the management of the project and WP6 to the dissemination activities

(Switzerland) of which two are undertaking research in social sciences (UAntwerpen (Belgium), UGOT (Sweden));

- (2)Two specialist consultants: Galson science ltd (United Kingdom), Nidia (Italy)).

Modern2020 focuses on monitoring of the near field during repository operational phases

WP2: MONITORING DURING THE OPERATIONAL PERIOD TO PROVIDE FURTHER CONFIDENCE IN THE POST-CLOSURE SAFETY CASE: STRATEGIES AND PARAMETERS

The work in WP2 of the Modern2020 was undertaken through consideration of programme-specific approaches and through development of common approaches in workshops. The work was separated into three tasks, each with its own deliverable: (i) Task 2.1 evaluated monitoring strategies, considered decisions requiring support from monitoring data, and proposed methodologies for screening monitoring parameter lists [13.]. Task 2.1 also included the collation of information from WMOs about specific monitoring strategies using a questionnaire, and a literature review of existing monitoring programmes. Two workshops were held through which a methodology for screening preliminary parameter lists was discussed, resulting in the development of a draft Modern2020 Screening Methodology. (ii) Task 2.2 evaluated safety cases for repositories in France (Cigéo repository), Germany (ANSICHT safety case), the Netherlands (OPERA safety case), Switzerland (Opalinus Clay safety case), Finland (TURVA 2012 safety case), Sweden (SR-Site safety case) and the Czech Republic (Reference Project 2011), and revised the Modern2020 Screening Methodology to develop a common approach for identifying potential monitoring parameters [1]. (iii) Task 2.3 aimed to develop decision-making methods, tools and workflows for responding to monitoring information, and to develop collective opinions on performance measures and response planning [8]. In addition, specific information on decision-making processes was provided by seven WMOs and their representatives, and a review of literature on the role of monitoring in decision making in carbon capture and storage Projects was undertaken.

Main Outcomes

Link to the Safety Case

Explicit consideration of the post-closure safety case, and how monitoring can be integrated with other methods to build confidence and demonstrate safety, needs to be clearly set out to ensure that monitoring programmes are discussed and developed in a wider context. Safety following closure is demonstrated through multiple lines of reasoning, including conduct of a safety assessment and comparison of the results with safety criteria. Residual uncertainties in the post-closure performance of a repository are managed in the safety case by applying specific approaches to the safety assessment and through other means. Uncertainty can be accounted for through mitigation, qualitative argument, or quantitative assessment approaches, none of which rely on monitoring. The development of design requirements, and demonstration of compliance with these through limits, controls (including quality control) and conditions, is used to verify that the as-built repository is consistent with the safety case.

However, the repository will be partially open and accessible for monitoring for several decades during the operational period and this provides an opportunity for gathering information on the performance of the disposal system following emplacement of the waste and the EBS. Consistent with stepwise implementation of geological disposal, periodic updates to the safety case will be produced during the operational period, and information from monitoring will be one input to these periodic updates. Information from repository monitoring could be compared with the arguments used to build the safety case to check whether the parameters of the repository system are evolving in a domain that is consistent with the safety case. The results from such monitoring could also form part of an ongoing stakeholder engagement plan and form part of stakeholder dialogue during repository operation.

High level monitoring strategies

In defining strategic elements consideration must be made of the complete system in a holistic sense. The repository near field is set in a natural environment which provides physical and chemical processes and boundary conditions for understanding the containment of the radioactive waste. The heterogeneity of the barrier systems also impacts on the strategy for sensor placement and interpretation of monitoring data utilised for model/modelling assessment and decision making. The correspondence between objectives of monitoring, modelling and decision making must harmonise and be clear at the outset whilst at the same time acknowledge that there might be "unknown unknowns". A strategy is a method or a plan for successfully achieving a specified objective. In the context of repository monitoring, there is a continuum between high-level strategy and detailed design. At each point on the continuum, consideration can be made of what will be monitored, and where, when and how monitoring will take place, at increasing levels of detail. A high-level strategy describes the overall manner in which these elements are combined in order to describe the main aspects of any specific monitoring programme.

Strategy elements (what, where, when and how) that were identified may be combined in different ways to form bespoke high-level monitoring strategies. Strategies that have been considered in WMO programmes include, for example:

- In situ monitoring of relatively broad scope.
- Limited monitoring focused on EBS elements/dummy packages.
- Monitoring in a pilot facility.

These strategies do not have to be employed in isolation; several of them can be used in a single monitoring programme. The choice of monitoring strategy depends on the national context. This includes the programme-specific legislation and regulatory guidance, the nature of the waste, the geological environment, the disposal concept upon which the repository design is based, and consideration of stakeholder views.

Identification of Parameters to Monitor

The development of the Modern2020 Screening Methodology was motivated by a desire to develop a justified and needs-driven monitoring programme. As noted in the previous international collaborations on repository monitoring, in particular the NEA guidance related to the need to "optimise" the selection of parameters to be monitored [14.], repository monitoring has the potential to affect passive safety and will impact repository operations, and it is therefore important that all monitoring activities are carefully considered and their need justified.

The Modern2020 Screening Methodology is a generic methodology for developing and maintaining an appropriate and justified set of parameters to be monitored in an implementable and logical monitoring programme. The methodology is based on the principles and context provided by the wider discussion of monitoring during the operational period in support of decision making and to provide further confidence in the post-closure safety case. The Methodology is detail in the Modern2020 deliverable D2.2

The Methodology is envisaged as an iterative process that would be repeated multiple times during the operational phase of the repository, it might be re-run in parallel with a periodic update to the post-closure safety case or in response to unexpected results from the monitoring programme. The philosophy that underpins the Methodology is to consider each potential monitoring process in turn at three interlinked levels of Processes, Parameters and Technologies (feasibility).

The Methodology is intended to be indicative and flexible rather than prescriptive, and can be regarded as a template that can be adapted by individual WMOs to suit particular needs. No prescriptive guidance on recording results has been provided, because multiple approaches are possible and WMOs may have their own systems (e.g. document templates or databases) that they wish to use. The principal justifications for the screening are firstly, that parameters are relevant to post-closure safety and/or retrievability and secondly, that monitoring of a process or parameter is judged to have value in building further confidence in the post-closure safety case.

Decisions Based on Monitored Parameters

Evaluating monitoring results will consider both individual results (i.e. monitoring of the same parameter, potentially in multiple locations and/or with multiple types of sensor) and also integrated consideration of the range of monitoring data. Evaluation of individual results will be undertaken on a continuous basis, whereas integrated evaluation will be undertaken periodically. For continuous evaluation of specific parameters, the main aspect will be to compare results to the range of expected evolution. For this evaluation, three scenarios are envisaged:

- Monitoring values and trends are consistent with the range of expected evolution.
- Results are inconsistent with the range of expected evolution, but insignificant to safety.
- Results are inconsistent with the range of expected evolution, and require further evaluation.

Results that are inconsistent with their expected evolution would act as a trigger for undertaking a periodic evaluation considering the integrated data set. A periodic evaluation should be made in an integrated way by considering holistically the spatial and temporal evolution of the system before adopting a response plan.

Responding to monitoring results is considered to be a stepwise process that first involves data acquisition on a parameter-by-parameter basis, followed by the comparison of these data to their expected evolution, and the integrated evaluation of the full range of monitoring results. From this, decisions can be made about whether to a) continue monitoring in the same way, b) change the monitoring programme, c) change the disposal process, or d) end the monitoring programme.

In addition, the following collective opinions on responding to monitoring results have been identified in the Modern2020 Project:

- It is not possible to define a direct link to safety for any specific monitoring parameter.

- Responding to monitoring results requires continuous evaluation of specific data and periodic evaluation of the monitoring dataset.
- Response plans should be developed to describe actions that could be taken following some specific parameter evolutions.
- Response plans need to be adaptable and should consider the system behaviour.
- Assessment of monitoring results might need to consider processes that have not been previously recognised or identified as being significant.
- Usually, the first response to unexpected results is to check the data and consider the implications for safety.
- The results from monitoring each parameter should be compared to the range of expected evolution of that parameter in time and space.
- Continuous evaluation would occur in response to parameter values being inconsistent with their expected evolution.
- Periodic evaluation might occur in response to the outcome of a continuous evaluation or at regular intervals.
- Monitoring programmes should include the organizational set-up for responding to monitoring results.
- The response to monitoring can be guided by consideration of a generic action list, comprising desk-based actions and physical actions.

WP3: RESEARCH AND DEVELOPMENT OF RELEVANT MONITORING TECHNOLOGIES

Based on the previous work [15.], one major goal of Modern2020 EU project was the adaptation of the existing technologies or the development of new ones for specific monitoring objectives, host rocks and repository concepts, for the monitoring of specific parameters, and for improving their long-term performance. In more detail, the objectives on repository monitoring technology were:

Wireless communication

Wireless systems allow transmitting monitoring data without impairing the safety of barriers, and they hence support the ability to survey the evolution of relevant safety functions of a disposal concept. In the project, a major step has been achieved in understanding, designing and demonstrating specific solutions that allow transmitting data through components of the engineered barrier system or the host rock. Different technological solutions covering transmission distances between several meters and more than 275 m have been successfully developed and tested, covering a variety of application situations, disposal concepts, and host rocks. The work was also done in a way to combine short range and long range technologies.

Since high frequencies lead to high signal attenuation when transmitting through a (partially) saturated barrier, all current wireless techniques, except for very short distances (<1 m) make use of the very low frequency (VLF) to – medium frequency (MF) range (3 kHz to 3 MHz). Table 1 summarizes data transmission experiments performed as part of Modern2020 in URLs under conditions relevant for underground disposal of radioactive waste. Additional to the data transmission experiments, Andra demonstrated signal transmission through 275 m of limestone and shales at the Tournemire URL, and over 300 m in a surface-surface configuration at the Tournemire URL and the Andra URL.

Table 1: Wireless data transmission experiments performed in URLs as part of Modern2020

Distance	Transmission mode	Frequency	Host rock/barrier (location)	Organization
4 - 6 m	λ/4 loop antenna	2.2 MHz	(Partially) saturated bentonite (Tournemire URL)	Arquimea
5 - 10 m	Magnetic loop antenna	8.5 kHz	(Partially) saturated bentonite (Tournemire URL)	Andra
23 m	Magnetic loop antenna	125 kHz	Granite + Air (Espoo research hall)	VTT
30 m	Magnetic loop antenna	4.0 kHz	(Partially) saturated bentonite (Tournemire URL)	Amberg
275 m	Magnetic loop antenna	8.7 kHz	Limestone & Shale (Tournemire URL)	NRG

Major step has been achieved in understanding, designing and demonstrating specific solutions that allow transmitting data through components of the EBS or the host rock. Different technological solutions covering transmission distances between 0.5 and more than 275 m have been developed and tested, comprising a variety of application situations, disposal concepts, and host rocks. A greater understanding of the underlying technical and physical principles has been achieved, and the provided solutions have been tested under realistic conditions, e.g. in the Tournemire Wireless Testing Bench (WTB), from the Tournemire tunnel to the surface plateau, or in the VTT underground laboratory. The performance of the developed technologies depends on a number of factors, allowing data transmission over distances of 275 m through the underground with a power consumption per transmitted bit below 5 mWs, or over 4 m or more of a (partially) saturated barrier with a power consumption below 1 mWs/bit.

Alternative power sources

Electric power is necessary for sensor units in nuclear repositories as well as for running wireless sensor units (WSUs) in nuclear repositories. The research has addressed three alternative cable-free power sourcing technologies for nuclear repository environment: thermal energy harvesting, wireless energy transfer and nuclear batteries. The applicability of these power sourcing technologies can be improved by an interim energy storage, the technology alternatives of which have also been investigated. Applied research methods have been technology reviews based on available material, theoretical performance analyses and simulations, laboratory pilots and field pilots in an environment that partly represents the final nuclear repository. The results indicate that all the three alternative power sourcing technologies are relevant for powering wireless repository monitoring sensors. Their comparison also indicated clear differences in their applicapility in various repository environments. In the design of the interim energy storage, some features of the existing energy storage technologies such as the self-discharge and the lifetime should be assessed case by case. Forthcoming energy storage technologies are expected to enable better interim energy storage solutions than the existing technologies. The follow-on steps of the research should be targeted to the further development, demonstration and verification of the powering subsystem as a part of more complete wireless sensor units (WSUs) and repository monitoring sensor systems.

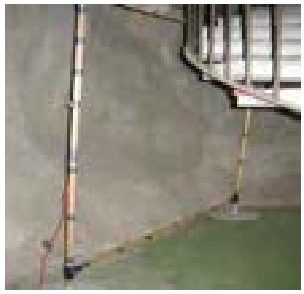

Figure 1: The pilot system in co-axial antenna configuration through host rocks with low electrical conductivity (Espoo, Finland). The left photo shows the power receiver and the right photo the repository external power transmitter

New sensors

Modern2020 aims to improve the durability of monitoring sensor components (design, materials, armour, etc.) with the goal to extend their lifetime under the aggressive conditions expected in the repository, in particular the presence of ionising radiation and aggressive corrosion conditions. Different sensors has been developed during the project . In this paper, we focus on optical fiber senors. Distributed strain measurements would rely on optical fiber selected for their tolerance to harsh environment, paired with a Brillouin scattering acquisition device. The frequency shift is known to be proportional to both strain ($\Delta\varepsilon$) and temperature variations (ΔT) via the so-called Brillouin central frequency shift $\Delta\nu_B$ following the equation

$\Delta\nu_B = C_T \Delta T + C\varepsilon \Delta\varepsilon$,

where C_T and C_ε are the temperature and strain sensitivity coefficients (in MHz/°C and MHz/με respectively) of the fiber used as the sensitive element for the distributed measurements [1].

It is known that the single influence of temperature, radiation [2] and hydrogen [3] impacts the optical fiber sensor properties, compromising strain results and measuring performances. There remains to analyze the coupled impact of these parameters affecting simultaneously the sensor, as the coupled influence of radiation and temperature and the impact of hydrogen on irradiated fibers. For this reason, different tests were set up by Andra together with IRSN, SCK-CEN and University of Mons, in order to understand the impact of radiation ageing under other physical constraints.

Geophysical methods

Geophysical techniques offer powerful means for the implementation of non-invasive monitoring of radioactive waste repositories. The indirect nature of geophysical measurements (i.e., material properties are not measured directly, but through the geophysical data that are affected by the material properties relevant to repository system) allows obtaining information on the repository and it engineered barrier system (EBS) without placing sensors within the regions of interest. However, this can result in considerable uncertainties and ambiguities and more research is required for obtaining meaningful diagnostic information. Previous studies have identified seismic full waveform inversion (FWI) to be the most promising option for delineating subtle changes within a repository using data acquired outside of the repository. Significant anisotropy of the host rock, particularly in clay environments, precluded so far application of FWI technology for repository monitoring. With the development of a novel model parameterization, this problem could be resolved. In addition to seismic methods, geoelectrical techniques can provide valuable information for repository monitoring. For that purpose, tomographic algorithms for geoelectrical and induced polarization data were established and tested with laboratory data. For transferring the electrical parameters, obtained from these tomographic inversions, into relevant physical parameters, such as temperature and moisture content, calibration measurements were performed, and constitutive relationships between these parameters were established.

Methodology for qualifying monitoring components

Finally, a common multi-stage methodology for qualifying monitoring components of the measurement chain (sensor, connecting cable and/or wireless system/controller) at a Deep Geological Repository (DGR) has been proposed. It is the result of a carried out multi-stage analysis, which comprises the study of transferable experience from other industry fields, the analysis of similar case studies operating in conditions close to those expected in repositories and different initiatives for the development of a qualification process for selecting and testing the monitoring components

WP4: DEMONSTRATION OF MONITORING IMPLEMENTATION AT REPOSITORY LIKE CONDITIONS

The demonstration of monitoring technologies in repository like conditions is essential to asses the quality of engineering design and determine safety strategies. Demonstration is an essential step in the validation of the work performed for the implementation of the monitoring strategy into a practical plan and the development and field assessment of innovative sensing systems like those in the Modern2020 project.). Four main demonstration cases have been developed in WP4, of which two will be detailed in this paper:

Long-Term Rock Buffer Monitoring (LTRBM), Tournemire (France) : the Long Term Rock Buffer Monitoring (LTRBM) test which sole aim is to assess the performance of new monitoring devices developed in WP3 (mainly wireless devices and new sensors) in conditions as close as possible to those expected in a real repository. The tested prototypes were designed to be placed in or around a multiple barrier system (shale, bentonite buffer and cement plug) to monitor key safety and performance assessment parameters (saturation, humidity, temperature, pressure, deformation and chemical composition). When possible the new sensors were installed next to standard commercial ones to validate their performance.

AHA experiment, Bure (France) The HLW disposal cell consists of a tunnel measuring approximately 70-93 cm in diameter and around 100 m in length. The annular gap between the metal casing and the clay rock is filled by a material imposes corrosion-limiting environmental conditions (cement and bentonite mixed-based grout, etc.). One of the key parameters in HLW retrieval operations is the evolution of the casing's diameter. In fact, the gap between container and metallic liner should be large/big enough to handle the canister.

Optical fiber sensors (OFS) are one of the fastest growing and most promising researched areas, due to their features of durability, stability, dimension (small diameter, long distance) and insensitivity to external electromagnetic perturbations, which makes them ideal for the long-term health assessment of engineered structure. The thousands of sensing points that the Distributed optical sensors techniques (Rayleigh or/and Brillouin techniques) can provide enables mapping of strain distributions in two or even three dimensions. Thus, real measurements can be used to reveal the global behavior of a structure rather than extrapolation from local point measurements.

This first demonstrator is the "AHA1604" experiment with a 112 m depth excavated borehole in 2017. One sleeve element of the casing has been instrumented for ovalization assessment. In addition, three longitudinal OFS cables, dedicated to temperature and axial strain measurements, have been installed at the external face of the casing along 15 m according three positions. Results obtained in the framework of this demonstrator allowed improving installation design of OFS longitudinal cables and optimization of acquisition parameters for grout injection monitoring of the gap between the casing and the host rock.

The second demonstrator is "ALC1605" with about 30 m of excavated borehole in 2018. The same configuration has been installed for ovalization monitoring with, for this second test, two sleeve elements similar to the one instrumented in AHA1604. In addition, three longitudinal OFS cables according to three positions were installed with optimization of OFS cables protections, taking advantage of the design evolution. Indeed, it has been added skates to center the casing in the borehole, which allow easier and safer emplacement of OFS cables at the external face of the casing. Although, all cables were protected, steel half shells used for AHA1604, which are no more necessary for the new design of ALC1605, were kept for the top cables only. As this second demonstrator is dedicated to heating test (heaters will be placed inside the casing to simulate thermal load of HLW) a new OFS cable has been developed to resist to 90°C (maximum temperature expected at the outer face of the casing). Additional tests on specimens are planned, in controlled thermomechanical conditions, for OFS cable performance assessment.

Several measurements were analyzed and first results are promising. For instance, real-time strain and temperature measurements were obtained during grouting phase for ALC1605, as monitoring of AHA1604 allowed determination of the best parameters for grout monitoring. The data will be acquired for several years in order to assess behavior over time, especially when the heaters will be placed inside the casing. The thermal effects on strains and ovalization will be determined in order to be removed. This will allow better understanding of the casing's behavior

WP5: EFFECTIVELY ENGAGING LOCAL PUBLIC STAKEHOLDERS IN R&D ON MONITORING FOR GEOLOGICAL DISPOSAL

Repository monitoring is a subject of interest for a wide-range of stakeholders. In particular, public stakeholders may expect monitoring to provide continuous information on repository performance. As such, early involvement of public stakeholders may improve their confidence in the monitoring program, as well as make clear what their concerns and expectations regarding such a program are. The focus specifically was on the challenge of involving local public stakeholders, that is to say, people in concerned communities (either potential repository host communities, or communities hosting an underground research laboratory (URL)). They represent the most directly concerned public, but are often the furthest away with regard to RD&D activity and the development of the technology with which they will eventually be confronted. The objectives of WP5 were:

- To actively engage local public stakeholders in repository monitoring RD&D within the Modern2020 project, and to analyse the impact this has on both the participating stakeholders' and the project partners' understanding of, and expectations regarding, repository monitoring.
- To define more specific ways for integrating public stakeholder concerns and expectations into specific repository monitoring programme.
- To develop ideas on how to ensure accessibility and transparency of monitoring data (of the type gathered through in-situ monitoring) to public stakeholders.
- To learn lessons on how local stakeholder groups could be engaged effectively with RD&D programme and projects at an EU level.

Various Forms of Engagement

To this end, local stakeholders (from Belgium, Finland, France and Sweden) have been involved in the project in different ways:

- A small core group of engaged community representatives regularly attended project meetings and workshops organized at the European level.
- Additionally, workshops (or so-called 'home engagement sessions') were set up in the home communities of the interested public stakeholders in order to discuss their concerns and opinions about monitoring in nuclear waste repositories.
- The same local public stakeholders were offered the possibility to further share experiences and opinions about their involvement in the project by participating in an online interactive survey, organized in two rounds, to which all Modern2020 colleagues also participated.
- Furthermore, the local stakeholders were given the opportunity to enter into discussion with the technical representatives from Modern2020 project in a workshop specifically designed to this end as a space of mutual understanding.
- Lastly, the local stakeholders were regularly consulted for feedback on a 'stakeholder guide' (see infra), as well as on other output produced in the project (such as workshop and research reports).

Honesty abides to admit that engaging citizens in a very expert driven technical research project was not always easy. Particularly, as the Modern2020 project explicitly chose to have these local public stakeholders participate in the actual project, in direct interaction with the (technical) researchers. For one, the choice to approach specifically directly concerned citizens implicated in national waste management programmes, meant that we had to take into account developments at the national level. This for example led to a late entrance of French stakeholders in the project or to a temporary hold in participation of the Swedish stakeholders at the time of the hearings of the Environmental Court. Also, the place of a research project does not necessarily coincide with the agendas of the local communities and the availability of their representatives. Furthermore, the nature of the project made many discussions and project related documents very technical. Both of these had a clear impact on the extent to which community representatives could attend Modern2020 project meetings of various work packages and the time and ability as well as interest they had in reading up material beforehand.

In the following section, we will focus on one specific result from the inter- (contribution from various scientific disciplines) and transdisciplinary (inclusion of concerned actors) approach taken in Modern2020, namely the development of a 'stakeholder guide'.

A Stakeholder Guide on Monitoring and Public Participation in GD

As part of WP5 the sociologist affiliated with the Modern2020 project coordinated the production of an (on-line) local stakeholder guide to repository monitoring in the context of geological disposal of high-level nuclear waste. This took place in collaboration with the technical experts and stakeholders involved in the project. The stakeholder guide is not only meant to communicate the state of the art on geological disposal and repository monitoring to a non-scientific audience. It should also serve to facilitate discussion between scientists and a variety of publics (citizens, policy-makers, Nuclear Waste Management Organizations and journalists) about various, often interrelated technological and social concerns. In fact, the production of the guide has itself been an exercise in stakeholder participation that aims to clarify the different societal perspectives, interests and concerns surrounding repository monitoring.

Figure 6: Illustration from the stakeholder guide

Conclusions

Modern2020 reached a broad approach to developing a monitoring programme to support the post-closure safety case and to provide input to decision-making. The documentation produced within Modern2020 provides an background for each national repository programme to develop a detailed monitoring programme taking their boundary conditions into account..

References

[1.] www.modern2020.eu

[2.] Modern Synthesis report, 2014

[3.] IAEA (1991): Guidelines for the operation and closure of deep geological repositories for the disposal of high level and alpha bearing wastes, IAEA-TECDOC-630, International Atomic Energy Agency,Vienna, October 1991

[4.] IAEA (2001): Monitoring of geological repositories for high level radioactive waste, IAEA-TECDOC-1208, International Atomic Energy Agency,Vienna, April 2001

[5.] IAEA (2014): Monitoring and Surveillance of Radioactive Waste Disposal Facilities, Specific Safety Guide No. SSG-31, International Atomic Energy Agency,Vienna, 2014

[6.] EC (2000): Concerted action on the retrievability of long-lived radioactive waste in deep underground repositories. EUR 19145 EN, European Commission, Brussels

[7.] EC (2004): Thematic Network on the Role of Monitoring in a Phased Approach to Geological Disposal of Radioactive Waste, Contract No. FIKW-CT-2001-20130, Final report, EUR 21025 EN, European Commission, Brussels

[8.] IAEA (2011). Disposal of Radioactive Waste. IAEA Specific Safety Requirements, No. SSR-5, IAEA Vienna.

[9.] IAEA (2012). The Safety Case and Safety Assessment for the Disposal of Radioactive Waste. IAEA Specific Safety Guide, No. SSG-23, IAEA Vienna.

[10.] EC (2013): MoDeRn - Monitoring in Geological Disposal of Radioactive Waste: Objectives, Strategies, Technologies and Public Involvement. Proceedings of an International Conference and Workshop, Luxembourg, 19 – 21 March 2013, European Commission, Brussels

[11.] NEA (2014): Monitoring of Geological Disposal Facilities: Technical and Societal Aspects, NEA/RWM/R(2014)2, Paris, February 2014

[12.] Farrow, J., White, M., Chabiron, A., Jobmann, M. and Gazul, R., Frieg, B., Hart, J., Rosca-Bocancea, E., and Schröder, T., Wildenborg, A., Karvonen, T., Pere, T., and Hansen, J., Reijonen, H., Morosini, M., Luterkort, D. and Vokal, A. (2019). Monitoring Parameter Screening: Test Cases. Modern2020 Project Deliverable D2.1.

[13.] MoDeRn (2013). Monitoring During the Stages Implementation of Geological Disposal: The MoDeRn Project Synthesis. MoDeRn Deliverable D6.1.

[14.] White, M., Farrow, J. and Crawford, M. (2017). Repository Monitoring Strategies and Screening Methodologies. Modern2020 Project Deliverable D2.1.

[15.] NEA (2014a). Monitoring of Geological Disposal Facilities: Technical and Societal Aspects. NEA Report NEA/RWM/R(2014)2.

[16.] MoDeRn (2013b). Technology Summary Report. MoDeRn Project

[17.] White, M., Farrow, J., Vivalda, C., Espivent, C., Frieg, B., Jobmann, M., Morosini, M., Simeonov, A. and Norris, S. (2019). Responding to Monitoring Results. Modern2020 Deliverable D2.3.

[18.] SEALEX in-situ experiments-performance tests of repository seals: experimental observations and modelling, Nadia Mokni and Jean-Dominique Barnichon, E3S Web Conf., 9 (2016) 04006

Session Two - Radioactive waste source term and science for final disposal

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Co-chair: Jean-Paul Glatz (DG JRC, EC)

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FISA 2019
EURADWASTE '19

4-7 June, 2019
Pitesti, Romania

Session Two Summary

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1 Scope

Session 2 of the EURADWASTE '19 conference related to the "Radioactive waste source term and science for disposal safety". The papers and presentations contained an overview of the science for the safety case in general and overviews of on-going and recently finalised EC projects related to post-closure safety. The panel discussed the current state of knowledge and the remaining challenges and the role of future coordinated activities. The papers, posters and presentations were of high quality; this also includes the contributions by PhDs. The discussions of the panel, during the poster sessions and during the breaks and the personal contacts made through the conference led to significant additional insight.

The summary below also takes advantage of the presentations, discussions and posters of the other sessions as far as they are of direct relevance for the topics of Session 2.

2 The development of the safety case and the importance of the underlying scientific basis

The methodology to develop a post-closure safety case is available and builds upon many years of experience and the numerous safety cases made in the different national programmes and also takes advantage of the work done within several international working groups and projects, e.g. by the EC, IAEA and OECD/NEA. The methodology is judged to be 'fit for the purpose'; this is also indicated by the successful use of safety cases for regulatory or government decision-making for HLW repositories (applications in preparation, under discussion, granted). By providing a suitable platform and methodology, the development of the safety case ensures the integration of the available scientific and technical understanding in a systematic and traceable manner into a set of arguments that should convincingly show that a repository will be safe for the period during which the radiotoxicity of the wastes disposed is of concern. A successful safety case has thus to be based on a sound scientific basis. The more advanced programmes developed such a scientific basis through a structured and goal oriented extensive research and development programme running over many years. For the safety case the information from a broad spectrum of sources (nature observations, results from lab and URL experiments, modelling, etc.) must be carefully analysed and – if needed – adapted to the specific properties and conditions of the repository analysed. This requires high quality interaction between the scientific community and those compiling the safety case – an area where the EC co-funded projects have been, and will continue to be, of high value by providing suitable platforms to interact.

Also, after receiving the construction and operation licence for HLW repositories, safety analyses and safety cases will be periodically updated up to the time of closure of the repositories. This means that dedicated efforts have to be made that both the scientific basis for the phenomena relevant for safety and the methodology to compile the safety case remain 'state-of-the art' over many years. This requires specific knowledge management activities (i) to remain 'state-of-the-art' taking advantage of information and knowledge available from specific research but also from research outside the waste management community, (ii) to transfer knowledge from one generation to the next within an organisation and (iii) to transfer knowledge between waste management programmes (incl. transfer from more advanced programmes to less advanced programmes). Due to the rather specialised knowledge and competences needed – geological disposal has to consider also some rather specific issues – specific measures may be needed to maintain also in future a high level of competence by attracting bright scientists. To achieve this, international cooperation will most likely play an important role.

3 Projects presented on repository science: an overview

The projects presented in Session 2 cover important areas for the post-closure safety case. They all focus on the near field of repositories. Some of the projects (CAST, CEBAMA and MIND) are relevant for both HLW and L/ILW, whereas REDUPP and DisCo are related to the disposal of SF and BELBaR/BEACON has the main focus on the buffer material for HLW but is also of relevance for sealing of all types of repositories. Most of the projects could build upon results of earlier projects (either within the EC framework or within national programmes).

This is the case for the dissolution of UO_2 fuel, where REDUPP extended the understanding of UO_2 dissolution and where DisCo will provide important contributions by complementing the existing knowledge on the dissolution behaviour of UO_2 to also allow the detailed evaluation of the dissolution behaviour of other fuel types (doped fuel, MOX). Looking at the release of C-14, some results were available for CAST from the EC-project CARBOWASTE and from work on the release and speciation of C-14 done within some national programmes. Also for BELBaR/BEACON, CEBAMA and MIND it was possible to build upon the results of earlier work done in different national programmes.

Most projects use a combination of experimental work and (process) modelling. This is considered to be important and valuable. The experiments provide hard evidence for the experimental conditions and the modelling helps to develop and test underlying (model) assumptions that are then used to transfer the observations from experiments to the specific properties and conditions of the repository analysed and to make – if needed – extrapolations to capture changes in properties due to long-term evolution. The models are also used to provide input to sensitivity studies for the post-closure safety case.

The use of the results of these projects and their importance in the safety case depend to some extent upon the waste (reprocessing vs. direct disposal of spent fuel), the host rock (crystalline rock with channelled flow in fractures vs. diffusion dominated transport in clay stones) and the repository concept with its underlying safety concept (radionuclide containment within very long-lived SF containers vs. radionuclide retention mainly in the host rock). This aspect has been addressed explicitly e.g. within CAST where within one task the meaning of the new findings for the different programmes with their specific repository concepts was investigated.

As the community at large has a strong interest in the implementation of geological repositories and the corresponding work done, it is broadly acknowledged that the scientific information should be made broadly available. In agreement with the project proposals, all projects had a dedicated work package related to information dissemination.

For each of the projects some of these issues are discussed in some more detail below.

3.1 Specific remarks about BELBaR

The BELBaR project looked at the potential erosion of bentonite. Bentonite is used as buffer material surrounding the disposal canister. In host rocks with flowing water, depending upon the bentonite properties and host rock pore water chemistry, stable bentonite colloids may form and thereby contribute to bentonite erosion. This would affect the long-term evolution and performance of the bentonite buffer. Furthermore, stable colloids may act as radionuclide carriers and thereby affect radionuclide transport, depending upon reversibility and kinetics of sorption and de-sorption. These phenomena are mainly relevant for host rocks with fracture flow (limited filtration of stable colloids) and have been, and are being, considered within individual national programmes. However, due to their importance it was decided to conduct a joint project to improve the detailed understanding and modelling capabilities within EC FP7. The project largely confirmed the understanding of colloid stability, colloids only form under unfavourable conditions. For the description of erosion, new information became available and may need some additional study. With respect to radionuclide transport, reversibility of sorption was broadly confirmed. The BELBaR project came to an end in 2016.

3.2 Specific remarks about BEACON

The BEACON project looks at the evolution of key mechanical properties of the bentonite. In addition to being a buffer material surrounding the disposal canister, bentonite is also used as backfill and sealing material. Some of the beneficial properties of bentonite are related to its pore structure (e.g. its ability to limit microbial activity and to provide excellent barrier properties). To ensure that the beneficial properties of bentonite are effective within all of the bentonite, homogenisation of existing heterogeneity is important. Heterogeneity arises e.g. due to gaps between bentonite blocks or between the bentonite blocks and the host rock or due to the pore space between bentonite pellets and due to heterogeneity in density and compaction at the time of emplacement. Gaps and heterogeneity may also arise due to deformation or mass loss due to erosion. The process of homogenisation and self-sealing due to water uptake and swelling and expansion of the bentonite into open or less compacted space is thus important and has been observed in experiments (including observations when dismantling large-scale URL experiments). However, detailed modelling of this process is complex (e.g. dependent upon stress path) and has been limited up to now. The modelling capability is important for the design process to develop the detailed requirements for the emplacement process (incl. QA measures) to ensure that the required properties of the bentonite will be achieved without using overly conservative/ambitious specifications. The aim of BEACON is to improve the detailed understanding and modelling of homogenisation of initial and/or evolving heterogeneity. For this purpose, existing data are revisited and new experiments are proposed. Then, the models and tools are further developed and tested with existing and in future with new experimental data. The analysis of existing data from the viewpoint of homogenisation and the modelling of these experiments has already given some new insights. Work within BEACON is still underway and will be finalized in 2021.

Homogeneity of highly compacted bentonite will ensure that solute transport will be diffusive and its small pore size will strongly limit or suppress microbial activity – issues that are important for repository concepts that strongly rely on radionuclide containment within the system of engineered barriers. However, the understanding of homogenisation and the ability to capture the corresponding key phenomena by modelling is important for all applications of bentonite to develop emplacement procedures that ensure that the required performance of the bentonite will be met without overly conservative specifications.

3.3 Specific remarks about CAST

The CAST project looked at the C-14 source term. C-14 can originate from different sources (corrosion of irradiated/activated metals (e.g. fuel cladding (zircalloy), activated metals (different steels) from decommissioned nuclear facilities, irradiated graphite, ion exchange resins, etc.). Measurements indicate that some of the released C-14 species are organic and show hardly any retention in contrast to inorganic C-14 with strong retention e.g. in cementitious environments. Because there is a significant C-14 inventory in many repositories, the release of non-retarded C-14 can be relevant for safety. Because the understanding and the experimental data on the release, speciation and sorption of organic C-14 available from earlier projects was still limited, it was felt worthwhile to expand the data base and understanding with a joint project as the challenges of the experimental work are significant and strongly profit from a coordinated approach.

For assessing the release of C-14, the following two issues are of special relevance: The rate at which C-14 is released from the waste matrix (for example, as determined by the corrosion rate of an irradiated metal and – if relevant – by the instant release fraction), and the speciation and mobility of the C-14 released into the porewater (with both organic and inorganic compounds). The CAST project provided data and information on C-14 release rates from the range of source terms studied, and showed that there is still significant uncertainty in the fraction of organic C-14 released into the porewater; thus, a non-negligible fraction of organic C-14 has to be assumed within safety analyses. Furthermore, CAST confirmed the earlier findings that there is no strong basis available to assume significant retardation of organic C-14. However, CAST also confirmed the low corrosion rates for irradiated metals – this is important, as it is associated with low release rates of C-14. This, however, does not apply to spent ion exchange resins containing C-14, where release rates were found to cover a wide range, dependent on the spent ion exchange resin investigated and its operating history.

The importance of C-14 for post-closure safety depends upon its inventory and the barrier concept of the repository analysed. In the case of zircalloy (fuel cladding) the fuel cycle and the concept of engineered barriers chosen (reprocessing and disposal of zircalloy as ILW vs. encapsulation of SF in very long-lived canisters or in canisters with a lifetime of only a few hundreds of years) have a big impact on the importance of C-14 release. In the case of reprocessing, C-14 can play a significant role; this is also the case for a direct disposal concept, in which no very long-lived canisters would be chosen for the spent fuel. In case of spent fuel encapsulated in very long-lived canisters, release of C-14 has no importance (except for the cases of assumed early canister defects). The importance of C-14 for safety is also strongly influenced by the type of host rock (e.g. fractured rock with groundwater and gas movement in open fractures vs. clay rock with diffusion dominated transport). The different aspects that affect the importance of C-14 for safety were explicitly addressed within CAST.

3.4 Specific remarks about CEBAMA

The CEBAMA project looked at cement properties and barrier functions in repository environments. In L/ILW repositories, cementitious materials are used for solidification of the waste, for disposal containers and as backfill. Furthermore, cementitious materials are used for construction of the disposal rooms (liner) and of other structures both for HLW and L/ILW repositories. Thus, the impact of cementitious materials on radionuclide retention (sorption, low solubilities) is an issue to be considered. Activities related to the development of sorption and solubility data bases for cementitious materials have been going on for many years and have been used in many safety analyses, also for licence applications. Because some progress is still made in the understanding of cementitious materials and their long-term evolution and their chemical properties, it was considered worthwhile to again look at radionuclide retention for some example elements within a joint project with the main emphasis on the less-investigated anionic species.

It is also well known that clay minerals are not stable if exposed to high pH porewater, and also cement minerals will degrade when exposed to typical host rock porewaters. Thus, the impact of the interaction between clay materials and cementitious materials through their respective porewaters needs to be considered. In several programmes this issue has been studied already for a long time. Nevertheless, it was judged worthwhile to expand and consolidate the knowledge in a joint project with a focus on the long-term evolution of the pH and the interface between concrete and clay materials. As already done in several national programmes, the value of so-called low pH cements was also investigated, both experimentally and by modelling.

For both topics experimental and modelling work has been conducted within CEBAMA. The results broadly confirm the conclusions from earlier projects although more details have been developed and a better understanding has been reached.

The importance and the role of the phenomena studied within CEBAMA differ between the different repositories as there are significant differences in the use of cementitious materials as liner/support of the disposal rooms/holes and of cement-based grouts and their impact on the bentonite buffer material and on the host rock. The earlier understanding that the impact of cementitious material on clay stones is limited to a small region just around the underground constructions has been confirmed and is thus of no significant concern for host rocks of sufficient thickness. The changes at the interface between cementitious material and clay material will lead to changes in porosity and other (radionuclide) transport parameters and are as expected. They are incorporated in performance assessment. The impact of a cementitious liner on a bentonite buffer, however, was not specifically investigated within CEBAMA but the information provided by CEBAMA can be used also for this purpose.

3.5 Specific remarks about REDUPP and DisCo

The REDUPP project was concerned with the dissolution of spent fuel (UO_2), while DisCo has a wider scope and includes the dissolution of doped fuel and MOX. In the case of direct disposal of spent fuel, after failure of the canister slow fuel dissolution is a very important mechanism for limiting the release of radionuclides. In case of slow dissolution rates, the releases are very small except for the instant release fraction (e.g. investigated within the EC project 'First Nuclides').

Spent fuel dissolution has been studied for many years in different national programmes and also in earlier EC projects (e.g. SFS, MICADO). Within REDUPP (part of FP7), the effect of the surface characteristics of the experimental material and groundwater composition has been investigated in more depth. To improve the detailed understanding, experiments were made with synthetic material and molecular modelling was used.

The work up to the end of REDUPP was mainly focussed on the dissolution of UO_2. Within DisCo the focus is on doped fuel and on MOX to investigate the effect of 'additives' on fuel dissolution. Also within DisCo synthetic material, complementary to spent fuel dissolution experiments, is used for experiments to enhance the detailed understanding of some phenomena of relevance for the dissolution behaviour. Both in REDUPP and DisCo the experimental programme is complemented by model development and modelling studies to improve mechanistic understanding. This is important when using the experimental findings to quantify long-term fuel dissolution rates in different environments and for the evaluation of the sensitivity of fuel dissolution e.g. in case of changes of the in-situ conditions.

Based on the many years of research in this area, a good understanding of fuel dissolution is now available. It is clear that oxidation of UO_2 is very important for fuel dissolution and that oxidation needs to be suppressed to reach very low dissolution rates e.g. by hydrogen from corrosion of iron (e.g. from the canisters). The work in DisCo to complement the knowledge on the dissolution of MOX and doped fuel to confirm the applicability of the basic concepts of dissolution of UO_2 also for these fuel types is still underway; DisCo is expected to be finalised in 2021.

Fuel dissolution is important for all repositories with spent fuel. For programmes that rely on reprocessing, this work has no direct relevance.

3.6 Specific remarks about MIND

The MIND project looked at microbial processes of relevance for geological disposal. Microbial activity must be considered when looking at chemical reactions and reactive transport. Microbial activity enables chemical reactions to take place that would otherwise not occur (kinetically hindered reactions). Some of the reactions potentially affected by microbial activity are important for post-closure safety, some of them being positive for safety, others not. These include degradation of organic material, decomposition of gases generated by degradation/corrosion, corrosion of metals (e.g. canister) and the potential impact of these processes on the long-term evolution of buffer and backfill materials. The processes occur mainly in the nearfield (engineered barriers and the interface with the host rock), but may also occur within the host rock. Observations show that under certain conditions microbial activity is strongly limited, and some reactions that would otherwise occur are limited or do not occur at all (e.g. in a cementitious environment with its (initial) high pH, in highly compacted bentonite with its small pores and limited water activity, in clay stones with their very small pores). Thus, one of the main aims of MIND was to develop a better understanding of conditions under which microbial activity will occur, will be limited or will not occur at all. This may also require consideration of heterogeneity with the potential to form niches with a different micro-environment as locations with microbial activity (with their overall impact also depending upon transport phenomena connecting these niches with the bulk material).

MIND offered the opportunity to bring together the different researchers into one project to integrate the knowledge and views of the different research groups. It looked at the degradation of organic materials and corrosion of metals in a cementitious environment typical for L/ILW repositories leading to degraded solids, corrosion products and gases that again may be affected by microbial activity, e.g. the consumption of some of the gases by microbial activity.

MIND also looked at the possibility of corrosion of metallic canister material embedded in bentonite in HLW repositories e.g. due to the potential reduction of sulfate to sulfide by microbial activity (in the geosphere or in the bentonite), with the possibility that this process does not occur due to suppression of microbial activity. For this purpose, a range of microbially supported processes were considered. Furthermore, the potential of bentonite degradation due to processes affected by microbial activity was also being looked at.

As with many other processes, also for the ones considered here it is important to have a sufficient understanding that allows the observations (and derived conclusions) made, e.g. with experiments, to be transferred to repository conditions taking into account also their temporal evolution. This may also require some modelling capabilities.

The work in MIND has broadly confirmed earlier findings, but for some issues more detailed information and better understanding is now available. To fully integrate the knowledge on microbial processes in the design of the repositories and the subsequent development of the safety case, a close interaction between microbiologists and specialists on the system of engineered barriers is essential.

4 Observations and conclusions

- The work done in the projects discussed in Session 2 is in line with the overall aim of Horizon 2020 to **increase the knowledge to start the safe operation of the first HLW repositories** in the advanced Member States within the next decade. The knowledge will also **support the other Member States** in advancing their national programmes in an efficient and timely manner.
- To achieve this goal there is a strong need for a sound scientific and technological basis and the ability to compile convincing post-closure safety cases for the licensing of these repositories. Work in this direction is well underway as can be seen from the projects discussed at the conference, from the projects conducted world-wide and from the progress made towards licensing and implementation of the first HLW repositories.
- For the advanced programmes with their specific repository projects the **knowledge available is considered to be sufficient to start implementation** although it is acknowledged that there are still issues that need further work.
- The areas chosen for the **cooperation projects within Horizon 2020** are **clearly focused** and their choice is **based on the needs of performance assessment** and focus on specific processes of importance for the **post-closure safety case**.
- The **coordinated approach** is advantageous as it ensures the **interaction between specialists** to take advantage of their special knowledge related to nature observations, experiments and modelling **and the end-users** to achieve a solid mutual understanding and to allow cross-fertilisation to develop new insights. This **'working together' in joint projects** is considered at least as important as the economic advantages. Furthermore, the projects also provide the possibility for education through PhD projects; this was the case in all projects discussed. However, the potential diversity in interests and background of the participants in larger projects can also be a challenge for managing such projects.
- All projects could to some extent build upon available experience and results and information from earlier projects. **None of the projects fundamentally changed earlier understanding**, but refinements have been made and a better understanding has been reached in all projects discussed, leading to an enhanced level of confidence.

- Some of the projects (e.g. BEACON) have a **direct impact on the implementation** of the repositories. This type of projects shows the importance of thinking about the 'industrialisation' of implementation not too late in the programme.
- The **direct relevance and the role of the different projects** depend on the specific repository considered (waste (reprocessing vs. direct disposal), host rock (advective transport in fractures in crystalline rock vs. diffusive transport in clay stones), the system of engineered barriers (e.g. very long-lived canisters vs. shorter lived canisters), etc).
- Most projects include **experimental work and modelling activities**. This is important as adequate models help to transfer the evidence from experiments and from other observations to the in-situ conditions of the repository analysed. The models also support the extrapolations of experiment observations and other observations to capture long-term evolution of the repository. Models can also provide information for sensitivity studies as part of the post-closure safety case.
- After completion of a project, often some uncertainties will remain. Whether these **uncertainties are acceptable or not**, needs to be analysed within specific performance assessments and post-closure safety cases as the importance of remaining uncertainties depends upon the whole repository system and cannot be judged for one process alone in isolation. Thus, projects coming to an end should specify remaining uncertainties in a manner that allows such analyses.
- This points to the **importance of performance assessment** and the development of post-closure safety cases that have the task, for a specific repository project, to provide an integrated view on post-closure safety based on the current scientific understanding of the phenomena relevant to safety. This also requires addressing the role and importance of uncertainties.
- As science will continue to evolve further also after the start of operation of a repository, there is a need to **maintain oversight and knowledge** in those areas of science that are important to post-closure safety until closure of the repository. Because each repository project is to some extent a 'first-of-its kind' undertaking, each programme should as a minimum be able to **act as a 'competent client'** and have the capability to collect and assess the information relevant for safety in an adequate manner and to compile a safety case taking into account the specific nature of the repository analysed.
- This points to the **importance of knowledge management** (the detailed understanding of the 'what', 'why', 'for whom' (identified end users with their specific needs), 'when', 'how', 'by whom' and 'with what level of detail'), being the far bigger challenge than information management (ensuring that the information stays accessible, can be found and be read). Knowledge management has to ensure that the necessary 'state-of-the-art' information is collected and stays available over time, but most importantly it includes the transfer of practical 'hands-on' knowledge and understanding on how to use this information (the 'what', 'why', 'for whom', 'when', 'how', 'by whom' and 'with what level of detail') both within an organisation from one generation to the next as well as between organisations (and also from more advanced programmes to less advanced programmes).

  Knowledge management has to ensure that progress in science and technology is captured and that any new relevant findings are adapted for their application for the repository at hand. This also requires **ensuring the availability of specialised knowledge** about the use and application of scientific issues that are not broadly looked at otherwise and are thus not directly available on the 'market'. Finally, the need to maintain the capability for independent peer reviews should also be adequately considered.

All these issues require maintaining a repository related scientific community by engaging bright scientists in a coordinated manner. This are issues where future cooperative activities will play an important role.

- Besides its impact on the development of repository projects and the corresponding safety cases, the work done in the science and technology projects is also of **importance for society at large** (including the broad scientific community) and especially for the local communities hosting the repositories. Society’s understanding of the work done to develop science and technology and direct contact of the local population with the people doing the work is important to build up a relation of mutual trust. This is essential for the success of implementing the repositories. Thus, all projects have to give **sufficiently high priority to the dissemination of information** in a manner suitable for society at large. This also requires to put the results of a project into a broader context.

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SCIENCE UNDERPINNING THE SAFETY CASE OF DEEP GEOLOGICAL REPOSITORIES – CHALLENGES IN THE PAST AND IN THE FUTURE AND HOW TO MAINTAIN KNOWLEDGE AND COMPETENCE DURING OPERATION

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Abstract. Final repositories for spent nuclear fuel are approaching implementation. A prerequisite for these advancements is that it has been shown that the repository can be constructed and operated in practice in such a way that safety can be assured both during operation and over very long time scales. The success rests on decades of structured and objective driven research and development. A key element of the research strategy has been to ensure adequate in-house competence and expertise. Also openness and international cooperation are essential. Workable procedures for data qualification, version control as well as internal and external peer review have gained importance. When the programmes now enter a new phase of construction and operation new challenges will arise. Even if the implementing organizations would need to keep a core competence on post closure safety assessment international cooperation will be even more important on developing, sharing and managing the knowledge needed.

1. INTRODUCTION

Final repositories for spent nuclear fuel are approaching implementation. In 2011, SKB applied for a permit to build a KBS-3 type final repository for spent nuclear fuel at the Forsmark site. The application has now been examined by the Swedish Radiation Safety Authority (SSM) under the Act on Nuclear Activities and by a Swedish Land and Environmental Court under the Environmental Code. On January 23 2018, SSM and the Court both issued their statements to the Swedish Government. SSM recommends the Government to grant permission for a final repository at the Forsmark site. It also points to issues that SKB needs to resolve in coming phases of the step-wise licensing process under the Act on Nuclear Activities. The Land and Environmental Court approved in its statement parts relating to the choice of Forsmark as the site for the repository, post-closure aspects related to the rock and the buffer and the environmental impact assessment. It also considered that supplementary information regarding five issues related to the long-term integrity of the copper canisters be presented and evaluated before permission is considered. In March 2019 SKB submitted supplementary material, as requested by the Government, demonstrating that these issues do not jeopardize the post-closure safety of a

KBS-3 repository at the Forsmark site. The matter now rests with the Government. Construction of the repository may start around 2023 and operation may start early 2030, provided the Government grants a decision during 2020. In Finland, a KBS-3 type repository for the spent fuel has obtained a construction license in 2015. Provided licenses are approved operation may start around 2024.

An application to expand the repository for low-level operational waste was submitted in 2014. In January 2019 SSM recommended approval of license in its statement to the Land and Environment Court. The main hearing in Environmental Court will take place in late September 2019, statements to the Government may follow late 2019 and a government decision may be at hand during 2021. Regarding the long-lived intermediate level wastes a safety assessment of a conceptual repository design will be presented during 2019. This will form the basis for further development of the engineered barriers, waste acceptance criteria, and the siting process.

A prerequisite for these advancements is that it has been shown that the repository can be constructed and operated in practice in such a way that safety can be assured both during operation and over very long time scales. The success of the programmes rests on decades of structured and objective driven research and development including both theoretical assessments and practical test in the laboratory and in full scale. This has been possible by a dedication to bring the repository programme to a conclusion with a structured siting strategy, sufficient and long term funding, and a clear strategy for research and development

2. Research strategy

2.1. Objectives

Research has been, and still is, one of the pillars in SKB's programme since its start in the 1970s. The objective of SKB's research programme is to secure safe management and final disposal of nuclear waste by ensuring access to the knowledge that is needed in order to assess a site, design, licence, construct and operate existing and planned facilities. This means that the research should:

- provide sufficient knowledge of post-closure safety and make sure that safety can be assessed for SKB's existing and planned facilities also in the future,
- provide sufficient information for the continued technology development and planning that is needed in order to obtain efficient and optimised solutions that at the same time provide safety both during operation and after closure of SKB's final repository.

2.2. Iterative development of safety case, requirements and design

SKB's programme has developed iteratively where repository designs are evaluated in safety assessments that in turn provide feedback to technology development, design and requirements, see Fig 1. At early stages, i.e. at the presentation of the KBS-3 concept [1] initial conceptual design and low resolution site data from study areas were used as inputs to safety assessments that in turn provided guidance for the future R&D. Since the start of the siting programme around 1992 safety assessment also provided input to determining siting factors [2] and guidelines to the surface based site investigations carried out during the years 2002 to 2008 [3].

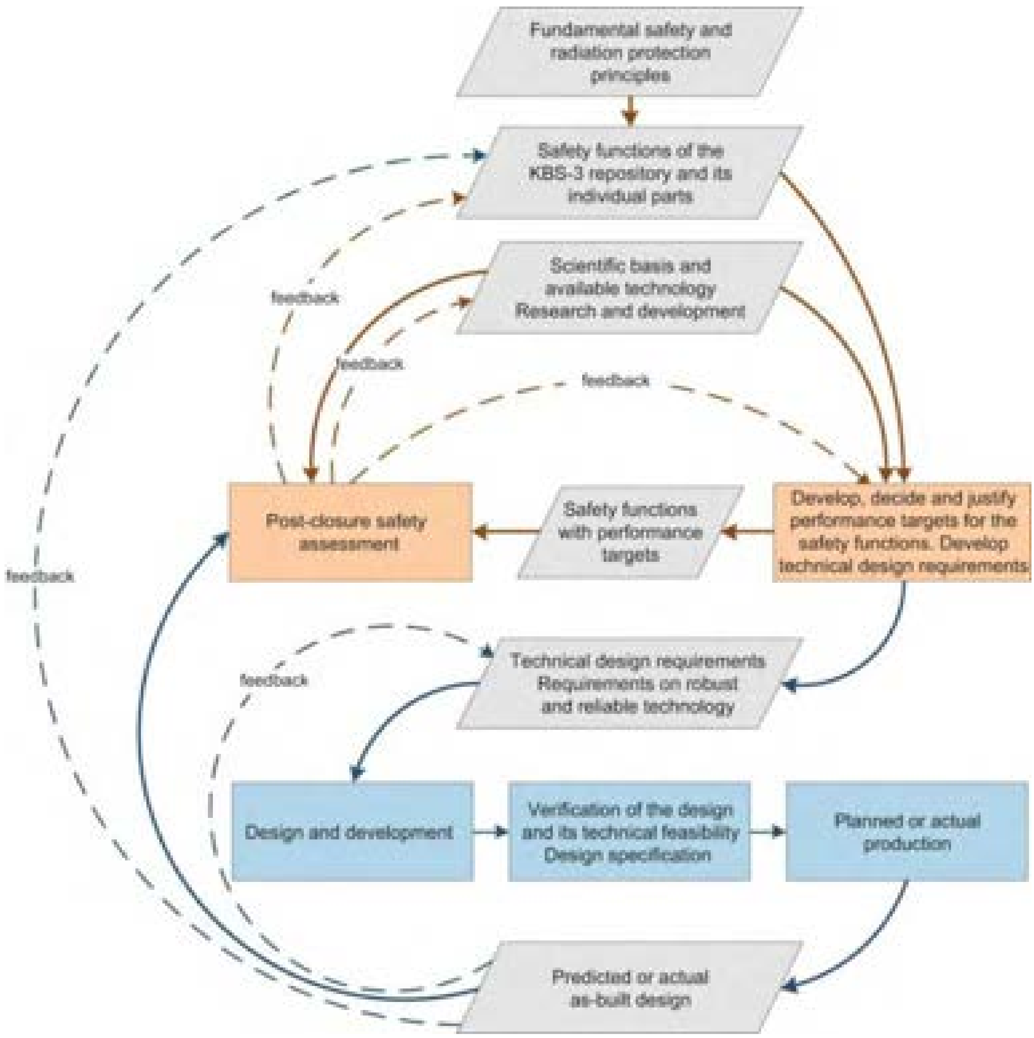

FIG. 1. The iterative process of design and safety assessment [4].

At the time of the submittal of the license application SKB presented a complete safe case, SR-Site [5] constituting the basis of the application. The SSM has reviewed the safety case and while they recommend a license SSM has also identified a long list of detailed issues that need to be resolved prior to operation [6]. Provided SKB's application is accepted by the Swedish Government SKB will then update this safety case into a formal Preliminary Safety Analysis Report (PSAR) also supported by updated requirements and more detailed designs, to be submitted to SSM as a basis for obtaining a license to start underground excavation.

At later stages the PSAR will be updated to a safety analysis report (SAR) that will form the basis for the construction and operation of the repository. Each decision step for a final repository requires an assessment of post-closure safety and prior to each decision the regulator (SSM) is expected to judge whether the knowledge base concerning post-closure safety is sufficient for SSM to approve that SKB should proceed to the next step.

2.3. In-house competence

A key element of the research strategy has been to have sufficient in-house competence in order to maintain its ability to assimilate the knowledge that is present in the community of importance for management and final disposal of nuclear waste, and to be a skilled research client. While a repository programme will need input from a very wide range of scientific and technical disciplines the core of the in house competence has been to maintain a coherent group of professionals with knowledge of the methodology for the assessment of post-closure safety with both wide and deep interdisciplinary insight on how the different processes that affect repository safety interact. Furthermore, by conducting its own research, SKB has ensured this maintenance of competence.

2.4. Openness

Another bearing principle has been that all research should be publicly available and a strive to publish results in open peer reviewed journals. In communicating with the public though media, open seminars or other event SKB also makes sure to let the internal experts be the main spokespersons and to foster a frank and open discussion. Openness and an strive to demonstrate that there is nothing to hide, is judged a basis for developing confidence with the public, the research community and authorities.

2.5. International cooperation

In building up and maintaining competence international cooperation has been essential. This cooperation entails direct cooperation with sister organisations and using experts trained in other programmes as well as participation in the work of International organisations like the IAEA, OECD/NEA and the European Commission. These different international bodies all have their different benefits.

Direct cooperation with sister organisations, like the close cooperation between SKB in Sweden and Posiva in Finland or NWMO in Canada, allows for sharing resources and ensuring that the expertise involved reaches critical mass. Both IAEA and NEA have provided platforms for interaction with peers from sister organisations and also allowed interaction with regulators from other countries. Over the years these interactions have strongly advanced the understanding on how to conduct a repository development programme and how to carry out safety assessments. While the direct funding of research projects by the European Commission has primarily not been an important means of funding, it has allowed networking on a detailed level directly with a broad range of researchers and other experts.

3. Knowledge management tools developed

As the programme developed from feasibility studies and basic research into site characterisation, and repository design, requirements management, workable procedures for data qualification, version control as well as internal and external peer review gained importance. These knowledge management aspects imply a major undertaking and needs to be planned.

3.1. Data qualification

Safety assessment and design work involves several different teams using data on e.g. fundamental processes, site characteristics and design solution and these data originate from various sources of different quality. Furthermore, different teams may need data on the same aspects and phenomena.

When SKB updated the safety assessment methodologies in the mid 1990:ies it was realised that it is necessary to ensure that different teams use the same data for describing the same things and that the quality of the data are assessed as well as their uncertainties [7]. Strict procedures for data and uncertainty qualification were introduced by the concept of data reports [8].

3.2. Site descriptive modelling

When surface-based site investigations were commenced in 2001 the concept of Site-descriptive modelling (SDM) was introduced to provide a description of the investigated sites to be used both as input to the safety assessment and to the engineering design work [9, 10, 11]. Developing an SDM entails transfer of the information from quality-assured databases produced by the site investigations to discipline-specific descriptions applicable to various subdivisions of the system made up of surfaces and volumes. The underlying field data is in its nature often point-wise, varying both spatially and temporally. Evaluation of uncertainties in values of parameters describing the material properties and states of the studied system and the realism in the subdivision of the studied system are central in the analyses. Included in the SDM work is control of primary data, followed by disciplinary and interdisciplinary integrated modelling providing basic geometrical descriptions and parameterisations of the bedrock and the surface system. Due to its nature and its uses, development and updating an SDM forces interaction, not only between experts from different geoscientific disciplines, but also between these experts and designing engineers and safety assessment teams.

3.3. Peer review

Both internal and external peer review are essential quality assurance tools. Starting with the site descriptive modelling works in 2001 SKB has developed and applied strict protocols for these reviews. Review plans are established defining the review criteria and the qualification of the reviewer. A review is conducted using standardized protocols where the reviewer both makes an overall assessment against the review criteria stated in the review plan and provides detailed comments. In completing the reviewed document the reviewee needs to respond to every such comment in writing. While these procedures may have been regarded as tedious in the beginning, they are now seen as essential and a safeguard against the many mistakes that otherwise would have been made.

3.4. Requirements and quality control of production and installation

Confidence in the post-closure safety assessment rests upon

– a sufficient understanding of the Thermo, Hydro, Mechanical, Chemical and Biological processes determining the evolution of the repository system, thereby providing a necessary basis for demonstrating the repository's ability to provide adequate containment and retention, and

– a demonstration that the installed engineered barriers and the underground construction work conforms to stated technical design requirements.

For the former, the thorough process understanding achieved by decades of research is complemented by a research program tailored to the specific conditions at the chosen site. For the latter a Quality Control programme is being developed. This implies possibilities to find potential manufacturing or installation errors or other deviations in material, equipment and handling. Before and during waste emplacement, quality control provides the main source for ensuring that the as-built stage complies with stated design requirements.

The basis for the Quality Control is that there are well-defined technical design requirements against which the compliance can be checked. Formulation of design requirements is not trivial. From the Safety Assessment perspective they should be sufficient to yield a safe repository. From the designers perspective they need to be possible to implement and verify. It is easy to formulate rules that would lead to safety, but are impossible to implement and verify. Iteration and "negotiations" between safety assessment and design work is needed.

An initial set of design requirements were specified in SKB's license application for the spent fuel repository [12]. These concern what mechanical loads the barriers must be able to withstand, limitations concerning the composition and properties of the barrier materials, acceptable deviations in the dimensions of the barriers and acceptance criteria for the various underground openings.

Together with Posiva, SKB has presented revised technical design requirements for the KBS-3 barriers [4] based on the findings from the Swedish and Finnish Safety Cases on how the repository conditions affect the evolution of the safety functions, and experiences from the ongoing technology development. A Technical Design Requirement concerns the characteristics an engineered barrier or underground opening shall fulfil to be approved as a part of a KBS-3 repository. They should be derived such that if an as-built repository fulfils the technical design requirements it would help to show that safety function will be upheld in the long-term evolution. The requirements must be technically achievable and possible to verify at the latest at the time of final installation, deposition or backfilling.

4. R&D challenges in coming phases

When the programmes now enter a new phase of construction and operation new challenges will arise. While the fundamental questions regarding post closure safety should be resolved there is nevertheless a need to be prepared for and adopt new findings that might, somehow, jeopardise long term safety. Furthermore, implementation and optimisation of the new technologies may present new challenges where new research may provide essential input, although not necessarily in subject areas that traditionally have been judged important. With respect to the previous approach for producing a safety case there are some new aspects to consider.

4.1. Safety case needs to be up to date during the entire operational time

Although a central milestone in the level of knowledge is achieved when SKB obtains permissibility and licence to construct a new facility, the need to be able to make assessments on the safety of final repositories both during operation and after closure does not disappear. These assessments entail requirements of knowledge regarding how both the engineered barriers and the natural processes in the rock and on the ground surface interact and evolve in time. Furthermore, research and new findings regarding the long term properties will continue, both as projects driven by SKB, projects within other implementing organisations and in the scientific community at large. There has to be a readiness to assess the safety implications of such new findings. According to the regulations, the Safety Assessment Report (SAR) should be constantly kept up-to-date. In addition, a periodic overall evaluation of the safety and radiation protection of each facility should be made every ten years according to the requirements of the Nuclear Activities Act.

4.2. Access to detailed data from the underground and local adaption of the repository

Once construction starts there will be new possibilities for characterization and monitoring. Underground construction implies that volumes of the host rock that are hard to characterize from the surface will be accessible to mapping and (short) borehole investigation from the excavated underground galleries [13]. Furthermore, during operation parts of the repository will already have been constructed, characterised and filled with deposited canisters, whereas other parts are yet to be excavated (Fig. 2).

FIG. 2 During operation parts of the repository will already have been constructed, characterised and filled with deposited canisters, whereas other parts are yet to be excavated.

The importance of detailed characterization depends on host rock and repository concept. Crystalline formations are strongly spatially variable in the sense that they are intersected by fractures and deformation zones that never will be fully characterized. Data from detailed characterization are there essential for local adaptation of the location of deposition tunnels and deposition holes and ultimately to confirm site suitability since suitability would depend to what extent such local adaption is possible.

During underground construction in crystalline formations it will be possible to adapt the location of deposition tunnels and deposition holes with respect to local rock conditions. The inclusion and evaluation of such local adaption will be an important part of the safety case. Issues to consider for crystalline rock repositories include distance of the major deformation zones, location of deposition holes to ensure that these are not intersected by large fractures or fractures with potential for high water flow, selection of deposition tunnel orientation and geometry in relation to rock mechanical conditions, and to select a sufficient distance between the canisters to ensure that the bentonite temperature does not exceed the maximum allowed temperature.

Information will be continuously obtained while the repository is constructed and characterised. Pilot holes are planned to be drilled and assessed as a basis to decide whether to excavate a deposition tunnel in a particular part of the repository volume.

Excavated tunnels will be mapped and characterised. Pilot holes will be drilled and characterised in potential locations for deposition holes.

While scientific issues and much of the technology to be used for this detailed characterisation is the same as was applied during surface-based operation, there is a difference in scale and resolution to consider. Conditions underground, in particular recognising that characterisation will take place jointly with excavation work, imply practical limitations to characterisation such as limited time, high water pressures and confined spaces. Workers safety need also be handled and the methods applied need to be applicable in practice. Also the speed of interpretation and modelling is essential to ensure that findings from the characterisation really can affect the decisions they are supposed to support.

4.3. Monitoring during construction and operation

Underground construction will also disturb the host rock. Monitoring these disturbances and comparing them with the prediction of disturbances made from the understanding based on the surface data, may provide essential information on the site properties and ongoing processes. In addition, monitoring aspects of the evolution during operation may provide further insights. While monitoring results essentially never can relate to direct safety impacts, a management structure should be in place to handle situations when monitoring results deviate from expectations.

This implies an increased need to understand also the short term changes due to the excavation. A challenge with this approach is that many disturbances caused by underground construction are of a short term transient behaviour and would often be irrelevant once the repository is finally sealed and drainage is ceased. Nevertheless, these short term issues need further attention while still maintaining the basic principle that research should focus on issues relevant to safety.

4.4. Relation between operational safety and post-closure safety

Actions during operation should not only consider impacts on operational safety, but also consider how they might affect post-closure safety. While these two aspects of safety are usually not in conflict, there are a few examples of the opposite. For example, stable rock reinforcement is needed both for workers' protection and to ensure that there are no mishaps during canister emplacement, and the standard means of rock reinforcement may be detrimental to post-closure safety. Further research and development could be justified to resolve such potential conflicts.

4.5. Proved quality control as an essential part of the safety case

As described in section 3.4, Technical Design Requirements (TDRs) have been updated for all barrier components. However, it is still a challenge to ensure that the TDRs are technically achievable and possible to verify at the latest at the time of final installation, deposition or backfilling. Ongoing and future technology developments focus on these aspects.

Quality control implies an assurance that the requirements made on the facilities during operation and after closure of the spent fuel repository are satisfied. Important activities in this process are to establish:

- principles for safety and quality classification,

- what is to be quality-managed and quality-controlled, and
- when quality management and control are to be performed and by whom in terms of first, second and third parties.

This needs to be established in order to qualify processes, methods, equipment and personnel for fabrication and installation, testing and inspection.

Establishing and qualifying all aspects of the quality control system for the spent nuclear fuel repository is a considerable undertaking since many of the quality needs and requirements will be unique for the repository. With respect to the canister, this implies carrying out numerical design and damage tolerance analyses. The results are used to establish dimensions and material properties (including acceptable defect frequencies and sizes) required to provide sufficient resilience to mechanical loads in the repository.

These more specific requirements are used as input to manufacturing specifications and to define the defects that need to be detected in the production and to be controlled during manufacturing, encapsulation and deposition. Among issues to consider for the bentonite components there is a need to establish practical laboratory procedures for establishing that a specific bentonite shipment confirms to the empirical (but brand-independent) TDR:s. Challenges relating to underground construction and local adaptation have already been addressed in section 4.2, above.

4.6. Implementation and optimisation

While SKB has established a technically feasible reference design and layout, detailed designs adapted to an industrialised process designed to fulfilling the specific requirements on quality, cost and efficiency need still to be developed. These updated designs should result in at least the same level of safety as the current reference design and should be implemented in the various production systems needed for the repository. These include canister production, encapsulation of spent fuel, transport, bentonite production, underground excavation and deposition activities.

Constructing and operating the repository implies that many procedures will have to operate in conjunction. While each component and each subsystem may have been tested many times new challenges will arise when all these system should operate together and in accordance with the practices of operating a nuclear facility. This means that new development needs, or even needs to revise requirements, will arise during implementation and operation.

Optimisation is another driver for additional research and development. Due to the complexity of the technical and scientific issues at hand research and development up to the license application primarily focus on developing a repository that is both safe and constructible, whereas questions regarding what is most economically optimal need to come second. Since the submittal of the license application SKB has now entered a phase of "value engineering". Value engineering is a systematic and organized approach to provide the necessary functions in a project at the lowest cost without sacrificing functionality. Issues considered include size of the underground openings, excavation methods, thermal dimensioning and deposition sequence logistics with associated need of machinery and storages. While optimisation studies appear to be very promising, they cannot be undertaken too early in the repository programme. On overall system understanding, a complete set of detailed safety functions and technical design requirements and understanding of the logistics is needed before such studies are meaningful. Otherwise there is a great risk of arriving at sub-optimal solutions.

4.7. Knowledge management and in-house competence needed

Research and development will need to continue also after a license to construct a repository is granted. There is also a need to apply, maintain and develop the knowledge management tools already established.

Workable procedures for information handling and QA are already developed and successfully applied but wealth of information and pressure to act quickly will increase when construction and operation starts. A structure for requirements management and quality control of production and installation is established and workable requirements are formulated, but the application during construction and operation still lies in the future. These tools will also be used by even larger groups of experts.

Due to the complexity of issues at hand implementing organisations would need to keep a core competence on post closure safety assessment including at least on overall understanding on how the repository components evolve over time. An important part in each assessment of post-closure safety is the evaluation of the knowledge base both with regard to processes and input data in the assessment. Safety assessments are thus fundamental for the prioritisations of the research programme. However, it may be more difficult to attract a new generation of researchers and to justify funding the R&D when the fundamental issues are less acute.

4.8. Role of international cooperation

In the future international cooperation will be even more important on developing, sharing and managing the knowledge needed. Guidelines and other recommendations issued by the international agencies will not only be important for developing programmes but would also serve as a fundamental memory in more developed programmes when the experts ones being authoring such guides now have retired or soon will retire. International cooperation is also essential for sharing competences where the national contexts is too small, especially on issues essentially only of interest to the nuclear waste community. Participation in international work may also be an inspiration and reason to carry on for internal staff, as well as researches at universities, to consider the work sufficiently interesting.

5. Conclusions

SKB is closing the back end of the fuel cycle, but research and development would need to continue, although with a new focus. There is also a need to apply, maintain and develop the knowledge management tools already established. In the future international cooperation will be even more important on developing, sharing and managing the knowledge needed.

REFERENCES

[1] KBS 3 - Final storage of spent nuclear fuel - KBS-3, Swedish Nuclear Fuel Supply Co/Division KBS (SKBF/KBS) (available at www.skb.se), 1983

[2] Andersson J, Ström A, Svemar C, Almén K-E, Ericsson L O, 2000. What requirements does the KBS-3 repository make on the host rock? Geoscientific suitability indicators and criteria for siting and site evaluation. SKB TR-00-12, Svensk Kärnbränslehantering AB.2000

[3] Geoscientific programme for investigation and evaluation of sites for the deep repository, SKB TR-00-20, Svensk Kärnbränslehantering AB. 2000

[4] Safety functions, performance targets and technical design requirements for a KBS-3V repository. Posiva SKB Report 01, Posiva Oy, Svensk Kärnbränslehantering AB, 2017

[5] Long-term safety for the final repository for spent nuclear fuel at Forsmark. Main report of the SR-Site project. SKB TR-11-01, Svensk Kärnbränslehantering AB. 2011

[6] Strålsäkerhet efter slutförvarets förslutning (In Swedish: Radiation Safety after closure of the final repository for spent nuclear fuel), Swedish Radiation Safety Authority 2018:07, 2018

[7] Andersson J. Data and data uncertainties. Compilation of data and data uncertainties for radionuclide transport calculations. SKB TR-99-09, Svensk Kärnbränslehantering AB, 1999

[8] Data report for the safety assessment SR-Site. SKB TR-10-52, Svensk Kärnbränslehantering AB

[9] Site description of Forsmark at completion of the site investigation phase. SDM-Site Forsmark SKB TR-08-05, Svensk Kärnbränslehantering, 2008

[10] Olkiluoto Site Description, POSIVA Report 2011-2, Posiva Oy, Finland 2011

[11] Andersson J, Skagius K, Winberg A, Lindborg T, Ström A, Site-descriptive modelling for a final repository for spent nuclear fuel in Sweden. Environmental Earth Sciences 69, 1045–1060. DOI 10.1007/s12665-013-2226-1., 2013

[12] Design premises for a KBS-3V repository based on the results from the safety assessment SR-Can and some subsequent analyses. SKB TR-09-22, Svensk Kärnbränslehantering AB, 2009

[13] Detailed site investigation programme in conjunction with construction and operation of a repository for spent nuclear fuel. SKB R-17-16, Svensk Kärnbränslehantering AB, 2017

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SPENT NUCLEAR FUEL DISSOLUTION RESULTS FROM COMPLETED PROJECT REDUPP AND ONGOING PROJECT DISCO

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Abstract. This contribution summarizes results and progress in two projects: REDUPP and DisCo. REDUPP finished a few years ago while DisCo is ongoing and only initial, preliminary results are available. The projects focus on processes occurring at the interface between spent nuclear fuel and aqueous solution. This includes redox reactions but also dissolution from high-energy sites and processes occurring at or near equilibrium. Uncertainties investigated here are if additives in modern fuels, such as Cr or Cr+Al, or, as in the case of MOX fuels, Pu, can influence these processes significantly. Reducing conditions are expected overall although local repository environment will influence the water composition. Therefore, experiments and models are set up to test the effect of different water chemistries. Real spent nuclear fuel experiments, complemented with studies on model materials, provide further insight in the detailed mechanisms involved in spent nuclear fuel dissolution.

1. Introduction

The safety assessments for the planned spent nuclear fuel and high level waste repositories in Europe can be considered to rely on two main principles: first to keep the radionuclides contained in the waste package, and secondly, in case of a container breach, to retard the outward migration of radionuclides. The second part starts with release from the waste itself to the transporting medium, normally water. Due to its central part in the safety assessment, dissolution of spent nuclear fuel in a repository environment has therefore been investigated for many years within the framework of Euratom in a succession of collaborative projects. This paper involves two projects: REDUPP and DisCo. REDUPP started in FP7 and was finished 2014, while DisCo is an ongoing H2020-project. Both projects deal mainly with issues concerning matrix dissolution of spent nuclear fuel: in light of very low matrix dissolution rates stemming from the dissolution inhibiting hydrogen effect, certain aspects need to be better understood, such as the effect of the solid phase characteristics on the oxidative and non-oxidative dissolution in reducing conditions. The results of REDUPP are available in the open literature, while the DisCo results are currently being produced and only preliminary data are available at the time of writing.

1.1. REDUPP

REDUPP (Reducing Uncertainty in Performance Prediction) investigated two remaining uncertainties regarding dissolution data used in safety assessments: the effect of surface characteristics of the solid state, and the effect of natural groundwater compared to synthetic. Any solid sample surface is characterised by varying amounts of so-called "high-energy sites". These may be found on different scales: atomic and nanoscale, microscopic, and macroscopic. Previous data indicated that the history of UO_2 fragments used in experiments affected the calculated dissolution rates [1]. The reason seemed to be that the high-energy surface sites disappeared and the surface matured and evolved towards equilibrium in the successive experiments. This hypothesis was investigated in the REDUPP project by using analogue materials avoiding the complex redox behaviour of uranium: CaO_2 and ThO_2. In addition, the effect of natural groundwater on the dissolution of UO_2 was investigated. Commonly, dissolution experiments are performed using some kind of simplified aqueous solution. Natural ground waters have a more complex composition which may affect aqueous speciation and the dissolution process. This was also investigated in the REDUPP project using alpha-doped UO2 in three different ground waters.

1.2. DisCo

Several decades of research into spent nuclear fuel dissolution has built a firm knowledge base for standard UO_2 fuel, including high-burnup fuels. Still, some uncertainties remain. The DisCo (Modern spent nuclear fuel Dissolution in failed container Conditions) project focuses on another uncertainty that has become more relevant in later years. As a way to utilise nuclear fuel more efficiently, nuclear power plants use modern types of nuclear fuel which contain additives (also called dopants) [2]. Most common dopants are Gd, Cr and Cr with Al. In addition, mixed-oxide fuel containing a certain amount of Pu (MOX) is also being used in some countries. Fuel developers are also looking into possibilities of using Th in the nuclear fuel. How these changes in chemical composition affect the characteristics of the spent nuclear fuel in repository environment is uncertain. The DisCo project therefore focuses on the experimental study of the dissolution of these types of materials and the development of models to enhance our understanding of these modern fuels in comparison with traditional fuels.

2. Methods

The details of the experimental methods are given in specific publications. Here we only present the general principles behind the approach, methods and experimental set-ups used in the projects discussed.

One approach in both REDUPP and DisCo is to use analogue materials to reduce some of the complexity of the spent nuclear fuel from the experiments. This allows the investigation of single parameters and their influence on the results. This is done to complement spent nuclear fuel dissolution experiments. The manufacturing of analogue materials can be done using different approaches, such as dry or wet synthesis followed by calcination and classic sintering, or sintering using Hot Isostatic Pressing; in the end, all routes aim for a final homogenous material with similar density and grain size as the spent nuclear fuel. This initial sample preparation step is quite time and resource consuming. Some analogue materials also employ an alpha-emitter (Pu-238) which requires a tried, tested and optimized synthesis route before final material is made. It is also of central importance that the initial state of the solid sample is sufficiently characterised, to identify changes caused by water contact. Methods used are for example X-Ray diffraction and electron microscopy using various features such as electron back-scatter diffraction patterns.

The core of the experimental investigations is the dissolution experiments. Since the aim is to investigate processes relevant to repository environments, most experiments are performed in reducing conditions. The expected Eh in a KBS-3-type repository, as envisaged by SKB and Posiva, is between -400 and -200 mV at near neutral pH conditions and regulated by the anoxic corrosion of Fe(0) and consecutive hydrogen production due to reduction of groundwater. This means that the experimental systems require very low pO2 and elevated hydrogen concentration, respectively, to be representative of the near-field environment of the repository environment. These conditions are commonly achieved by using autoclaves with controlled atmosphere. In an appropriate inert-gas glove box this environment can also be achieved if an additional reducing agent is used to remove traces of oxygen. For spent nuclear fuel experiments in autoclaves, hydrogen or hydrogen mixed with an inert gas is used to achieve representative, reducing conditions in the close vicinity of the spent nuclear fuel surface. In an anaerobic glove box, corroding iron is used to produce hydrogen and Fe(II) in solution which results in the required low Eh. Some experiments are performed also to observe the dissolution under higher Eh: that is in oxic conditions with or without hydrogen peroxide which accelerates the oxidation of UO2. In the REDUPP project, dissolution was also performed in acidic conditions, in order to produce observable effects during the planned experiment.

The composition of the aqueous solution is analysed at various times during the experiment to determine the concentration of uranium and other relevant elements. This is normally done by inductively coupled plasma mass spectrometry (ICP-MS). It should be noted that the materials investigated are, in neutral and reducing conditions, insoluble or very sparingly soluble, and the concentration in solution is very low. This requires high resolution instruments with low detection limits. For some radionuclides, radiometric methods are also used. When dissolution experiments are finished, the samples are investigated with various techniques such as Scanning and Transmission Electron Microscope, to be compared with the initial state of the samples.

The dissolution process is also explored through different modelling approaches. In REDUPP, modelling was performed from first principles so look at dissolution at an atomic scale. This was combined with thermodynamics to analyse the effects of the different water reactions on UO_2 surfaces when exposed to water environments. In DisCo, thermodynamic modelling approaches are used both to investigate the solid (oxygen potential, solid solution model), and to develop reactive transport models involving both the dissolution of the solid and the transport in the failed container environment. Specifically, the codes used are GEM-Selektor, Chemisimul, PhreeqC coupled with Comsol Multiphysics, CHESS-HYTEC. In addition, an electrochemical mixed-potential model is developed for the modelling of corrosion of fuel in storage ponds.

3. Results

An overview of final results of REDUPP and initial, preliminary results of DisCo are provided below. In general, the results point towards the importance of including solid state characterisation both before and after dissolution experiments to improve interpretation of aqueous concentration data collected during the experiment.

3.1. REDUPP

Results from the REDUPP project have been published both as open reports and scientific, peer-reviewed articles. REDUPP was presented at Euradwaste 2013 in Vilnius, and an overview of results up to that point is given in the conference proceedings [3]. The project finished in 2014 and the final project report [4] gives an overview of the achievements. Some results have been published at a later date.

Experiments on CeO_2 show fast initial leaching rates that are decreasing as dissolution proceeds. The use of polycrystalline samples show that initial dissolution is focused on grain boundaries. Grain boundaries with high misorientation angle retreats more rapidly than those with low misorientation angles. A strong crystallographic control was exerted. It was also noted that sample preparation may induce defects and strain which enhances the dissolution rate [5]. To further explore the importance of intrinsic defects, oxygen vacancies were introduced in the CeO_2 material through treatment in a reducing atmosphere form CeO_{2-x}. This material was then dissolved in nitric acid at 90°C. The results show that replacement of vacancy sites by oxygen during dissolution caused changes in the lattice volume and strain. This process increased dissolution rate and caused grain boundary decohesion. The results indicate the importance of defect sites and grain boundaries on dissolution kinetics [6].

The dissolution rate of ThO_2, with a very low solubility at the experimental conditions, is seen to be clearly affected by pH and complexing ligands. By using an isotopic tracer (Th-229) in some of the experiments, information was gained regarding the surface processes. At apparent chemical equilibrium, a continued isotopic exchange indicates that both

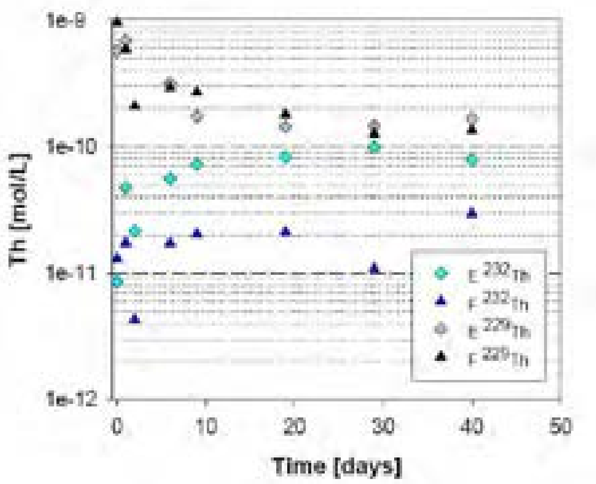

FIG. 1. Isotopic exchange observed in experiments with ThO2, using Th-229 as a tracer. From Figure 4-6 by Myllykylä et al., in the final REDUPP report [4].

dissolution and precipitation is occurring (Fig 1). The dissolving material provides the Th-232 to the aqueous solution, indicating that the original solid surface keeps dissolving, while precipitation also occurs in the vessel [7]. An alpha-spectrometry study of the ThO_2 surface after the experiments indicated the presence of a surface layer, maximum 0.1 µm thick, which had been affected by the dissolution precipitation reactions [8].

The results point to the importance of surface characteristics at least for initial dissolution rates in experimental conditions. A closer look at the solid surface and solid-liquid interface can reveal crucial information regarding the dissolution processes is of interest. In the REDUPP project, surfaces of minerals with fluorite structure were modelled using Ab Initio methods. The focus was the reactivity towards H2O, and this was explored using Ab Initio Molecular Dynamics, combined with atomistic thermodynamics. The results show that a hydroxylated surface is formed through dissociative chemisorption of water and this is stable at all environmentally relevant conditions [9]. This adjustment of the surface is predicted for certain surfaces and for varying environmental conditions, ie temperature and pressure (Fig. 2).

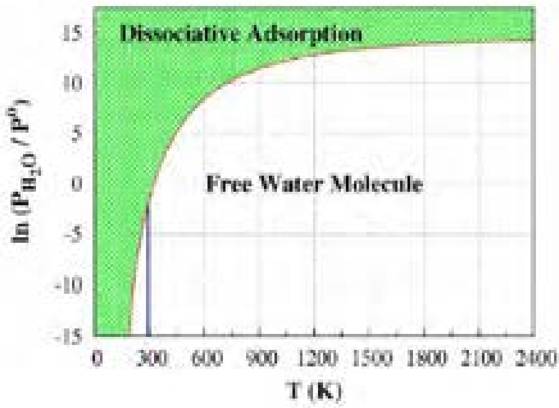

FIG. 2. Phase diagram computed from first principles showing the temperature and pressure where dissociative adsorption of water (green area) is expected on the (111) UO_2 surface. From Figure 7-2 by Maldonado et al, in the final REDUPP report [4].

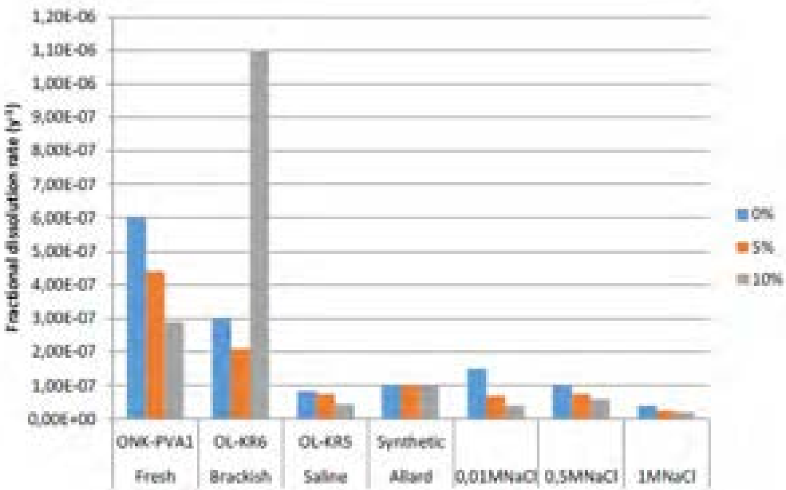

FIG. 3. Fractional dissolution rates calculated from isotope dilution experiments using UO_2 doped with 0%, 5%, and 10% U-233. Data is taken from Table 5-3 and 5-4 of Ollila et al. in the final REDUPP report [4]. Results from natural ground waters are given for the higher surface to volume ratio data.

Aqueous fluids in contact with dissolving solids contain various components that may influence speciation, solubility and interfacial reactions. Effects of three different natural ground waters were seen as a slight elevation of the calculated dissolution rates of UO2; the effect is most pronounced for fresh groundwater which had the highest carbonate and silicate content of the different waters [4, 10]. The lowest rates were found for the most saline ground water (Fig. 3).

Experiments using an isotope tracer (U-235 in aqueous solution), showed that isotope exchange occurred during the experiment when the system was close to chemical equilibrium. This isotope exchange is a result of dissolution and precipitation and/or sorption in the reaction vessel. The measured concentration of uranium in fresh groundwater was, after ca 250 days, between 10-11 and 10-12 M. Some precipitates, found on the Fe-strips used in the experiments, contained both U and Si [4], but it was not possible to perform X-ray diffraction on these small precipitates.

3.2. DisCo

At the time of writing, the DisCo project has been running for 20 months. Initial results have been presented at the first Annual Meeting, the proceedings of which are available for download at the project web page (www.disco-h2020.eu). During the first part of the project most work has been focused on synthesis and characterisation of fuel analogue materials as well as on preparation and characterisation of specimen sampled from real irradiated fuel rods, in preparation for the dissolution experiments. Information regarding samples and sample characterisation is found in Deliverable D2.1 [11]. The preparation of samples of real spent nuclear fuel is done by means of remote handling in shielded cells. Irradiated fuels investigated are standard UO2 fuel (as reference), Cr-doped UO_2 fuel, (Cr+Al)-doped UO_2 fuel and MOX fuel, (i.e. (U, Pu)O_2 fuel). Samples destined for dissolution are prepared either as segments of an irradiated fuel rod, with the cladding still present, or as fragments with the cladding removed (Fig. 4). Samples are also prepared for ceramography (microscopic characterisation) and for determination of chemical inventory and burn-up. In order to use the autoclaves in the dissolution experiments, they have been modified to enable remote handling by manipulators in shielded cells, intensively cleaned, and tested for air tightness.

FIG. 4. Spent MOX fuel (38 GWd/t burn-up) prepared at KIT-INE (Fig. 2.1.1 in [11]).

Synthesis of analogue materials involves characterisation, such as testing for density and grain size, during the process to ensure optimized final products. The following materials have been synthesized and characterised: UO_2 (as reference), UO_2+Gd, UO_2+Cr, UO_2+Cr+Al, (U,Th)O2. UO_2 doped with U-233 and unirradiated, homogenous (U, Pu)O_2

were already available. Using a wet coating technique, Cr-doped UO_2 has been produced with enhanced grain size, as is desired (Fig. 5). X-ray diffraction of the final product suggests that introducing Cr and Al into the UO_2 produces a contraction of the cubic lattice.

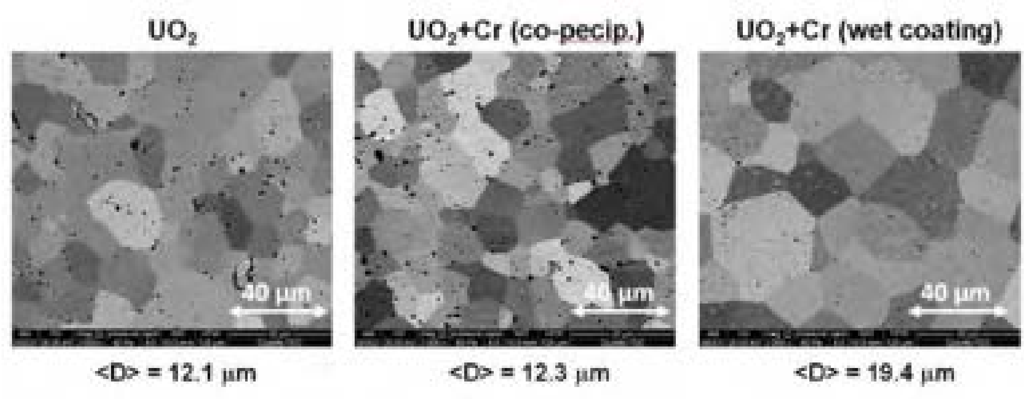

FIG. 5. UO_2 and Cr-doped UO_2 prepared at Forschungszentrum Juelich (Fig. 3.1.4 in [11]).

The preparation of UO_2 doped with Pu-238 to mimic aged spent nuclear fuel is on-going at the time of writing. An overview of planned and started dissolution experiments is given in Table 1. Some initial, preliminary results from the dissolution experiments are presented below.

TABLE 1. Experimental matrix for DisCo. Status at the time of writing (February 2019). BW= Bicarbonate water. YCWCa= Young Cement Water with C., GW= Ground Water. Cox = Callovo-Oxfordian Water.

Reducing (H_2, mix H_2+ Ar/N_2, or anoxic with corroding Fe)				
Water type	**BW**	**YCWCa**	**Natural GW+Fe**	**Synthetic Cox+Fe**
Solid				
UO_2 (reference)	**Started**	**Started**	Planned	
UO_2+Gd	**Started**	**Started**		
UO_2+Cr	**Started**	**Started**	Planned	
UO_2+Cr+Al	**Started**	**Started**		
(U,Th)O_2	Planned	Planned		Planned
UO_2 ref - ^{238}Pu/^{233}U	Planned	Planned	Planned	
UO_2+Cr- ^{238}Pu	Planned	Planned	Planned	
(Pu,U)O_2				**Started**
Spent nuclear fuel UO_2	Started	Planned		
Spent nuclear fuel Cr&Al- UO_2	Started			
spent nuclear fuel Cr- UO_2	Planned			
MOX	Started			

Oxidizing/Anoxic (Ar, H_2O_2, or Air)				
Water type:	**BW**	**YCWCa**	**Natural GW+Fe**	**Synthetic Cox+Fe**
Solid				
UO_2 (reference)	**Started**	**Started**		
UO_2+Cr	**Started**	**Started**		
Spent UO_2 fuel		**Started**		
Spent MOX fuel	Planned			

Standard UO_2 fuel dissolved in young cement water with Ca (YCWCa, high pH) has been performed in air-saturated conditions. Preliminary results show rapid initial release of radionuclides followed by slower dissolution. Comparing with results from previous experiments performed with bicarbonate water and neutral pH, two observations can be made: 1) higher initial Mo release in YCWCa 2) lower U release and U concentration in YCWCa.

Oxidative dissolution of UO_2 has been investigated using pure and Cr-doped UO_2 in hydrogen peroxide containing aqueous solutions. A successive decrease in uranium concentration is observed in each successive experimental run. This decrease appears to be independent of the initial hydrogen peroxide concentration. Preliminary experiments imply that the dissolution rate of Cr-doped pellets is independent of the doping method (co-precipitates or wet-coating). The direct view on dissolution is unclear because of the apparent passivation of the pellet surface due to the formation of precipitates. Further experiments will clarify the process of surface passivation for comparison between pure UO2 and Cr-doped UO2 materials.

Homogenous, unirradiated MOX pellets with a high amount of Pu (ca 25%, $2.2 \cdot 10^9$ Bq/g) have been dissolved in synthetic Callovo-Oxfordian (COx) water, pre-conditioned with corroding Fe. The radioactivity of the sample is expected to cause radiolysis and thus produce oxidants such as hydrogen peroxide. The experiment was run with an atmosphere of an Ar/CO_2 gas mixture. Preliminary results indicate that the Fe has a significant effect on the oxidative dissolution; uranium concentration after several months is less than 1 µg/L, i.e. less than ca 4.2 10^{-9} M.

Thermodynamic calculations of Cr-doped UO_2, simplified as an ideal solid solution, have been performed. This results in slightly lower oxygen potentials than the pure Cr and Cr_2O_3 systems. Calculations involving a full model spent nuclear fuel composition results in much higher oxygen potentials. These initial, preliminary results indicate that the stable oxidation state for Cr in the spent nuclear fuel will be Cr(III), and that the oxygen potential of the Cr-doped and spent nuclear fuel will be similar. It should be noted that this is based on the assumption of ideal solid solution.

For spent nuclear fuel dissolution, a model involving the catalytic effect of metallic aggregates (simulated with Pd) on the electron transfer from hydrogen to uranium is being developed. A first version was presented at the first annual DisCo meeting. The model employs the Chemsimul code to simulate the water radiolysis. The results from Chemsimul is then used in a reactive transfer model implemented in iCP (interface coupling COMSOL Multiphysics and PhreeqC). Validation of this first version of the model, using existing data

(Fig. 6), shows that including the hydrogen activation results in a more realistic description of the spent nuclear fuel dissolution process.

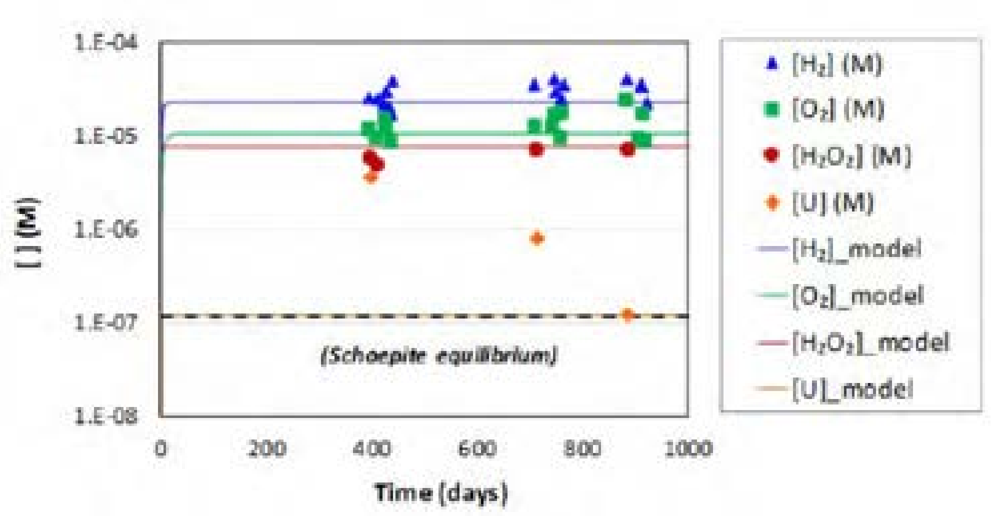

FIG. 6. Experimental data from Cera et al [12] and model results from the DisCo project (Fig. 2 in Riba et al., in [13]).

The development of the electrochemical model is on-going and results not yet available. However, it has been noted that, after some adjustments to remedy observed issues with previous models, the model now is able to produce the expected responses to the presence of hydrogen, noble metal particles, iron and alpha radiolysis.

The effect of Fe, observed in dissolution of unirradiated MOX fuel in synthetic COx water, has been successfully modelled by a preliminary version of the CHESS-HYTEC model. The model considers the kinetics of the reaction expected at the pellet surface, resulting in a progressive decrease of pellet dissolution and hydrogen peroxide concentration over time.

4. Discussion

Based on results from decades of research, there is now a general understanding and an accepted view of what processes control the rate of spent nuclear fuel dissolution. Most important is the oxidation of the fuel matrix; in an oxidizing environment, uranium will oxidize and UO_2 will transform, through dissolution and precipitation, to various minerals containing U(VI). This oxidation can be quite rapid and thus has the potential to control the overall dissolution rate of spent nuclear fuel. However, in experiments using alpha-doped material, used to simulate aged spent nuclear fuel, it is noted that when the alpha-radiation is below a certain value, there is no observable oxidation. Suppression of the oxidation of spent nuclear fuel with an overpressure of hydrogen has been experimentally observed. In the repository environment, at the time when water comes in contact with fuel, both of these situations will be expected: aged spent nuclear fuel, and hydrogen overpressure from the anoxic corrosion of iron. Therefore, the situation where UO_2 oxidation caused by radiolysis is negligible, or occurs at a rate which is not observable on an experimental time scale, is not unreasonable but rather expected, c.f.[14]. This is the view developed from studies made on standard UO_2 fuel in simple groundwater simulates. The question is if this is applicable also on doped fuels and MOX fuels?

The interfacial reactions that are at the core of these processes involve electron transfers. In the case of the dissolution inhibiting hydrogen effect, electrons are transferred from the hydrogen to the UO_2 matrix via the particles of metallic fission products (so-called ε-phases). Galvanic coupling of H_2 oxidation on metallic particles to UO_{2+x} reduction on the fuel surface appears to reverse the U oxidation at the U(V) stage [15]. The use of modern fuels which employs additives such as Cr or Cr and Al, may interfere with the UO_2 lattice and these electron transfer processes, potentially affecting the efficiency of the hydrogen effect. This is also possible for MOX fuels. Preliminary results from DisCo shows that the hydrogen effect can be incorporated in the models and when experimental data are available, this will be tested.

The chemical composition of the waters in the repositories may also influence these processes. In oxidizing conditions with real spent nuclear fuel, such as tested in DisCo, lower uranium concentrations are found in cementitious water (YCWCa) compared to bicarbonate water. It is hypothesized that this is due to the formation of a secondary phase. If saturation is reached with regards to a secondary uranium phase it is not possible to use the change in uranium concentration over time as an indicator of dissolution rate, or rate of radionuclide release. A secondary phase precipitated on the surface of UO_2 might also have formed in the DisCo experiments employing hydrogen peroxide to accelerate UO_2 oxidation; in this case, the secondary phase appears to have affected the reactivity of the original surface. Uranium concentrations above the expected U(IV) solubility indicates U(VI) in solution. As long as the concentration measured is below saturation level of a U(VI) solid, a continuous rise in concentration can be interpreted as oxidative dissolution and a dissolution rate can be estimated. Uranium speciation is affected by both pH and various components in the water, so these aspects need to be taken into account when interpreting the data. For example, in the case of natural groundwater, it was observed during REDUPP that calculated rates were higher for the fresh water with higher carbonate and silicate contents. Some secondary phases were observed that contained both U and Si; thus, it is possible that uranium speciation and solubility limiting phases (potentially coffinite) was affected by the different groundwater compositions.

In the case of low level alpha radiation, as in aged fuel, or when there is hydrogen and iron present that keeps the Eh low even at the surface of the fuel, the rate of oxidation may be lower than the rate of dissolution of UO_2 driven by the degree of deviation from equilibrium, ΔG_r. If so, one has to consider processes relevant for when the system is close to equilibrium. This was the focus of the Euratom project SKIN and discussed by Grambow et al. [16]. The radionuclide release in this situation can be controlled by the removal of U from the water either through advection (water flow) or through the precipitation of a more stable phase, keeping the water unsaturated with regards to the spent nuclear fuel matrix. The latter process can be recrystallisation or chemical alteration of the spent nuclear fuel matrix. There are isotopic exchange data that indicate that this process occurs [1,7,16]. Results from REDUPP show that during the initial phase of dissolution, the sample surface adjusts to a lower energy state. This occurs by dissolving sites with higher energy such as defects and grain boundaries, but also higher surface energy crystallographic faces will preferentially dissolve. It seems, however, for UO_2 and ThO_2 that the amount altered during the experiment is limited to only a part of the sample surface [16]. The REDUPP results indicate that the high-energy sites at the sample surface are indeed releasing material to solution at a rate which is initially fairly rapid, but which slows as the experiments proceeds. The DisCo experiments, involving both pre- and post- dissolution characterisation, will enhance our understanding not only of the effects of additives, but of how the sample surface is changed by dissolution.

5. Concluding remarks

This contribution aims to provide an overview of the final results of the REDUPP project and some initial results of the DisCo project. The research performed in these projects enhances our understanding of the processes involved in spent nuclear fuel dissolution. Based on knowledge gained from previous Euratom projects, it is possible to focus specifically on processes expected during reducing conditions, and test how solid and fluid state composition may affect these.

We have shown that during the initial stages of dissolution experiments, there is an interval where the solid surface adjusts towards a state of lower energy. This happens also when the experimental system is close to equilibrium. Surfaces with a fluorite structure, such as CeO_2, ThO_2 and UO_2, are predicted to cause dissociation of water to form a hydroxylated surface. In this process, depending on which crystallographic structure is being exposed, the surface structure will be adjusted on an atomic scale. Surface defects and grain boundaries are also show to be preferentially dissolved during this initial stage, which is characterised by a higher dissolution rate. The dissolution is accompanied by precipitation when the system is close to equilibrium. This dissolution-precipitation is observed through isotopic exchange in experiments with UO2 and ThO2. A clear crystallographic control and effects of surface characteristics on an atomic scale indicates that anything that may affect the crystal lattice, may also affect these processes. Therefore, the effect of additives is being studied in the DisCo project.

The initial results from the DisCo project presented here relates mainly to the successful production of analogue materials, preparation of specimen sampled from irradiated fuel rods and the characterisation and control of the experimental systems. The synthesis of these various materials has been optimized. By characterising the final solid product by X-ray diffraction, the effect of additives on the cubic lattice can be observed: doping UO_2 with both Cr and Al produces a homogeneous material but with slightly contracted lattice. Regarding dissolution, some reference experiments have been performed, such as UO_2 and spent nuclear fuel dissolution in oxidizing environments in different aqueous solutions. Observed differences in results are now being interpreted. Experiments and models concerning Pu-rich unirradiated MOX in synthetic, Fe-calibrated Callovo-Oxfordian water have produced some initial results. The redox reaction between iron in solution and hydrogen peroxide is central in the system, and the preliminary results indicate that uranium is kept reduced. Preliminary modelling also suggests that the hydrogen effect can be included in the models and successfully predict experimental results.

The research presented here will have an impact on the safety assessments of the spent nuclear fuel repositories in different environments. The results will reduce some remaining uncertainties in the parameters of the assessments and be informative for future discussions concerning the possible challenges of disposal of the newly developed fuels before they are included in the nuclear fuel cycle on a large scale. This is important for the steps taken towards implementation and licensing of the repositories.

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References

[1] Ollila K, Oversby VM, 2005. Dissolution of unirradiated UO2 and UO2 doped with 233U under reducing conditions. SKB Technical Report TR-05-07. Svensk Kärnbränslehantering AB

[2] Arborelius et al., 2006. Advanced Doped UO2 Pellets in LWR Applications, Journal of Nuclear Science and Technology, 43:9, 967-976.

[3] Evins et al., 2014. How the surface properties of spent nuclear fuel materials influence dissolution: Results of the REDUPP project. In: Proceedings of the 8th European Commission conference on the management of radioactive waste,Euradwaste´13, 14-16 October 2013, Vilnius, Lithuania. EUR 26846 EN, European Union.

[4] Evins et al., 2014. REDUPP Final report. Posiva Working Report 2014-12, Posiva Oy, Finland.

[5] Corkhill et al., 2014. Contribution of Energetically Reactive Surface Features to the Dissolution of CeO2 and ThO2 Analogues for Spent Nuclear Fuel Microstructures ACS Appl. Mater. Interfaces, 6, 15, 12279-12289

[6] Corkhill et al, 2016. Role of Microstructure and Surface Defects on the Dissolution Kinetics of CeO2, a UO2 Fuel Analogue. ACS Applied Materials &Interfaces 8, 16, 10562-10571

[7] Myllykylä et al., 2017a. Dissolution of ThO2: study of dissolution process with initial 229Th spike. Journal of Radioanalytical and Nuclear Chemistry 311, 225-235.

[8] Myllykylä et al., 2017b. Direct alpha spectrometry for analysing leached ThO2 pellets. Journal of Nuclear Materials, 493, 69-76.

[9] Maldonado et al., 2014. Ab initio atomistic thermodynamics of water reacting with uranium dioxide surfaces. The Journal of Physical Chemisty C 118, 8491−8500.

[10] Ollila et al., 2013. Dissolution rate of alpha-doped UO2 in natural groundwater. Journal of Nuclear Materials 442 , 320–325.

[11] Farnan et al., 2018. Initial state report: sample characterisation and experimental set-up. Horizon 2020 Euratom project DisCo, Deliverable D2.1

[12] Cera et al., 2006. Experimental determination and chemical modelling of radiolytic processes at the spent nuclear fuel/water interface. Long contact time experiments. SKB technical reort TR-06-07. Svensk Kärnbränslehantering AB.

[13] Evins et al., 2018. 1st Annual Meeting Proceedings. Horizon 2020 Euratom project DisCo, Deliverable D1.10

[14] Grambow et al., 2011. Spent nuclear fuel Waste Disposal: Analyses of Model Uncertainty in the MICADO Project. Energy Procedia 7 (2011) 487–494

[15] Wu et al., 2014. An improved model for the corrosion of used nuclear fuel inside a failed waste container under permanent disposal conditions Corrosion Science 84, 85–95

[16] Grambow et al., 2017. Solubility equilibrium and surface reactivity at solid/liquid interfaces of relevance to disposal of nuclear waste. Journal of Chemical Thermodynamics, 114, 172-181.

OVERVIEW OF CARBON-14 SOURCE TERM GENERATION AND RELEASE FROM IRRADIATED METALS, ION-EXCHANGE RESIN AND GRAPHIT

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Abstract. The European Commission CAST project (CArbon-14 Source Term) aimed to improve the scientific understanding of carbon-14 (radiocarbon, ^{14}C) release mechanisms and associated release rates from the corrosion of irradiated steels and Zircaloys and from the leaching of ion-exchange resins and irradiated graphites, under geological disposal conditions. The project considered the release of carbon-14 as dissolved and gaseous species from these materials, evaluating new understanding in the context of national safety assessments and disseminating this understanding to stakeholders. This paper provides an overview of the CAST project and its output.

1. Introduction

Carbon-14 (radiocarbon, 14C) is present in important amounts in the radioactive waste inventories of many national waste management programs, particularly in irradiated steels, irradiated Zircaloys, spent ion-exchange materials (resins) and irradiated graphites. The knowledge regarding the chemical form and the release mechanism of carbon-14 from these wastes in disposal conditions — be they surface-based or an underground geological repository — is limited. Therefore, in precedent safety assessments it is often assumed that carbon-14 is released from irradiated metals in a single chemical form at a rate dependent on the corrosion rate of the metal and the inventory of carbon-14. Similarly, estimates of the rate of release from irradiated graphite may be based on simple assumptions about the proportion of the carbon-14 that is 'labile' and on short-term leaching results. Such conservative treatments possibly give rise to over-estimated radiological impacts.

The European Commission CAST project (CArbon-14 Source Term) aimed to improve understanding of the potential release mechanisms of carbon-14 from radioactive waste materials under conditions primarily relevant to disposal to underground geological disposal facilities. The project focused on the release of carbon-14 as dissolved and gaseous species from irradiated metals (steels, Zircaloys), from spent ion-exchange materials and from irradiated graphites.

Carbon-14 shows different behaviours in typical repository environments depending on whether it is in inorganic or organic form. As carbonate, carbon-14 shows excellent retention in cementitious and clay environments due to isotopic exchanges, whereas it is an unretarded element, possibly in the gaseous phase, when it is an organic species.

The primary focus of CAST was thus to discriminate experimentally between these two different forms, with possibly a more precise characterisation of the speciation of the carbon-14 bearing compounds released from these wastes investigated in this project.

The CAST consortium brought together 33 partners with a range of skills and competencies in the management of radioactive wastes containing carbon-14, geological disposal research, safety case development and experimental work on gas generation. The consortium consisted of national waste management organizations, research institutes, universities, and commercial organizations. Although CAST was funded by the European Commission, the participation of non-EC partners was welcomed.

The interested reader is also directed to the CAST website (www.projectcast.eu) and the special issue of the Radiocarbon journal dedicated to CAST (Volume 60, Number 6, 2018), where further project deliverables are publicly accessible.

2. Summary of project output

For steel and Zircaloy, exhaustive literature reviews and experimental studies on their corrosion rates were carried out in CAST, to bound the carbon-14 source term.

Steel corrosion rates in alkaline conditions are very low because of the presence of a passivation layer [1, 2]. Many experimental studies have shown that uniform corrosion rates for carbon steel in anoxic, alkaline conditions are below 0.1 µm/yr. Recently, an increasing number of studies indicate upper values in the range of few tens of nm/yr. Uniform corrosion rates for stainless steel are very low. In anoxic, alkaline conditions, recent studies reported measured values below 0.01 µm/yr. The corrosion rates of stainless and mild steels are higher in neutral conditions than in alkaline conditions. This might affect the carbon-14 release in a pessimistic scenario where the alkalinity of the near field decreases i.e., because of ageing of the cementitious environment. However, the radiological impact remains limited since the pH decreases significantly only in the long-term when most carbon-14 has decayed. The experimental studies indicate an early, fast release of carbon-14 from steel between a negligible fraction up to a few percent. There is no consensus on how to abstract these observations in safety assessment.

The experimental works conducted on the corrosion of Zircaloy in CAST tends to confirm the data reported in the literature with corrosion rates in the order of a few nm/yr at the most at low temperature, in alkaline or neutral conditions [3, 4]. CAST allowed progress in the knowledge of the corrosion mechanism of Zircaloy. Should the corrosion regime change in disposal conditions (transition to pseudolinear kinetics), it is not expected to lead to higher rates. Further, the CAST results on Zircaloy confirm the hypotheses formulated 15 years ago by the Japanese program of a mechanism in which carbon-14 is not released immediately by Zircaloy corrosion but is retained inside the oxide film. Indeed, the total leached fraction of carbon-14 from long-term Japanese experiments of several years on pressurized water reactor (PWR) and boiling water reactor (BWR) cladding samples is less than 0.1%. The carbon-14 released in this experiment seems to originate from the oxide layer [5]. These experimental results suggest that the 20% instant release fraction (IRF) used traditionally in safety assessment is overconservative. Unfortunately, there are not enough data and currently no consensus over the release mechanism of carbon-14 from the oxide layer to abstract these very low fractions in quantitative safety assessments. In addition, the influence of hydrides on the corrosion behaviour on the long term in disposal conditions remains uncertain. Lastly, it is to be noted that the review work performed in CAST in relation to the Zircaloy inventory in the claddings reduced the uncertainties on the concentration of the nitrogen impurity [3, 6]. However, uncertainty remains in relation to the carbon-14 inventory in reprocessed waste (vitrified and compacted waste). The assumptions regarding the carry-over fractions of carbon-14 inventory from the different components of the assemblies need to be consolidated. Also, accounting for an accessible carbon-14 in the oxide layer in compacted waste (after acid treatment) is still a matter of debate [6].

The measurements of carbon-14 speciation released from steel show that both organic and inorganic compounds are present in the liquid phase [2]. Methane and minor contributions of CO are found in the gas phase. However, applying this speciation to long-term releases of carbon-14 in disposal conditions is debatable. The oxygenated species measured in experimental conditions might in fact result from the radiolysis induced by the activated materials. It could thus be expected that the carbon-14 speciation will shift to reduced compounds, such as—gaseous—hydrocarbons, when the radiolysis becomes ineffective in the disposal system. Carbon-14 from Zircaloy shows the same behaviour in terms of speciation: the liquid phase is shared between inorganic and small oxygenated organic compounds. Methane, ethane, and CO_2 were mainly detected in the gas phase. Precise distribution as an input to safety assessment is still challenging at this stage, nevertheless, it can be concluded that the organic form of carbon-14 released from Zircaloy and steel is present in non-negligible fractions.

Spent ion-exchange resins (SIERs) are a heterogeneous source term. The range of activity of SIERs depends on specific factors such as reactor and circuit type, history of the physicochemistry in the fluid as well as pre-disposal storage conditions and conditioning processes of the resins. Likewise, carbon-14 speciation is expected to be influenced by these factors. In the case of BWR, more than 90% of carbon-14 was found under the form of inorganic carbon. For PWR, the situation is more contrasted. CANDU reactors seem to induce a major part of inorganic carbon-14, whilst for PWR around 20% of carbon-14 was obtained [7]. The speciation of the organic fraction suggests formic acid as the main organic form in SIERs. The conditioning matrix of SIERs (epoxy and cement) is assigned a safety function of water ingress limitation and possibly retardation in safety assessment [6]. Experimental studies brought to light the lability of carbon-14 in—unconditioned—SIERs during predisposal processing: the presence of atmospheric air during storage, temperature increase, transient decrease in the pH upon contact with alkaline solutions as well as drying procedures of the SIERs seems to cause a release of inorganic carbon [7, 8]. SIERs are a telling example illustrating the strong dependency between predisposal and long-term disposal management strategies.

The study of carbon-14 in irradiated graphite in CAST is, to an extent, a continuation of work undertaken in the preceding European Commission CARBOWASTE project. A certain number of outcomes were highlighted in [9]. First, regarding the release rate, a substantial fraction of the carbon-14 in irradiated graphite is not releasable. Some carbon-14 will initially be released rapidly, and some will be released more slowly at a rate that decreases over time. 99% of the carbon-14 that is released in the inorganic form. Carbon-14 can be released to both the gas and aqueous phases. A number of different species, including organic species (e.g., CH_4), CO_2 and CO may exist in the gas phase. For high pH conditions, the proportion released as gaseous carbon dioxide is small in comparison to the fractions released as carbon monoxide and methane. CAST provided a consensual parameterisation of the carbon-14 source term in irradiated graphite as basis for safety assessment. However, these data should be considered with care as the release rate and speciation of carbon-14 is a function of the graphite type used in different reactors and the disposal concept and conditions.

3. Upscaling to geological disposal systems

Due to its relatively short half-life (5,730 years), the carbon-14 radiological release from the waste through the host rock is sensitive to the release and migration processes in the disposal system.

Clay-based disposal systems provide an excellent performance regarding carbon-14, provided transport times in the disposal system are of the order of a few tens of thousands of years. The carbon-14 activity releases from the geological barrier (whatever its chemical form) are barely sensitive to the instant release fractions (IRF) up to 20% due to the spreading effect of the diffusive transport [10]. Sensitivity studies show that, in the present state of knowledge reported by PSI in CAST, the possible uptake capacity of the carbon-14 bearing organic compounds identified in CAST is too weak to influence the carbon-14 transport [6]. The impact of organic carbon-14 might become more relevant in scenarios where diffusion through the geological barrier is cut short, as could occur for example in the case of a scenario that considers transport of groundwater and dissolved species by advection. The impact of this scenario is very dependent on the uncertainties pertaining to corrosion rates, amount of metals and their specific surfaces. Reducing these uncertainties would make it possible to better estimate the source term of both the hydrogen carrier and carbon-14. Different design strategies can also be applied to limit the impact of both the hydrogen pressurisation and the advective transport of carbon-14 [10].

Locating the repository caverns in crystalline rocks away from any major fracture zones at a sufficient depth limits the groundwater flow through and in the vicinity of the repository caverns. This provides favourable near-field conditions for the engineered barrier system, limits the radionuclide transport, and isolates the waste from the biosphere. In crystalline rocks, any open fractures can provide pathways for both gas and aqueous transport. The release and migration of carbon-14 in organic gaseous form is expected to occur at a rate comparable to the migration of organic carbon-14 dissolved in groundwater. Sensitivity analyses carried out in CAST of carbon-14 releases from a repository located in a crystalline rock indicate a strong impact of the near field processes, i.e., groundwater flow rates and sorption, on the release rates. Consequently, the transport and retardation properties of the ageing cementitious environment are critical. Radiological impact in crystalline rock is more sensitive to IRF and (potential) low distribution coefficients (assigned to cement and host formation) than in clay. Reducing the uncertainties related to the metal corrosion rate as well as a good knowledge of the cementitious evolution is of primary importance for crystalline systems [10].

A repository for radioactive waste in a salt formation is characterized by mostly dry conditions. Therefore, radionuclide transport occurs dominantly through the gas phase. The convergence of the backfill starts as soon as the repository is closed. This process can be the driver of an advective transport of gases though the EBS up to the biosphere. A potential release of carbon-14 from the repository in salt depends thus on the amount of gaseous carbon-14 made available in the early few hundreds of years after repository closure, due to corrosion by water brought in inside waste packages alongside the waste itself during the operational period or due to initial canister failure. The experimental conditions of CAST (saturated and alkaline) are not directly representative of the conditions prevailing in a salt disposal (unsaturated & high saline brines). Water being a limiting factor, the impact in salt is very sensitive to the gaseous IRF. Although conditions are different, the literature (First Nuclides) relevant for salt system is in line with CAST. It shows increasing indications that the gaseous release of accessible carbon-14 from Zircaloy (oxide layer), spent fuel rods and steel are relatively low (1% altogether). The highest priority for salt disposal systems is to reduce the uncertainty on the release behaviour of gaseous carbon-14. This is mainly related to three questions: (1) What is the percentage of carbon-14 which can be released in volatile form? (2) What is the temporal distribution of this release? (3) Is water necessary to transfer carbon-14 into a volatile form or does this occur in dry conditions? [10].

4. Key messages to safety case

In conclusion, the experimental studies of CAST have confirmed the release of a non-negligible fraction of carbon-14 organic compounds from steel, Zircaloy and Spent Ion Exchange Resins in alkaline and anoxic conditions.

Regarding Zircaloy and steels, hydrocarbons, and carbon monoxide were found in the gas phase whereas the aqueous phase contained small oxygenated organic compounds. The mechanism of formation of these organics remains uncertain, in particular the source of oxygen. Although the organic nature of carbon-14 products generated from steel and Zircaloy corrosion has been confirmed, long-term generation of carbon-14 in disposal conditions might give a different picture with respect to its organic speciation and compound distribution. Consequently, conservative treatment still applies in safety assessment regarding specific organic speciation. CAST gave the opportunity to reinforce the understanding of the corrosion mechanisms of these metals, in alkaline, anoxic conditions. As a result, the confidence that these corrosion mechanisms will remain generally unchanged in the long term (within a certain Eh/pH window of the near field) has increased. Also, the interplay of the oxide layer in the carbon-14 release mechanism of Zircaloy is now acknowledged. The literature review carried out in CAST confirms the low corrosion rates for these metals as well as the general trend to even lower rates as observed in more recent studies.

CAST emphasized the heterogeneous character of irradiated graphite and spent ion exchange resins. The relative importance in the safety case of carbon-14 (aqueous) versus carbon-14 (gaseous) for these wastes varies by disposal concept, predisposal activities, and power plant operational conditions. Applying the results determined from few specific samples to broad inventories of waste with various operational and predisposal histories must be done with caution. This generalisation process might bring a certain level of uncertainty to be accounted for in the safety case. Safety assessment studies carried out in CAST highlighted the critical influence of the chemical and physical evolution of the cementitious environment on different aspects of the carbon-14 source term (e.g., corrosion rates, carbon-14 release rates), but also on more global aspects pertaining to the confinement properties of a geological disposal (e.g., fate of the hydrogen produced by corrosion, near field hydraulic properties). Carbon-14 in the form of a mobile organic compound will give a more relevant radiological impact than if considered in the inorganic form, and this particularly in rapid transport scenarios. Reducing the uncertainty on carbon-14 speciation shifts the conservatism introduced in safety assessment of carbon-14 release to the corrosion and transport rates.

The results from CAST will be evaluated in the context of national safety assessments and disseminated to interested stakeholders. The new understanding should be of relevance to national safety assessment stakeholders. CAST provided an opportunity for training for early career researchers.

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References

[1] Swanton SW, Baston GMN, Smart NR. 2015. Rates of steel corrosion and carbon-14 release from irradiated steels – state of the art review. European Commission. CAST Project (Carbon-14 Source Term) Deliverable D2.1. Available from http://www.projectcast.eu/cms-file/get/iFileId/2501.

[2] Mibus J, Diomidis N, Wieland E, Swanton S. 2018. Final synthesis report on results from WP2. European Commission. CAST Project (Carbon-14 Source Term) Deliverable D2.18. Available from http://www.projectcast.eu.

[3] Gras J-M. 2014. State of the art of 14C in Zircaloy and Zr alloys—14C release from zirconium alloy hulls. CArbon-14 Source Term WP3. European Commission. CAST Project (Carbon-14 Source Term) Deliverable D3.1. Available from http://www.projectcast.eu/cms-file/get/iFileId/2681.

[4] Necib S, Ambard A, Bucur C, Caes S, Cochin F, Fulger M, Gras JM, Herm M, Kasprzak L, Legand S, Metz V, Perrin S, Sakuragi T, Suzuki-Muresan T. 2018. Final report on 14C behaviour in Zr fuel clad wastes under disposal conditions. European Commission. CAST Project (Carbon-14 Source Term) Deliverable D3.20. Available from http://www.projectcast.eu/cms-file/get/iFileId/2685.

[5] Sakugari T, Ueda H, Kato O, Yoshida S, Tateishi T, Yamashita Y. 2018. Corrosion behaviour of irradiated and non-irradiated zirconium alloys: investigations on corrosion rate, released 14C species (WP3), and IRF, European Commission. CAST Project (Carbon-14 Source Term), poster presentation. Final Symposium in Lyon, France. Available from http://www.projectcast.eu/cmsfile/get/iFileId/2680.

[6] Capouet M, Boulanger D, Vandoorne T, Gaggiano R, Norris S, Williams S, Schumacher S, Rübel A, Nummi O, Poskas P, Narkuniene A, Grigaliuniene D, Vokál A, Mibus J, Rosca-Bocancea E, Hart J, Ferrucci B, Levizzari R, Luce A, Diaconu D, Cuñado Peralta M, Owada H, Kienzler B, Wieland E, Van Loon L, Walke R. 2017. Knowledge supporting safety assessments of 14C. European Commission. CAST Project (Carbon-14 Source Term) Deliverable D6.2. Available from http://www.projectcast.eu/cms-file/get/iFileId/2571.

[7] Reiller PE. 2018. Final synthesis report of spent ion-exchange resins 14C source term and leaching. European Commission. CAST Project (Carbon-14 Source Term) Deliverable D4.9. Available from http://www.projectcast.eu/cms-file/get/iFileId/2679.

[8] Rizzato C, Shcherbina N, Reiller PE. 2017. Compilation and comparison of data from spent ion exchange resins. European Commission. CAST Project (Carbon-14 Source Term) Deliverable D4.8. 1-44. Available from http://www.projectcast.eu/cms-file/get/iFileId/2589.

[9] Toulhoat N, Moncoffre N, Narkunas E, Poskas P, Bucur C, Ichim C, Petit L, Schumacher S, Catherin S, Capone M, Shcherbina N, Bukaemskiy A, Rodríguez Alcalá M, Magro E, María Márquez E, Piña G, Fachinger J, Fugaru V, Norris S, Zlobenko B. 2018. Final report on results from Work Package 5: Carbon-14 in irradiated graphite. European

Commission. In: Norris S, editor. CAST Project (Carbon-14 Source Term) Deliverable D5.19. Available from http://www.projectcast.eu/cms-file/get/iFileId/2606.

[10] Henocq P, Robinet J-C, Perraud D, Munier I, Wendling J, Treille E, Schumacher S, Hart J, Dijkstra JJ, Meeussen JCL, Capouet M, Meert K, Vandoorne T, Gaggiano R, Dorado E, Nummi O, Diaconu D, Constantin A, Bucur C, Grigaliuniene D, Poskas P, Narkuniene A, Vokál A, Vetešník A, Ferrucci B, Levizzari R, Luce A, Rübel A, Gray L, Carter A, Mibus J, Smith P, Kämpfer T. 2018. Integration of CAST results to safety assessment. European Commission. CAST Project (Carbon-14 Source Term) Deliverable D6.3. Available from http://www.projectcast.eu.

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CEBAMA: RESEARCH AND INNOVATION ACTION ON CEMENT-BASED MATERIALS, PROPERTIES, EVOLUTION AND BARRIER FUNCTIONS

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Abstract. CEBAMA is a research and innovation action granted by the EC within the HORIZON2020 programme in support of the implementation of the first-of-the-kind geological repositories. The 4-year project started the 1st of June 2015 and lasted until 31st May 2019. It was carried out by a consortium of 27 partners consisting of large Research Institutions, Universities, one Technical and Scientific Support organization (TSO), and one small-medium enterprise (SME) from 9 EURATOM Signatory States, Switzerland and Japan. IGD-TP and the National Waste Management Organizations supported CEBAMA, for instance by co-developing the work plan, participating in the End-User Group, granting co-funding to some beneficiaries, and providing for knowledge and information transfer.

Introduction

The overall strategic objective of CEBAMA was to support the implementation of geological disposal by significantly improving the knowledge base for the Safety Case for European repository concepts. R&D in CEBAMA was largely independent of specific disposal concepts and addressed different types of host rocks, as well as bentonite. CEBAMA was not focusing on one specific cementitious material but aimed at studying a variety of representative cement-based materials for nuclear waste disposal in order to provide insight on general processes and phenomena which can then be transferred to different applications at national and international levels. Specific objectives and research activities of CEBAMA are summarized as follows:

- Experimental studies analysing interface processes between cement-based materials and potential host rocks (crystalline rock, Boom Clay, Opalinus Clay (OPA), Callovo-Oxfordian (COX), Toarcian mudstone, Borrowdale Volcanic Group) or bentonite backfill, and assessing the impact on physical and chemical properties.
- Investigation of radionuclide retention and migration processes in high pH cementitious environments, focusing on radionuclides which have high priority from the scientific and applied perspective.
- Improved validity of numerical methods to predict changes in transport processes as a result of chemical degradation, including advanced data interpretation and process modelling.

In this contribution, the main results and scientific highlights from the CEBAMA project are presented, and the potential impact of CEBAMA on the Safety Case discussed. It is also indicated which project events were organised and how the individual technical results from CEBAMA can be accessed, i.e. via peer-reviewed publications, public Deliverables, Annual Workshop Proceedings, etc. The experimental and modelling work in CEBAMA was to a significant extent performed by young researchers and within PhD theses. This contributes to the continuing availability of highly trained specialists for implementers and regulators.

1. CEBAMA, project aims and overview

The HORIZON 2020 EURATOM Collaborative Project "Cement-based materials, properties, evolution, barrier functions (CEBAMA)" was developed to support the implementation of nuclear waste disposal in deep underground facilities. Radioactive waste poses potential health hazards and risk to the biosphere including humans. The best way to handle and dispose this material is a topic of broad public debate and concern. Supporting safe options for the long-term disposal of nuclear waste is therefore a key component in developing sustainable strategies to implement nuclear energy as part of the energy mix in Europe but also within decisions taken by some countries to finally phase out the use of nuclear energy.

Cement-based materials are highly relevant for nuclear waste disposal safety, because they are widely used in a repository, e.g. as waste matrix, liners and structural components or backfill / sealing materials. In order to make reliable assessments of the potential evolution and performance of a repository with time, it is important to understand the specific chemical and physical processes affecting cement materials and their effect on radionuclide behaviour and migration. Previously to CEBAMA, significant advances were already achieved in extensive experimental programs at all scales as well as in model development and application. The ambition of CEBAMA was to considerably improve the state-of-art on several topics which were still open for discussion. Specific technical objectives tackled within CEBAMA were chosen to answer key questions and organized into three Work Packages:

WP1: Experiments on interface processes and their impact on physical properties. How do cement-based materials affect the isolation properties of other barriers, like the host rock and the clay backfill material? Experimental studies were performed in CEBAMA to understand the interface processes between cement-based materials and the host rocks (crystalline rock, Boom Clay, Opalinus Clay, Callovo-Oxfordian, etc.) or bentonite backfill and assess the impact on physical and geochemical properties.

New experimental studies on interface processes and the impact on physical properties evolution constituted the main working effort in CEBAMA. The multifold studies were considering several different interfaces and a large variety of specific cement-based materials. The main work was focused on the characterisation of different interfaces between cement-based samples and applying new methodologies. Additionally, partners were characterising and investigating the specific CEBAMA reference material (low-pH concrete and paste) prepared and distributed within the CEBAMA consortium.

WP2: Radionuclide retention. How do specific radionuclides or toxic elements of interest behave in the presence of cement-based materials considering as well that these materials will alter under long-term repository conditions? Experimental investigations focused on the behaviour of elements (Be, C, Cl, Tc, Se, Mo, I, Ra, Sr) which have high priority from the scientific and applied perspective in environments dominated by presence of cementitious materials.

Processes were investigated at high pH environments, considering various cement pastes and relevant individual hydrated cement phases and alteration products. The studies performed addressed sorption, diffusion, solid solution formation and solubility experiments. The information derived can be incorporated in complex models to predict radionuclide retention or mobilization processes in a repository.

WP3: Interpretation & Modelling. How well are we able to predict changes in transport properties coupled with chemical and physical processes on the cementitious matrix or in the cement host rock interface? Modelling work performed in CEBAMA supported advanced data interpretation and process modelling, covering mainly physical and chemical processes responsible for the changes in transport properties and extrapolate the models to different scales for application in Safety/Performance assessment.

Modelling approaches and modelling tools were developed in CEBAMA in order to analyse and predict processes that can impact the physical and chemical properties of cementitious materials and the interface between cement-based materials and host rocks or bentonite. Work was performed in close connection to the experimental studies conducted in CEBAMA, for instance within the joint studies focusing on the CEBAMA reference material. Work by the partners in CEBAMA also included the development of modelling tools for pore-scale applications, and the modelling of physical and chemical processes related to other experimental studies performed in WP1 and WP2 of CEBAMA. A Common Modelling Task was developed for organising the integration of the reactive transport modelling approaches and experimental data of the reference material in CEBAMA and to benchmark the reactive transport codes. Modelling in CEBAMA also established a close link with the Safety Case and Performance Assessment requirements.

In addition to the above three R&D Work Packages, WP4 was on Documentation, Knowledge Management, Dissemination and Training, and WP5 on Management. Detailed information on CEBAMA is available at the project website at www.cebama.eu.

2. Experimental Workplan and R&D programm (WP1, WP2, WP3)

The specific objectives in CEBAMA were separated into three main scientific and technical topics (WP1, WP2 and WP3, see above), which are interconnected with each other. In the following sections, the experimental Workplan and R&D program of CEBAMA is summarized. For WP1 and WP3, joint activities organised within CEBAMA, emphasising the specific advantages of performing research within a large international consortium with complementary expertise and experiences, are highlighted.

WP1: Experiments on interface processes and the impact on physical properties.

The largest amount of resources (~50%) and the most work effort was used for WP1 with 19 institutions participating, led by VTT (Finland), BRGM (France) and the University of Bern (Switzerland). The main objectives were: (i) to perform experimental investigations to better understand and quantify the alteration processes between cement-based materials and different host rocks of interest to Waste Management Organizations (i.e. crystalline rock, Boom Clay, Opalinus Clay (OPA), Callovo-Oxfordian (COX), Toarcian mudstone, Borrowdale Volcanic Group) or engineered barrier components (bentonite backfill) and (ii) to assess their impact on physical (i.e. diffusivity, hydraulic conductivity, porosity, strength,…) and chemical (i.e. porewater composition, mineralogy) properties.

Two types of cementitious materials (based on ordinary Portland cement (OPC), and/or “low-pH cement”) were studied, which were in contact with either aged or fresh interfaces (i.e. claystone, bentonite, other rock types) or with model pore water / groundwater solutions. A key source for aged interface materials were ongoing experiments from existing underground research labs (URLs, samples up to 10+ years old) from 6 European URLs in Switzerland, France, Czech Republic and Belgium (i.e. Grimsel test site, Mont Terri laboratory, HADES, Tournemire, Meuse/Haute, Josef) and from Japan. The work of the partners in WP1 focused on five main topics:

- Quantifying transport parameters of altered and unaltered cement-based samples by performing through- and in-diffusion experiments and development of new non-invasive techniques (i.e. GeoPET method).
- Study of hydro-mechanical processes in the interface cement - Callovo Oxfordian claystone, measuring the evolution of flow and strength properties of different cementitious-based materials (i.e. low-pH concrete).
- Study of thermo-hydro-geochemical processes in the interface cement-clay, measuring changes on transport properties due to mineralogical alteration and microstructure changes (e.g. Ca leaching, carbonation).
- Analyses of interface reactions, with respect to changes in mineralogy and porosity evolution, between different materials in contact with solutions with different compositions (i.e. pH, redox, carbonate, sulphate concentration, salinity) by percolation and leaching experiments.
- Manufacturing and characterisation of the reference materials of the CEBAMA project as a benchmark to other studies by various partners.

As reference materials within the CEBAMA project, ternary low-pH concrete (RCM) and a paste (RPM) were manufactured, setting a specific focus on high-performance low–pH materials. Mixtures were cast at VTT in March 2016 and distributed among several CEBAMA partners early in the project. This reference material was also used in WP 2 and WP 3 of CEBAMA, thus further exploiting synergies between the partners and different WPs in CEBAMA.

The reference mix designs and materials were characterised by different partners in CEBAMA using several techniques (i.e. XRD, XRF, TG/DTA, ^{29}Si and ^{27}Al MAS NMR, X-CT, SEM/EDX, XAS, ICP-OES, etc.) providing complementary information on mechanical, chemical, transport properties and microstructure. Table 1 provides an overview of the applied characterisation methods used by the partners.

TABLE 1. CEBAMA reference concrete and paste characterisation methods.

Quality	Partner	Paste (RPM)	Concrete (RCM)
Fresh-stage properties			
Workability	VTT	yes	yes
Air Content	VTT	no	yes
Heat of hydration	USFD	yes	no
Setting	USFD	yes	no
Mechanical properties			
Compression strength	VTT, USFD, CTU, UJV	yes	yes
Chemical composition			
X-ray diffraction (XRD)	KIT, USFD, JUELICH, SURREY, CSIC, UAM	yes	yes
X-ray fluorescence (XRF)	SURREY	initial materials	
Thermogravimetry (TG/DTA)	KIT, USFD, CSIC, UAM	yes	yes
^{29}Si and ^{27}Al MAS NMR	KIT	yes	no
Energy dispersive microscopy (SEM, Back Scattering+ EDS)	KIT, CSIC, USFD, JUELICH	yes	yes
X-ray absorption spectroscopy (XAS, Fe and Cl K-edge)	KIT	yes	yes
Pore solution pH	KIT, VTT, CSIC	yes	yes
Microstructure			
Scanning electron microscopy (SEM)	KIT, CSIC, USFD, JUELICH	yes	yes
Porosity	CSIC, USFD, UJV, BRGM	yes	yes
X-ray computed tomography	USFD	yes	no
Transport properties			
Leaching	VTT	yes	yes
Percolation	USFD, SURREY, CSIC, CTU, UJV	yes	yes
Diffusion	JUELICH, CSIC, UAM, KIT	yes	yes
Other			
Density	VTT, USFD	yes	yes
Spectral induced polarization (SIP)	JUELICH and BRGM	yes	no

Most of the results were in agreement but also some disparities were observed. Mineralogical composition, diffusion coefficient and pore solution pH were determined with multiple methods. The results enable comparison between different experimental set-ups and increases cohesion of individual experiments. Low diffusion coefficients (RPM: $10^{-(12-13)}$ [mol(HTO)/(m^{2}s^{-1})] and high compression strengths (RCM: 115 MPa, RPM: 150 MPa) were determined with multiple methods. The results confirmed that nanoporosity has a large effect in high performance cementitious materials' total porosity and thus long term performance. In the studies, the importance of curing temperature on pH development was observed, meaning that pH decreases significantly slower in cold environments.

WP2: Radionuclide retention.

There were 10 institutions working in WP2 of CEBAMA which was led by ARMINES/SUBATECH (France). The work of the partners in WP2 was focused on radionuclide retention/migration processes. The main efforts were dedicated to (i) high pH cementitious environments characteristic for cementitious materials, (ii) relevant individual hydrated cement phases and cement pastes and (iii) aged cement pastes. Additionally, the low-pH reference materials of the CEBAMA project as developed in WP1 were considered. The investigations in WP2 include retention or sorption, diffusion, solubility and co-precipitation studies. Focus was put on elements and nuclides for which only insufficient information was available before CEBAMA was started and rather large related uncertainties existed. Work performed by partners in WP2 is divided into the following topics:

- Detailed solid characterisation performed on the experiments with radionuclides using several complementary analytical techniques. (e.g. XRD, XRF, BET, SEM/EDS, TG-DSC and ^{29}Si NMR).
- Solubility experiments with Be, Mo and Se under high pH conditions. Providing for realistic solubility limits and radionuclide speciation schemes was a prerequisite for meaningful sorption studies allowing to derive advanced models on radionuclide retention.
- Sorption/desorption experiments were carried out using various radionuclides or toxic elements (i.e. Be, Mo, Ra, Tc, I^-, IO_3^-, SeO_3^{2-}/SeO_4^{2-}, Cl^-, Ra, Sr and ^{14}C) and various hardened cement paste formulations as well as individual cement phases.
- Solid solutions formation between various radionuclides in a range of oxidation states (Se, I and Mo) and main components (OH, S, Cl…) in cementitious phases (AFm).
- Diffusion experiments were performed with various anionic species ($^{36}Cl^-$, $^{99}TcO_4^-$, $^{125}I^-$, ^{14}C) or sorbing radionuclides (Ra, Sr) through saturated hardened cement pastes considering as well partially water saturated conditions.

As examples of research performed within WP2 of CEBAMA, studies on Se and Be retention are summarised in Fig. 1. The joint research performed by CEBAMA partners offered a significantly improved description of Se retention in a variety of systems, while studies on Be within CEBAMA give clear experimental evidence of a strong Be retention in cementitious system, contrary to previous assumptions.

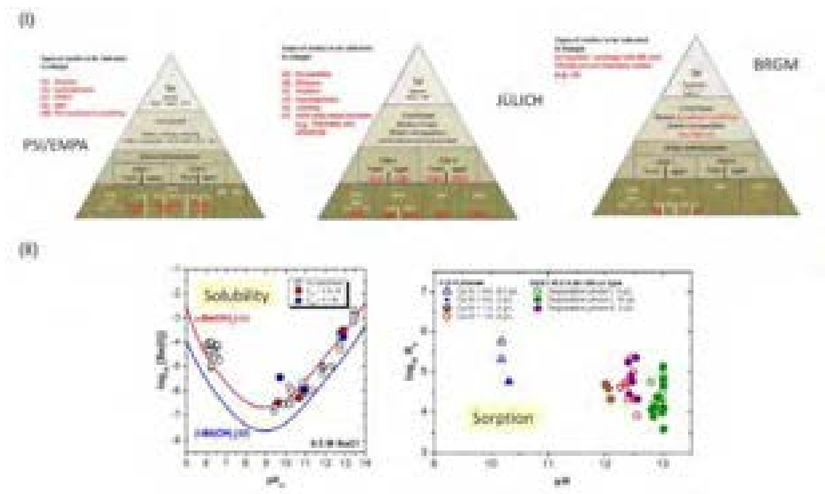


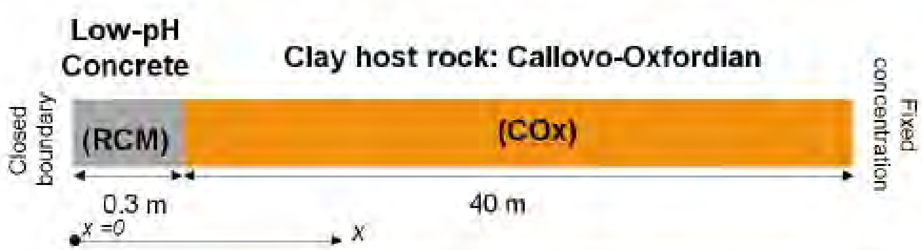
FIG. 1. (i) Overview on the specific systems studied in CEBAMA on Se retention by PSI/EMPA, JUELICH and BRGM. (ii) Studies on Be retention by KIT indicate strong Be retention in cementitious systems.

WP3: Interpretation & Modelling.

In WP3 of CEBAMA, advanced modelling approaches were developed and improved to predict coupled THMC processes at the interface between cement-based materials and engineered or natural barriers in crystalline and argillaceous host rocks. A total of 13 partners were working in this WP led by AMPHOS21. Activities within this WP were mainly dedicated to the modelling and interpretation of experimental data, also generated within CEBAMA in WP1 and WP2. WP3 was additionally contributing to extrapolate modelling to system-level for Safety Case applications and validate different modelling tools. Main modelling work was focused on four main tasks:

- Development of modelling tools with pore- and continuum-scale applications including new capabilities (i.e. Poisson-Nernst-Planck equations, Poisson-Boltzmann equations, coupling with geochemical solvers, coupling between chemistry and mechanics, etc.) in already existing or new codes (i.e. iCP, ORCHESTRA, MATLAB, iPP, Yantra, etc.).
- Modelling work with application to WP1 and WP2 experiments (i.e. through-diffusion tests, leaching tests, cement-clay interaction, etc.), including reactive and mass transport simulations, cement hydration models, solubility calculations and hydromechanical simulations.
- Long-term modelling of concrete-clay interactions including reactive transport and hydro-mechanical-chemical coupled analyses.

To optimize the integration of different modelling approaches and the experimental data obtained in CEBAMA, a Common Modelling Task was developed within the project. The goal of this task, which was supported by 8 different partners, was to cluster WP3 activities around a common long term simulation case, using a low-pH cement (CEBAMA reference material) / clay interface, based on the set-up shown in Fig. 2. The figure shows the geometry used in the simulations. The interface investigated is resolved with cm-scale elements at both sides of the interface. Initial properties and composition of the low-pH cement used in the simulation were based on the experimental findings obtained for the reference ternary low-pH concrete. The Common Modelling Task helped to increase confidence in the consistency of the different modelling approaches (see contribution to EURADWASTE by A. Idiart et al.) for the simulation of the long-term behaviour of low-pH cementitious materials with reactive transport tools.



Material	Porosity	Pore diffusivity (m²/s)	Effective diffusivity (m²/s)
COx claystone	0.18	$1.44\cdot10^{-10}$	$2.60\cdot10^{-11}$
Low-pH concrete	0.04	$2.50\cdot10^{-11}$	$1.00\cdot10^{-12}$

FIG. 2. Geometry and key parameter of the system investigated within the Common Modelling Task.

3. CEBAMA Results, Application to Safety Case and Future Recommendations

CEBAMA addressed key issues of relevance for long term safety and key scientific questions related to the use of cement-based materials in nuclear waste disposal applications. The scientific quality and impact of the project built on joining the best expertise available to tackle these problems and emphasising how the knowledge can be applied in Performance Assessment and the Safety Case. According to IAEA (2012) [1] the Safety Case is the collection of scientific, technical, administrative and managerial arguments and evidences in support of the safety of a disposal facility, covering the suitability of the site and the design, construction and operation of the facility, the quantitative assessment of short and long term risks as well as more qualitative safety indicators and assurance of the adequacy and quality of all of the safety related work associated with the disposal facility. Safety Assessment, an integral part of the Safety Case, is driven by a systematic assessment of radiation hazards.

CEBAMA has improved the knowledge base for the Safety Case via the following specific items: (i) safety impact of microstructural and porosity changes of cementitious materials (i.e. cement paste, mortar and concrete), (ii) safety impact of cement degradation, (iii) creation of long-term models, (iv) decrease of uncertainties in radionuclide retention processes, (v) development of modelling expertise and methodologies and (vi) upscaling modelling in time and space. A specific focus was put on the (vii) investigation of low-pH cement-based materials, and hence conclusions can be drawn from the work within CEBAMA on the potential use of this relatively new material in waste disposal applications. In the following, potential links between CEBAMA to new activities within the new EURAD joint research program (2019-2024) are indicated.

To ensure that the project was directed towards implementation and application, the End User Group (EUG) represented the view of the main users of the research performed in CEBAMA. The organisations taking part of the EUG of CEBAMA were: NAGRA (CH), ANDRA (FR), POSIVA (FI), SKB (SE), COVRA (NL), ONDRAF/NIRAS (BE), RMW (UK), ENRESA (ES) and SURAO (CZ). These waste management organisations come from countries in very different stages of implementation, so that the implication that the results of CEBAMA have on their interests may vary from case to case.

Regarding the **study of the cement-clay interfaces (bentonite and clay host-rocks)** related to WP1, the results obtained within CEBAMA provide evidences of the effect of different cement formulation on the clay-cementitious materials interfaces. Experiments have included in-situ large-scale long-term data gathered from Mont Terri and Grimsel in Switzerland, HADES in Belgium, Bure in France as well as laboratory tests.

The studies provided evidence of a relatively good understanding of key processes in all systems, also resulting from the wide range of mature and tested analytical and experimental techniques available. The most relevant results are summarised below.

- At low temperature (25°C), whatever the concrete mixture formulation, both very little clay and concrete alterations were observed during the early phases (0-13 years) with respect to mineralogical changes being limited to the mm scale. The cement-internal extent of alteration in low-pH material was at least as extensive as in OPC (although rather difficult to compare due to many relevant parameters). However, it needs to be realised that another advantage of “low pH” cements compared to OPC is a low-heat hydration temperature, which minimises the microcracking that can have negative consequences on the cement's long-term durability. Therefore, mineralogy is not the only driver to consider for cement-based materials formulation.

- Regarding porosity (and mass) re-distribution at small scale, an only partially coherent pattern was observed, indicating a potential tendency of permeability reduction.
- According to the results and with specific focus on radionuclide mobility, low pH cementitious materials did not minimise the extent of reaction between bentonite and cementitious materials in the "high-performance" materials investigated (having dense paste structure). There also was no significant reduction of the mobility of highly mobile anionic radionuclides like $^{36}Cl^-$ and $^{129}I^-$ in cement (see contribution by N. Ait Mouheb et al. to EURADWASTE).

Based upon the R&D performed within CEBAMA WP1, recommendations were derived to provide input for future research activities. It was noted that there is still a relatively small database for measured hydro-mechanical-diffusion (H(D)M) properties with interfaces, a problem which could be elaborated with new in-situ experiments (i.e. CI-D at MontTerri, Switzerland). Some experiments seem to indicate that the concrete-clay interface does not appear to be a weak zone of permeability, contrary to previously accepted hypothesis. However, the mechanical stability of mm-scale porosity-reduction zones is difficult to assess (impact of skin on transport, i.e. performance with hydraulic differential pressure induced by gas overpressure). The impact of interfaces on gas transport need to be further investigated (which is the scope of the new EURAD-GAS project). Rather little information is available on the increased amounts of organic additives associated with low-pH cements (which is the scope of the new EURAD-CORI project). The question of upscaling results and models will be partially addressed in the new EURAD-DONUT project, and thus these additional activities seem justified for future added value to the end users. In terms of extrapolation of time from decades to centuries and millennia, the CEBAMA methods may be used to assess natural analogues. Moreover, there is a rather thin database on temperature effects potentially impacting the above interface processes.

The results obtained within WP2 of CEBAMA provide an increased understanding of the **behaviour of several safety relevant radionuclides** within cementitious barriers in the repository environment, thus decreasing uncertainties with respect to relevant radionuclide retention processes. The results can be used to substantiate and justify assumptions made with respect to the radionuclide migration behaviour in Safety Assessments. The excellent collaboration between the different research teams involved was key to the success. The collaborative approach for instance featured many research visits and exchanges between laboratories (RATEN/SUBATECH, BRGM/KIT, AMPHOS/JUELICH, USFD/JUELICH, CTU/JUELICH) and the organisation of a focussed anion cluster meeting. The experiments performed and the interactions between partners contributed to identify new research directions of less advanced projects. WP2 has realised an important step forward in the understanding of retention processes on cementitious materials, in particular for anionic species, based on the largely coherent scientific results obtained by the different groups. Key findings are:

- For the uptake of anions in AFm phases a continuous solid solution was found between the end members Se(IV)-AFm and S(VI)-AFm, with a continuous peak shift towards higher basal spacing with increasing amount of SO_4^{2-}. Solid solution formation was also observed between the pairs I-OH and I-OH_CO_3. At an iodide fraction of 0.1 a miscibility gap is observed. In the I-OH_CO_3 pair no miscibility gap is observed. The solid solution formation between the I-AFm and monocarbonate

(CO_3-AFm), is incomplete and a miscibility gap with the composition 0.5 ≤ $CO_3/(2I+CO_3)$ exists. The thermodynamic properties of each of the pure Se- and I-AFm phases and of AFm phases containing binary mixtures of Se and I with the common anions present in cement, were determined.

- Due to the higher amounts of aluminate phases in HCP based on CEM I, the retention capacity for the selenite and selenate is higher in this case compared to the low–pH CEBAMA reference paste.
- Flow-through studies have shown that the Se(VI)/Cl exchange on AFm-Cl is rapid and reversible. The exchange can be modelled by 2 anion exchange sites. Exchange constants were obtained with associated selectivity coefficient based on the Gaines and Thomas convention. Accurate rate laws were determined implementable in reactive transport modelling.
- CEBAMA has provided a first set of sorption parameters of Beryllium onto cementitious phases. In contrast to the traditional hypothesis of very weak Be sorption, assumed on the basis of the negative charge of the Be(II) species at high pH values, a strong uptake has been confirmed for all investigated systems. This finding helps decreasing the conservativism when conducting calculations supporting Performance Assessment and decreases previously existing uncertainties. (see contribution by X. Gaona et al. to EURADWASTE).
- Project studies have shown that the sorption of molybdenum in cementitious environments is not associated with ettringite, in contrast to what has been traditionally assumed. This finding has important implications on sorption analogies - the project recommends not to use arsenic as analogue for molybenum in sorption estimations, as it has been done in previous exercises.
- CEBAMA results showed a significantly higher retention of Ra than that of Sr onto cementitious materials. This again, decreases uncertainty and conservativism, and leads to a recommendation to revise sorption analogies used in SC to date. (see contribution by J. Kittnerova et al. to EURADWASTE).
- A strong reduction of sorption of ^{14}C(inorg) has been observed with the increased degradation of cement pastes. In contrast, Ra sorption increases with increased degradation.

Looking beyond the work in CEBAMA, future recommendations were identified. Regarding quantitative description, the thermodynamic models developed in the present project with individual cement phases should be validated in real cement-based material systems. Future studies should also extend to include Fe(II)-bearing phases, which might significantly affect the behaviour of redox-sensitive radionuclides, and focus on the kinetics of mineral dissolution and precipitation. In this context, differences in data from various teams (i.e. regarding kinetics, pH, S/L ratio, etc.) should be resolved and eventually interpreted beyond the Kd-concept to clearly identify a boundary between adsorption and solid solution phenomena and to include advanced molecular level understanding. As capacities to assess the effect of competition have advanced, considering other anionic species (sulphate…) or organics (ISA, gluconate…) on radionuclide retention is needed (link to EURAD-CORI). A better understanding of the pH effect in AFm/AFt interactions with radionuclides would be positive. Stability of AFm phases at the claystone concrete interface should be clarified. Last but not a least, quantification of transport and retention in unsaturated conditions still is challenging. With view towards EURAD, work performed in CEBAMA shall be included in state-of-the-art (SOTA) documents.

CEBAMA has represented a step forward in **model development on the behaviour of cementitious materials and the cement-clay interfaces** in WP3. Models have included new thermo-hydro-mechanical (THM), chemo-mechanical (CM) and reactive transport developments. Overall, a very good level of collaboration between the different partners and with WP1 and WP2 in CEBAMA was reached. In general, good agreement between results obtained by different models and the available experimental data was observed. Interpretation of CEBAMA experiments with WP3 models has served to increase confidence in system understanding and identify remaining gaps. It also supported development of modelling tools and incorporation of new features in existing codes. The outcomes of WP3 represent a significant step forward in the quantitative assessment of physical and chemical processes of cementitious materials and their interface to clayey host-rocks. Results showed a high level of understanding of governing processes and the good agreement between reactive transport codes, which is essential for the use of these tools in a Safety Case. The specific focus put on low-pH cement-based materials, allows drawing conclusions on their potential use for nuclear waste management. CEBAMA has improved the knowledge base for the Safety Case by improving the following modelling aspects: (i) impact of cement degradation, microstructural and porosity changes of cementitious materials, (ii) development of long-term and upscaled models, (iii) development of modelling expertise and methodologies. CEBAMA clearly represents a step forward in modelling the behaviour of cementitious materials and cement-clay interfaces.

Some of the most prominent results are detailed below:

- THM models of clay-concrete interfaces, based on elasto-plasticity, have been developed that can now be used in future assessments of the behaviour and evolution of interfaces between concrete and different host rocks.
- New model features developed and implemented in WP3 include: diffusion-porosity changes couplings, electro-chemical multi-component diffusion capabilities, homogenization schemes for mechanical and transport properties, more efficient pore-scale reactive transport tools, and extended membrane polarization models for porosity and pore size distribution.
- CM models have been developed to predict the impact of chemical interaction of concrete with other materials in the repository on the mechanical integrity of cement-based barriers (i.e strength, stiffness, pore space). Additionally, new couplings were established regarding electrochemistry, diffusion-porosity couplings, CM models, HM coupling of clay/concrete interfaces, etc.
- New insights on newly developed low-pH cement and concrete were derived, including: hydration modelling in low-pH and low w/b ratio systems; assessment of diffusion properties from microscopic considerations; pore structure (pore-scale reactive transport models, homogenization models and membrane polarization models); assessment of thermodynamic data in low-pH systems: C-S-H, C-(A)-S-H, Fe speciation, alkali uptake, etc.; and hydro-mechanical behaviour of clay/concrete interfaces.
- For the first time, reactive transport models have explicitly considered the hydration of low-pH cement and how water consumption during hydration impacts the final mineralogical composition. This information is essential in Safety Assessments to determine the initial state and the early evolution in the post-closure period.
- The Common Modelling Task of CEBAMA has built confidence on the reactive transport tools used when simulating the long-term behaviour of an interface

between low-pH concrete and a clayey host rock. The results show not only the high level of understanding of the governing processes but also the good agreement obtained with different codes, which is essential to demonstrate for the use of these tools in Safety Assessments (see contribution by A. Idiart et al. to EURADWASTE).

In view of open questions for future research, more validation work in general is needed, also including the development of more quantitative data of mineralogical changes in the cement/clay interface or in low-pH cement-based materials (M-S-H, low C:S C-S-H, C-(A)-S-H), also considering associated changes in transport properties (pore-structure, effective diffusion, permeability) and porewater composition, and the consideration of aggregates and superplasticizer chemical interactions. Numerical capabilities and efficiency of models should be further improved, especially for repository-scale or pore-scale simulations in 3D. Upscaling from pore-scale to continuum scale modelling is still not trivial. Further development of conceptual modelling of Ra uptake in cement-based materials is needed. Evaluation of long-term HCM behaviour of interfaces still needs to consider time-dependent deformations of clay and concrete. Surface complexation modelling is still needed to interpret zeta potential results on RCM.

4. Project dissemination and indicators

CEBAMA featured several dedicated activities to disseminate the results of the project to the technical/scientific community and all interested stakeholders making use of several complementary tools. The project website at www.cebama.eu served as a successful platform for information exchange within the project partners and with interested stakeholders. CEBAMA distributed a Newsletter on a regular basis to inform on project activities and selected research highlights, specifically targeting non-technical stakeholders.

Key events in the project were the four Annual CEBAMA Workshops (2016 – Barcelona, Spain, hosted by AMPHOS21; 2017 – Espoo, Finland, hosted by VTT; 2018 - Nantes, France, hosted by ARMINES; 2019 – Karlsruhe, Germany, hosted by KIT). The Annual CEBAMA Workshops were clustering several activities, including information exchange, monitoring of work progress, dissemination of results, interaction with End Users and other stakeholders, amongst others. The technical presentations were summarised in the Workshop Proceedings, made available at the project website and published at KIT Scientific publishing following a peer-review process involving the End User group (EUG) including persons affiliated with European Waste Management Organizations. Specific topical sessions were integrated into the Workshops, with the Socio-political Stakeholder panel discussion organized by E. Holt (VTT) of CEBAMA focusing discussion on the Finnish repository project, or the Session on the significance of cement-based materials in decommissioning organised at Nantes meeting being two of the highlights. In order to enhance the visibility of CEBAMA for the interested international scientific community, the Final CEBAMA Workshop was organised in connection to the 5th International Workshop on “Mechanisms and Modelling of Waste / Cement Interactions” in Karlsruhe, March 2019, gathering more than 100 participants. CEBAMA partners were invited to present results generated in the project to this conference and submit manuscripts for publication in a special issue of a peer-reviewed scientific journal.

In addition to these dissemination actions, a comprehensive set of public Deliverables was prepared by CEBAMA and made available at the project website. These documents provide plenty technical details and allow an in-depths view on the R&D carried out in the project, but also include Deliverables prepared with the aim of integrating results and outcomes.

Key Deliverables allowing an integrated view on the CEBAMA project results are mainly D1.7, D2.6 and D3.8 (manuscripts for peer-reviewed publications on the results generated within WP1, 2, 3, respectively), and D4.20 (report on the relevance of the outcome of CEBAMA for the Safety Case).

FIG. 3. Participants at CEBAMA Final Workshop, March 2019, Karlsruhe, Germany.

Significant efforts were also devoted by the individual project participants to disseminate the technical information and knowledge generated in the frame of this project. More than 60 articles have been published, submitted or are in preparation (as of February 2019) for their submission in several peer review scientific journals. A list of publications is available at the CEBAMA website. Additionally, researchers have attended to different international conferences and workshops to present their work by either oral talks or in poster sessions. CEBAMA has produced 90 presentations (oral talks and posters) at conferences and meetings, highlighting the results of partners including joint contributions between partners in CEBAMA. Additional presentations were given by the members of the Coordination Team on the overall CEBAMA project.

The CEBAMA project has gathered together more than 100 participants, including renowned senior researchers, a significant number of students and young PostDoc researchers, as well as technicians and administrative staff. About 50% of the participants in CEBAMA hold a PhD. In terms of gender, a good balance was achieved in the project with 47% female participants, however, gender inequality exists when analysing category profiles. Some examples can be found when looking at gender indicators of professors/main investigators vs. administrative, the former dominated by men (80%) and the latter by women (88%). Project external partners joining in the frame of an Associated Group Agreement were Moscow State University (MSU), Russia, Los Alamos NL Carlsbad Office (LANL-CO), USA, and the Swiss Federal Nuclear Safety Inspectorate (ENSI), Switzerland.

A very important point is that CEBAMA has been very successful in training young scientists: 7 students did their master thesis and 14 students performed their PhD thesis within the CEBAMA project. Several early career PostDoc researchers were likewise working in CEBAMA. The young researchers were specifically supported by targeted mobility measures, giving the opportunity for working at hosting CEBAMA organisations with special tools or expertise, following an internal proposal system. Specific PhD sessions at the Annual CEBAMA Workshops or PhD workshops organized by one of partners (i.e. PSI) put a further focus on supporting young talent.

5. Summary and impact

As main outcome and key impact of the scientific studies carried out in the CEBAMA project, advanced modelling approaches were developed which allow predicting the performance of cement-based materials in contact with the engineered and natural barriers of repositories in crystalline and argillaceous host rocks and the retention of radionuclides by cement-based materials. These improved models may be applied for high level waste disposal but also for scenarios in low and intermediate level waste disposal, currently implemented in several countries. CEBAMA has enhanced the publicly available knowledge on the performance and reliability of the engineered barrier systems (EBS) for nuclear waste repositories. This has impact on the public debate on nuclear waste disposal, also by keeping non-scientific stakeholders informed.

CEBAMA established cooperative international research for basic understanding of EBS systems, with main highlights addressing design issues, safety assessment issues, radionuclide retention and modelling. CEBAMA influences several design issues (which thus (i) impact optimisation of repository dimensioning; (ii) aid specification/selection of material parameters, material compatibility, evolution; (iii) aid specifications for experimental methods, i.e. for material quality control). CEBAMA has likewise advanced several safety assessment issues (which thus (i) provide evidence that interfaces (concrete-bentonite-host rock) can co-exist safely; (ii) provide better understanding of impacts from material interface processes for realistic description of the system performance affecting strength, flow properties, etc. and transport processes variation with time; (iii) evidence porosity changes – if and when clogging occurs; (iv) offer improved accuracy in robustness and weighting of safety functions; increased modelling accuracy with new data and process understanding (WP3)), accounting for evolution of the system. With the view on radionuclide retention the results can be used in particular by WMO, TSOs or regulators for the evaluation and assessment of radionuclide migration in cementitious repository near fields by (i) decreasing uncertainties and increasing safety margins with respect to relevant radionuclide retention processes, (ii) substantiating and justifying assumptions made with respect to the radionuclide migration behaviour in Safety Assessments, and (iii) improving sorption databases for cementitious environments for so far less studied systems and different stages of system evolution (i.e. cement-based material degradation) in the long-term. Furthermore, there is a direct input to case studies like for the LLW-ILW repository Bratrství (Czech Republic) and the licensing process for the near surface repository in the proximity of Cernavoda NPP (Romania). Regarding modelling, CEBAMA increases the level of confidence in reactive transport models for further use in Safety Cases for near-field applications. The project provided improved reactive transport modelling tools, available as open source or upon request, to quantify how bentonite barrier or clayey host rocks could affect the integrity of normal and low-pH cementitious materials. The developed models can be used by end users to study the impact of reactive transport processes, but also other THMC coupled processes on the long-term performance of the near-field, including low-pH cement-based materials. Pore-scale reactive transport models can be used as process models in support of the Safety Case to enhance understanding of the impact of alteration of cement-based materials on their transport properties.

Besides pure scientific and technical based impacts in terms of generating specific knowledge and decreasing uncertainties, the enhanced cooperation/exchange and knowledge transfer between different institutions on an international level is highly valuable. This is including cooperation between research institutions in different fields (i.e. Geosciences, Environmental Engineering, Radiochemistry and Computational Sciences) with access to specific sophisticated state-of-art analytical equipment and modelling tools. CEBAMA Consortium members thus became aware of the respective complementary competencies, and, based on this experience, will likely tackle future challenges in a focused, cost-saving, collaborative approach.

The experimental and modelling work in CEBAMA was to a significant extent performed by young researchers and within PhD theses. The dedicated support of young talent actively involved in the CEBAMA project contributes to the maintenance of competences, aiming to ensure continued availability of highly trained specialists for implementers and regulators.

Last but not a least, CEBAMA has contributed to European integration by bringing together experts from several European member states and Japan. The involvement from experts coming from countries at very different stages of implementation likewise poses a positive achievement, for instance in view of sharing of expertise and resources and integrating new member states.

Acknowledgements

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References

ASAMPSA - General issues for PSA

[1] IAEA (2012) The Safety Case and Safety Assessment for the Disposal of Radioactive Waste. IAEA Safety Standard Series, Specific Safety Guide. No. SSG-23. International Atomic Energy Agency Vienna, 2012.

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BENTONITE EROSION: EFFECTS ON THE LONG-TERM PERFORMANCE OF THE ENGINEERED BARRIER AND RADIONUCLIDE TRANSPORT – THE BELBAR PROJECT

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Abstract. BELBAR was a Collaborative Project within the Seventh Framework Programme of Euratom for nuclear research and training activities. The main aim of BELBaR was to increase knowledge of the processes that control clay colloid stability, generation and its ability to transport radionuclides (RNs). More specifically the aim of BELBaR was to reduce uncertainties in the description of the effect of clay colloids on the long-term performance of the engineered barrier and on RN transport. This was done by:

- improving the understanding of when bentonite colloids are unstable — for a given site/site evolution, to determine whether or not clay colloids need to be included in the long-term assessment;
- improving the quantitative models for erosion on the bentonite barrier for cases when the colloids are stable;
- improving the understanding of how RNs attach to clay colloids — this information is used to formulate improved transport models for the assessment of RN transport.

1. Introduction

The Collaborative Project was based on the desire to improve the long-term safety assessments for repository concepts that combine a clay EBS with a fractured rock. The formation and stability of colloids generated from the EBS may have a direct impact on the assessed risk from the repository in two aspects, as illustrated in Fig. 1:

- generation of colloids may degrade the engineered barrier;
- colloid transport of RNs may reduce the efficiency of the natural barrier.

An increased understanding of processes will have an effect on the outcome of future assessments.

2. Background and the problem

Clay colloid chemistry and the properties of bentonites and smectites have been studied intensively over a long time, both within and outside the waste management community. There is a sound theoretical basis for the forces acting on and between smectite particles in gels and suspensions and how these are influenced by water chemistry. Much experience has been gathered on practical use of bentonite suspensions used as drilling muds and as additives to various products including paints to give them thixotropic properties.

Nevertheless, there are areas where the behaviour of smectite gels and sols, which have important impact on the possible erosion of a bentonite buffer, are not sufficiently understood.

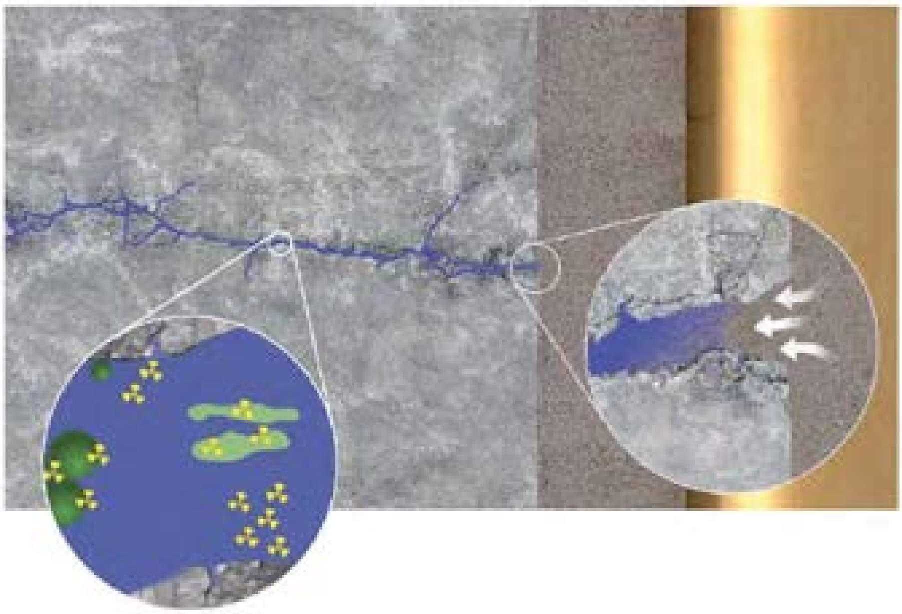

FIG. 1. Generation of colloids from a bentonite buffer and radionuclide transport in fractures.

The uptake of water and resulting swelling of the bentonite buffer is counteracted by the walls of the deposition hole, and a swelling pressure is developed in the bentonite. Fractures intersecting the deposition hole mean that rigid swelling restrictions are not present everywhere, and that localised swelling continues into the fractures until an equilibrium or steady state is reached. This free swelling may lead to separation of individual montmorillonite layers (dispersion) and part of the buffer could be transported away by groundwater.

Clay colloids released could be a carrier of RNs. Colloid mobility is strongly dependent on fracture geometry (aperture size distribution and fracture surface roughness) as well as chemical heterogeneity induced by the different mineral phases present in the fracture-filling material and the chemistry of the matrix porewater. In the case where bentonite colloids are stable, the high concentrations of colloids that may be present in the water may have a significant impact on the RN transport in the geosphere.

3. Concept and methodology

The main aim of BELBAR was to reduce uncertainties in the description of the effect of clay colloids on the long-term performance of the engineered barrier and on RN transport. This was done by:

- improving the understanding of when bentonite colloids are unstable for a given site/site evolution — this is critical information since it determines whether or not clay colloids need to be included in the long-term assessment;
- improving the quantitative models for erosion on the bentonite barrier for cases when the colloids are stable;
- improving the understanding of how RNs attach to clay colloids — this information is used to formulate improved transport models for the assessment of RN transport in the geosphere.

To meet the main aim, a number of experimental and modelling activities were undertaken within the project.

With respect to the erosion of a bentonite EBS and the RN transport with colloids in a fractured host-rock far-field, and application to the associated safety assessments, the work plan aimed at:

- identification of the key issues in safety assessments;
- implementation of a training package;
- survey of modelling needs and current capabilities;
- review of the understanding of the clay colloid stability field;
- definition of the need for data and observations from the experimental programmes;
- implementation of extensive experimental work in the relevant fields;
- development of improved conceptual and mathematical models;
- formulating the results based on its use for decreasing uncertainty in safety assessment;
- encouragement of publications of results in peer-reviewed journals;
- provision of overall project management.

BELBAR consisted of six RTD WPs and one project management WP. The focus of the RTD WPs was on:

WP1: Safety assessment;

WP2: Erosion;

WP3: Radionuclide and host rock interactions;

WP4: Colloid stability;

WP5: Conceptual and mathematical models.

There was also one WP on knowledge management and dissemination and training (WP6). The targeted training package was closely associated with the RTD programme through the project workshops and exchange of researchers among partners. The last WP was on 'Project Management' (WP7).

4. WP1 Safety assessment

This WP collected and presented the current treatment of the relevant processes in safety assessments in a report. The report achieved the following:

- The current treatments of colloid issues in performance assessments PA (on the basis of national organisations involved in BELBAR only) was described;
- The limitations of previous studies and uncertainties related to colloids was noted;
- The needs for additional studies of colloids issues, and their PA relevance, was discussed;
- Such additional studies were linked to planned work in the BELBAR project, and the relevance of, and expected benefit from, BELBAR WPs 2–5 were identified.

Each of the three national WMOs represented in BELBAR WP1 produced a description of how it currently considered colloids in PA — the current state of the art. This information has subsequently been used to identify current issues affecting the treatment of colloids in PA in national programmes.

At the end of the project WP1 provided a synthesis (Shelton et al 2017) of the progress that was made as a result of the work undertaken within the BELBAR project along with recommendations for the potential to review the treatment of colloids in performance assessment.

The following points represent a summary of recommendations:

1. With respect to the safety assessment, the results of BELBAR suggest that assumptions made by WMOs relating to the dependency of mass loss rate on groundwater flow velocity could potentially be reviewed under highly 'erosive' conditions. It has been shown that bentonite erosion overall is driven more significantly by chemical forces rather than mechanical forces and thus it is recommended that the current treatment could be reviewed with respect to the driving mechanism controlling bentonite erosion.
2. All exchanger sites in the clay are currently assumed to be occupied by Na^+. This assumption leads to high erosion rates and overly pessimistic mass loss calculations since the current modelling capability is not able to take into account the effects of divalent cations such as Ca^{2+}. However, in a natural system, it would be difficult to exclude that the Na content of clay is less than the 20-25% threshold that favours colloid generation and thus the current treatment is considered to be appropriate within the overall system uncertainties.
3. The presence of different cations in solution can effect coagulation, with divalent cations being more effective than monovalent ions as coagulants. It is currently assumed that mass loss ceases when groundwater salinity exceeds a stability limit of 4-8 mM NaCl for Na-bentonite. Should the assumed composition of the clay be reviewed (Recommendation 2) then consideration should also be given to addressing the conservatism that would be inherent in the assumed bentonite stability limit. However, within the bounds of the current knowledge, it considered that this assumption remains appropriate.

4. In terms of the ionic strength of groundwater assumed, given that deionised water may not be representative of a real dilute groundwater, it may be considered that the maximal zero charge limit is an overly conservative scenario. However it is considered that this assumption remains appropriate within the overall system uncertainties, particularly with regard to the need to address the potential for a change on groundwater composition for example due to glacial meltwater.
5. With respect to the angle of the fracture aperture, it is observed that the mass loss mechanisms between a horizontal and sloped fracture are different. Current performance assessment assumptions assume a horizontal fracture and thus the results observed suggest that this treatment may not necessarily be conservative. It is strongly suggested that this assumption is reviewed and potentially further work is required to account for the observed effects of slope angle/ gravity.
6. Significant retardation of clay colloids in a rock fracture has been observed. However, the uptake of colloids is not complete (i.e. some remain in solution), which means that colloid transport needs to be considered, if colloids are present. It is recommended that colloid retardation could be included in safety assessment calculations. However, the effect may be limited under most conditions and the process could therefore be optimistically neglected.
7. It is clear that the current assumption of linear sorption is valid. Sorption reversibility is nuclide specific and should possibly be treated on a case by case basis. However, for most radionuclides sorption reversibility can be assumed (the exception is potentially tetravalent elements where caution should be taken) over repository time scales.
8. Organic matter (humic or fulvic acid) was demonstrated to be able to stabilise clay colloids in NaCl electrolyte. In all the other electrolytes investigated ($CaCl_2$, $MgCl_2$) and at higher Ionic strength, the clay colloids undergo fast coagulation, independently of the presence of organic matter. This is true in various aqueous media containing different inorganic cations, showing that the ionic strength remains the key parameter. In addition, Ca^{2+} ions alone are able to initiate clay colloid agglomeration even at low concentrations. The presence of Ca, even at only low concentration in natural media, is thus recommended to be considered in performance assessments (as per Recommendations 2 and 3).
9. Regarding validation and advancing the models, sufficient confidence was obtained to predict clay mass loss rate on laboratory scales using numerical simulations, whereas mass loss rate predictions on repository relevant scales remain to be assessed using analytically derived expressions for bounding estimates. According to the bounding estimates referred to, the agglomerate/floc migration rate in fracture is the mass loss rate determining feature.
10. The reasoning of dominant processes was succeeded considering agglomerate migration but was based only on expert judgement for clay swelling and gravity. Moreover, data needs specifications to assess the relative importance of clay swelling and gravity were raised but only when it was too late to commit experiments within BELBAR.
11. It can be stated that a new bounding estimate is proposed to be used in the safety cases to assess clay mass loss rates; loss of clay at the clay-water interface is limited by migration of newly formed clay agglomerates in fractures. This estimate can be obtained with far less effort and uncertainty than used in the previous safety cases.

5. WP2 Erosion

In WP2 several research groups collaborated to identify the most important mechanisms involved in bentonite erosion and to quantify its possible extent under different environmental conditions. Different possible scenarios were considered: the static system, where the transformation of the hydrated bentonite gel to a sol is mainly a chemically driven process and the dynamic one where other hydraulic aspects, as water velocity or fracture geometry must be considered. In fact, the worst scenario for a HLRW repository in crystalline rocks includes the presence of hydraulically active fractures near the bentonite surface.

In both scenarios, the extent of erosion is expected to depend mainly on the combination of water chemistry and clay properties; however, in the dynamic system, the water flowing at the bentonite surface (the gel-front) may increase colloid detachment.

In order to address the goals of this WP, different experimental sets-up were used by the different organisations. Most of the tests were carried out simulating the potential extrusion/erosion behaviour of bentonite buffer material at a transmissive fracture interface. A schematic of this type of test can be seen in Fig. 2. With this system, the effect of solution chemistry, material composition, flow velocity, fracture geometry (aperture, slope angle) and other parameters could be analysed. In this set-up, the swelling clay material can extrude/erode into an artificial fracture and it was selected for performing the tests of the benchmark exercise, also carried out in WP2.

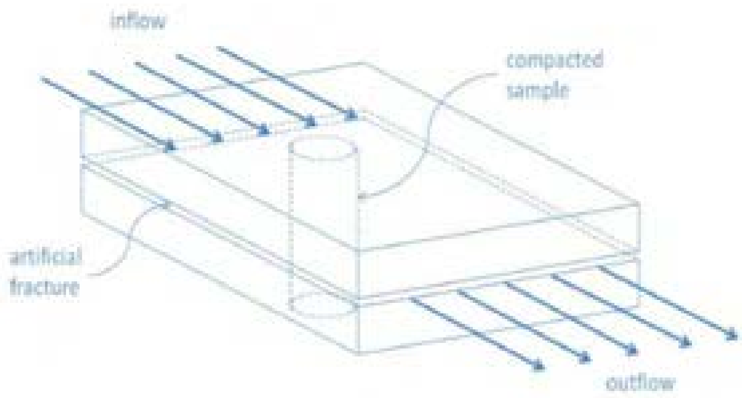

FIG. 2. Schematic representation of the flow-through, artificial fracture test.

To analyse the results obtained from the different organisations and to be sure that the data provided in the Annex are comparable, is important to make clear how the "mass loss" or the "average mass loss rate", needed for quantitatively estimating erosion, is measured in each case. When the clay is confined, with no significant extrusion, the mass loss is limited to the particles dispersed in the liquid phase (or eluted mass) plus some particles retained in the sintered filters, which can be determined by difference from the initial and final weight of the initially emplaced mass. In the artificial fracture tests, the mass loss is determined via post-mortem analysis considering also the material extruded in the fracture.

6. WP3 Radionuclide and host rock interactions

In WP3 of BELBAR in total six partners investigated colloid mobility controlling processes in the geosphere and the effect of the mobile colloidal phase on the transport of radionuclides in the far-field environment of a deep geological repository in crystalline formations.

The work in BELBAR has increased our understanding of bentonite colloid effects on radionuclide transport. It has shown that radionuclides bound by bentonite colloids may be released slowly. In this state, they are bound 'non-exchangeably'. The extent of the effect depends upon the chemistry of the radionuclide. Tri- and tetravalent f-block elements seem to be prone to slow dissociation, with the tetravalent elements able to show slower dissociation than the other species. Actinyl species appear more weakly bound, but may still dissociate slowly. Monovalent and divalent cations show a rather fast dissociation kinetic with the exception of Cs, where the geological origin of the clay mineral triggering the frayed edge sites is determining the reversibility of sorption. The first order dissociation rate constants found in the literature for colloid dissociation have been significantly enlarged through the BELBAR project and already published values have been to a large extent reconfirmed.

7. Colloid stability

Both the erodibility of the clay barrier and colloid transport in the environment are strictly related to the water chemistry and also to the intrinsic properties of colloids and their stability behaviour. Thus, the analysis of the chemical conditions that make colloidal systems stable or unstable is important because the conditions that favour colloid stability are also expected to favour colloid transport and erosion processes. In general, a colloidal system is considered as stable, if suspended particles do not undergo coagulation at least during the observation time.

Because colloid stability depends on the chemistry of the aqueous environment, the stability studies analyse whether or not clay colloids aggregate depending on several chemical and physical parameters, such as pH, ionic strength, temperature, presence of different inorganic ions and organic ligands, amongst other factors. It is also important to understand what intrinsic physico-chemical properties of the bentonite may affect the stability of colloids. So, the knowledge about the stability of clay colloids in the site-specific host rock conditions is important for assessments of long-term performance of radioactive waste repositories.

Based on the analysis in WP1 the main crucial issues for WP4 were identified at the beginning of the project (Fig. 2). Many coagulation studies of colloidal clay dispersions were performed under different geochemical conditions during the last decades. However less attention was given to find the main reason for different behaviour of different clays. In this project some insight was made concerning the trend or correlation between the bentonites characteristics and its stability.

The coagulation of colloids is a fast process, if the conditions are favourable for coagulation (e.g. the concentration of some cation(s) is above critical coagulation concentration for given clay dispersion - CCC). But if we are at the boundary, close to conditions which are favourable for clay colloids coagulation, the aggregation process can be very slow. In this means, the long term experiments are important and were performed in this project. Highlights from WP4 are listed below in accordance with issues from WP1.

Phase transitions of montmorillonite in a repository – the investigations suggest that, provided the ionic strength of the ground water is above the CCC, the highly compacted clay in engineered barriers will act as a swelling repulsive paste and expand. Once the lowest clay concentration at the swelling front is below the clay concentration required for paste formation, the clay will form a gel. The lowest limit appears to be about 60 g/l.

Influence of bentonite properties on its stability – one of the possible causes of the difference in the stability / erosion behaviour could be related to the different mineralogy (mainly clay minerals and its properties) of the different bentonites (trioctahedral vs. dioctahedral clays, different exchange complex, different charge density, and different charge location). In general, those clays having the charge located in the tetrahedral layer form larger colloids: these particles sediment easier being less stable than others even in de-ionized water DI.

Role of inorganic compounds and (ir)reversibility of coagulation process – changing anion has only minor effect on the CCC, provided that the anion does not directly influence the overall clay particle charge, as in the case of polyphosphates and to some extent OH^-. The effect of cations (CCC) was also investigated. It has to be noted, that such tests must be evaluated taking exchange into account. Sodium and potassium, and magnesium and calcium act in a similar way during the coagulation process and in real systems. Their effect can be simplified to the effect of M^{1+} (Na+K) or M^{2+} (Ca+Mg) cations, where M^{2+} are more effective in coagulation.

Role of organic matter – organic matter (like humic or fulvic acids) is able to stabilize clay colloids in NaCl electrolyte (experimental concentration up to 0.1 M NaCl). This means that in presence of organic matter more concentrated NaCl electrolyte is needed to coagulate clay dispersion (the CCC is higher). For example the CCC is four times higher in a suspension containing 0.5 mg/L total organic carbon (TOC) compared to the same suspension without humic acid.

8. WP5 Conceptual and mathematical models

The objectives for WP5 were derived from the main aim of BELBaR that was to reduce the uncertainties in the description of the effect of clay colloids on the long term performance of the engineered barrier and on radionuclide transport. The objective of the development activities was to improve the conceptual and the mathematical models used to predict mass loss of clay in dilute waters, clay colloid generation in particular, as well as clay colloid facilitated radionuclide transport. A target of validating advanced model(s) for the purposes of spent nuclear fuel disposal was set at the beginning. Regarding validation and advancing the models, sufficient confidence was obtained to predict clay mass loss rate in laboratory scales using numerical simulations, whereas mass loss rate predictions repository relevant scales remain to be assessed using analytically derived expressions for bounding estimates. According to the bounding estimates referred to, the agglomerate/floc migration rate in a fracture is the mass loss rate determining feature. The reasoning of dominant processes was succeeded considering agglomerate migration but was based only on expert judgement for clay swelling and gravity. Moreover, data needs specifications to assess the relative importance of clay swelling and gravity were raised but only when it was too late to commit experiments within BELBAR. As to conclude it can be stated that a new bounding estimate is proposed to be used in the safety cases to assess clay mass loss rates; loss of clay at the clay-water interface is limited by migration of newly formed clay agglomerates in fractures. This estimate can be obtained with far lesser efforts and uncertainties than used in the previous safety cases.

9. WP6/WP7 Dissemination and management

To ensure that BELBAR had the appropriate impacts, a specific work package (WP6) was established for dissemination. The purpose was that a range of tools would be used to reach a wide audience. In particular, the results were disseminated to international conferences, and high level publications. A training course on laboratory methods in colloid science was arranged.

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References

[1] Shelton A, Sellin P, Missana T, Schäfer T, Červinka R and Koskinen K, 2018. Synthesis report: Colloids and related issues in the long term safety case. SKB TR-17-17, Svensk Kärnbränslehantering AB.

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BEACON: BENTONITE MECHANICAL EVOLUTION

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Abstract. BEACON aims at the development of understanding fundamental processes that lead to material homogenization, as well as improved capabilities for numerical modelling. In earlier assessments of bentonite EBS, the mechanical evolution of the installed bentonite was neglected, and an “ideal” final state was optimistically assumed. Key features of the project are:

- Re-evaluation of the existing database to extract the important information to compile the qualitative and quantitative observations and to develop the conceptual understanding.
- Enhanced, robust and practical numerical tools firmly grounded on a good conceptual understanding, which have the required predictive capabilities concerning the behaviour of engineered barriers and seals.
- A complete experimental database for the need of the assessment models.
- Verified models based on experimental results from experiments in different scales.

The BEACON project is needed for the pan-European aims at building confidence amongst regulators and stakeholders regarding the performance of safety barriers in a geological repository.

1. Introduction

The overall objective of the project is to develop and test the tools necessary for the assessment of the mechanical evolution of an installed bentonite barrier and the resulting performance of the barrier. The goal is to verify the performance of current designs for buffers, backfills, seals and plugs. For some repository designs mainly in crystalline host rock, the results can also be used for the assessment of consequences of mass loss from a bentonite barrier in long term perspective.

The driver for this project is repository safety, and the demands of waste management organizations to verify that the material selection and initial state design fulfil the long-term performance expectations. For this project, the initial state refers to the period at installation of the barrier, while long-term performance refers to the period for barrier saturation and evolution of the hydro-mechanical state, which could range from 10 to 1000s of years. In current and future applications for repositories, the regulators will expect the applicants to have a sufficient predictive capability of the barrier evolution from the installed to the final state.

BEACON is focused on the direct application to real assessment cases in actual repository systems. A few cases from relevant repository systems have therefore been selected as test examples.

The systems intended to be evaluated in Beacon include three cases: 1) a tunnel plug based on The ANDRA design, 2) a disposal cell from the Nagra concept, 3) the KBS-3 deposition tunnel backfill. These are representative of the primary areas of uncertainty in density homogeneity.

These examples cover a broad range of issues and the results should be applicable to other concepts and systems as well. The cases are illustrated in Fig. 1, Fig. 2 and Fig. 3 below.

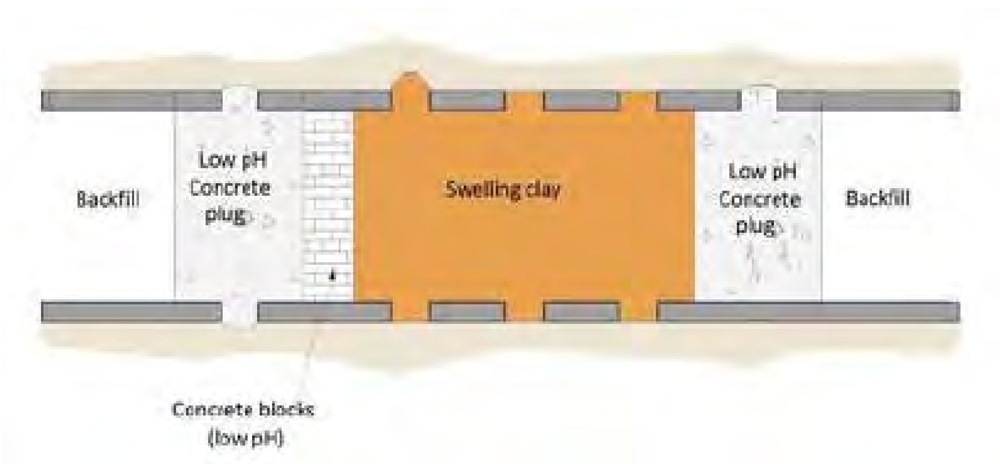

FIG. 1. Tunnel plug in the ANDRA concept.

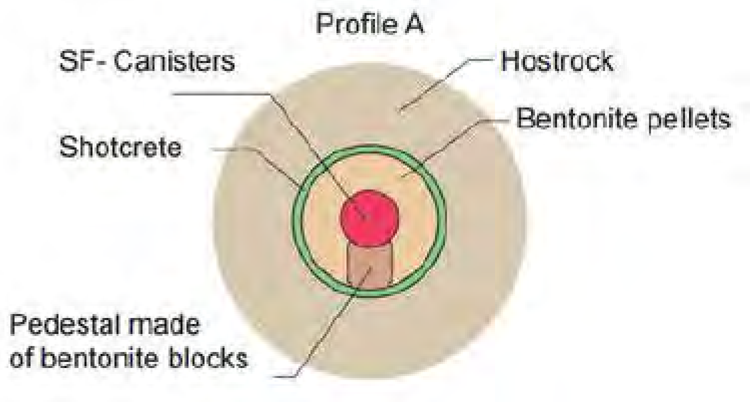

FIG. 2. Disposal cell in the Nagra concept.

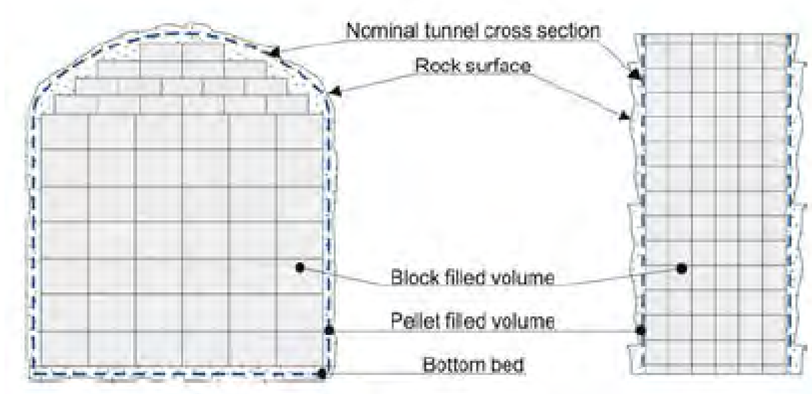

FIG. 3. KBS-3 Tunnel backfill.

BEACON builds upon experience by waste management organizations from different countries and technology providers over the past 30+ years. Great gains have been made in understanding individual bentonite components through experimental and modelling work. Yet shortcomings in the state-of-the-art knowledge exist which still inhibit confidence toward repository operation.

The sealing ability is essential for the engineered clay (bentonite) barriers in all geological repository concepts. This is normally achieved by a swelling pressure and a low hydraulic conductivity. The swelling pressure may also impact the barriers in the repository. The mechanical properties of the installed EBS, that may consist of a mixture of blocks, pellets and engineering voids, will be entirely different from the situation after full saturation. It is therefore important to understand:

- The mechanical evolution during the saturation phase;
- The final situation after reaching equilibrium.

A good knowledge of the mechanical evolution is necessary to ensure that a given design is adequate to meet the performance targets.

The scientific-technical work in Beacon is structured in five work packages (WP1-5), dissemination and training is handled in two work packages (WP6-7) while coordination and project management is covered in one single work package (WP8). The interconnections between the work packages are illustrated in Figure 4.

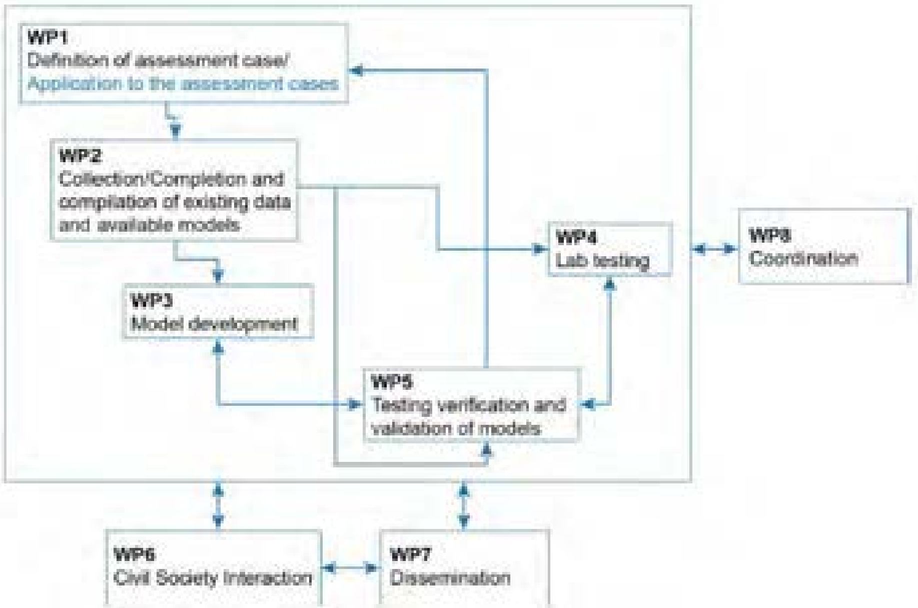

FIG. 4. Interconnections between the work packages in BEACON.

WP1 is the main driver for the entire project. The waste management programs involved are all represented in WP1, through the implementer or equivalent organization. The objective of WP1 is to define the important issues concerning the mechanical properties of bentonite and to define how these should be treated.

In WP2 the existing knowledge base is treated. The key objective of WP2 is the sharing of knowledge and experience. The partners will distribute information and results from earlier assessments, design considerations, experiments and modelling tasks.

A strong driver for a joint project is the current limitations in the predictive capability in the numerical models. The issue of homogenisation and swelling is challenging both from a conceptual and a numerical point of view. The purpose of WP3 is to identify and resolve the shortcomings of current models.

Although there is a substantial experimental database available for the project, it will be necessary to perform additional experiments to support the model development in WP3 and the model testing in WP5. The experimental work will be coordinated in WP4. WP4 will consist of experienced experimental groups, which have the flexibility to adapt the experimental work to support the needs of WP3 and WP5.

The core component of Beacon is WP5. The main effort will be performed in this work package. The overall objective of WP5 is to simulate the assessment cases defined by WP1. In order to do this, the available models have to be tested first on results from laboratory experiments and later on results from large scale field tests to gain confidence in their predictive capability. The next step is to actually test the predictive capability, by means of "blind" predictions of experimental results. Finally, the models will be used to evaluate the assessment cases.

2. WP1 Definition of assessment case/Application to the assessment cases

In the framework of WP1, the needs of safety assessment regarding the evaluation of nonhomogeneous backfill properties are addressed, in particular to what extent non-homogeneous material property distributions comply with safety requirements. The outcome of this work package is planned to be a (hydro)-mechanical assessment of the case studies, given a range of uncertainties in the boundary conditions based on empirical and numerical evidence, that, based on a probabilistic approach, would ultimately result in a set of requirements under consideration of the host rock and the repository design.

The first deliverable was a report compiled with the answers to a questionnaire that was distributed to the different WMOs or their representatives. The questionnaire aimed at reflecting the state-of-the-art regarding the treatment of heterogeneous bentonite density distribution and properties in the safety case. The questionnaire consisted of three different parts: (1) application of bentonite in the specific design (2) the required performance of bentonite (3) detailed characterization of the required properties of the bentonite.

The conclusions from the answers to the questionnaire were that occurrence of heterogeneity in the repositories could impact the safety functions of bentonite components. Therefore, it needs to be determined to what extent this could affect the safety case of the repositories. Heterogeneity can occur in the initial material, through the emplacement or the re-saturation phase as well as on the long term after re-saturation of all repository components. The heterogeneities in the initial state, i.e. after installation of the EBS, are mainly due to density differences. Inhomogeneous saturation and swelling of bentonite could cause irreversible damage. The role of uncertainties related to these bentonite heterogeneities is addressed in most repository concepts using a deterministic approach, defined with a preferred density value. There are several natural properties of bentonite that may impact the degree of homogenization. Most waste management organizations consider water content, original exchangeable cations, bulk density, swelling pressure and hydraulic conductivity as relevant natural properties for the bentonite regarding heterogeneity, while organic carbon or thermal conductivity seem to be incidental to the homogenization process.

All participating waste management organizations agree that the most valuable output from Beacon would be material models that are accurate enough to be used as a tool for design and engineering purposes, i.e. to assess the behaviour and performance of the bentonite-based EBS both on the short- and long-term under variable design and environmental conditions. It is expected that, if preparation of the sealing material (e.g. pellets) and emplacement method are performed properly, heterogeneity will not be problematic for safety cases and that the buffer material can be represented in the safety assessment by a well-chosen homogeneous material.

3. WP2 Collection and compilation of existing data and available models

The primary deliverable of WP2 so far was a report that documents the information that has been made available to the BEACON project by the project partners and associated organisations. The information relates to experiments at a variety of scales and also modelling studies that have been undertaken. The report uses information supplied by Beacon partners on experiments that have been carried out in previous projects, to build a database of experiments which can be used during the Beacon project and beyond. The report documents the available data but does not attempt to propose any experiments for consideration within the BEACON project. This will be left to the Work Package leaders to undertake, based on the information contained herein. The report provides a summary of information on a range of experiments, as well as clear referencing to the underlying reports which contain further information, to facilitate the process of selecting datasets for modelling within BEACON. The process for collecting and compiling information into the database involved:

- Designing a data form to collect appropriate information;
- Requesting that Beacon partners and associated organisations fill out the data form for any studies they feel could be relevant to BEACON;
- Collation of the completed data forms into a preliminary database;
- Discussion of the database at a workshop and definition of additional fields that would aid future selection of experiments for study within BEACON;
- Request for additional information to complete additional fields in database;
- Finalisation of the database.

The process relies on the judgement of the Beacon participants as to which experimental datasets may be relevant to Beacon. The data forms have been entered into the database in three categories: laboratory experiments, mock-up experiments and in-situ experiments. The laboratory experiments include experiments designed to measure material properties, as well as experiments that simulate scaled-down repository conditions. There are many experiments listed in the database, at a range of scales (from bench top laboratory experiments to full scale field experiments), a small number of which were designed specifically for studies of bentonite homogenisation, but the majority of which were originally designed for other purposes. Nevertheless, these experiments provide a valuable source of information on the mechanical properties of bentonite and the likely mechanical evolution of bentonite within a repository. The database contains information on the type of bentonite considered in the experiments, the boundary conditions and heterogeneities within the experiments and also the range of measurements taken in the experiment. This will allow Beacon partners and especially Work Package leaders to interrogate the database and find experiments of interest for consideration in the Beacon project. Furthermore, knowing experiments that have been undertaken previously, decisions on new experiments to be undertaken within the Beacon project itself can be taken in the light of understanding derived from international work on bentonite derived to date.

4. WP 3 Model development

Work Package 3 plays a central role in the structure of the project as it is devoted to the development of the constitutive models for describing the hydro-mechanical behaviour of the bentonite in an appropriate manner. It is recognized that current models face limitations in their predictive capabilities and significant advances are required. The models must prove their predictive capabilities, reliability and robustness and they should preferably be grounded on a good understanding of the phenomena involved. To this end, they will be validated using several laboratory and field-scale tests. Ideally, those constitutive models should consider the following cases:

- Saturated and unsaturated materials
- Compacted bentonite (Blocks) and granular bentonite (e.g. pellet-based)
- Isothermal and non-isothermal conditions

although it is recognised that not all models will necessarily have this comprehensive level of generality.

To facilitate a more common assessment of the models, the teams were asked explicitly what the model capabilities were concerning a number of features of behaviour:

- Dependence of swelling strain on applied stress and on dry density;
- Irreversibility of strains in wetting/drying cycles;
- Behaviour during swelling stress test. Dependence of swelling pressure on dry density;
- Stress path dependence from an unsaturated to a saturated state (Fig. 5);
- Stress path dependence from a saturated to an unsaturated state ;
- Dependence of strains developed in a temperature cycle (increase/decrease) on OCR (Overconsolidation Ratio) (or stress).

The first five items correspond to an isothermal formulation whereas the sixth one requires the incorporation of temperature effects. The features selected for this purpose are those that are deemed, in principle, most relevant to explain the evolution of engineered barriers and seals during the transient phase.

FIG. 5. Suggested suction-stress paths to check stress path dependency from an unsaturated to a saturated state. Stress may be vertical total stress (in oedometer tests) or mean total stress (in isotropic loading tests).

The model capabilities at the beginning of the project are available as deliverable 3.1.

5. WP4 Lab testing

The objectives of the Beacon experimental studies are to provide input data and parameters for development and validation of models and to reduce uncertainties about conditions and phenomena influencing bentonite homogenisation. Both the homogenisation of an initially inhomogeneous bentonite system and the persistence or development of inhomogeneities in the bentonite systems under various mechanical and hydraulic conditions are investigated. Eight experiment teams perform tests involving different bentonite materials and hydraulic and mechanical boundary conditions. As an example, CIEMAT's hydration tests in large-scale isochoric cells are presented here.

The work focuses on the conceptual understanding of the evolution of bentonite fabric and microstructure upon hydration and the factors affecting them. To accomplish this, hydration tests are being performed in isochoric cells (Fig. 6) to analyse the fabric and microstructure evolution of initially inhomogeneous FEBEX bentonite. In the tests half of the sample was composed of bentonite pellets (initial dry density 1.3 g/cm^3) and the other half of a bentonite block (initial dry density 1.6 g/cm^3). The two samples were prepared in the same way, but one of them was hydrated under a constant flow rate of 0.05 cm^3/h (MGR22) and the other one under a constant injection pressure of 14 kPa (MGR23). The first boundary condition tried to simulate a host rock with limited water availability, whereas the other one simulated a repository with plenty of water in which the water intake is controlled by the bentonite permeability. The axial pressure development in the two tests is shown in Fig. 1. There was a significant difference in swelling development kinetics, but although it took much longer to reach an equilibrium value for the test performed under low water inflow (MGR22), the final swelling pressure value, once the samples were saturated, was the same in the two cases, about 3 MPa, which is the expected value for a granular FEBEX sample compacted to the average dry density of the block/pellets set (1.42 g/cm^3).

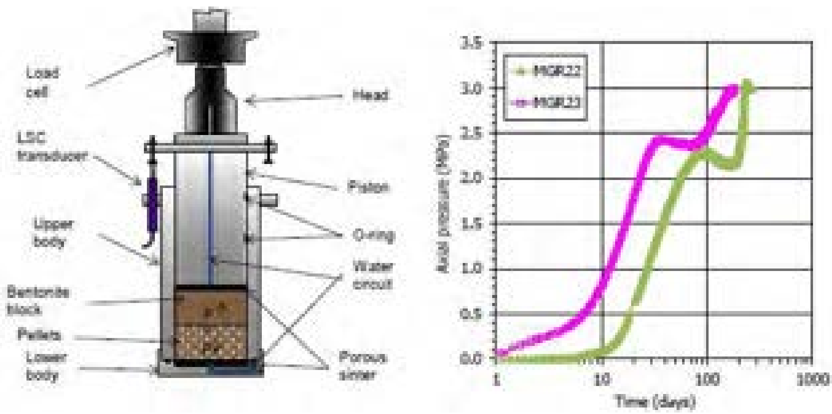

FIG. 6. Isochoric cell for hydration tests on bentonite block/pellets and swelling pressure evolution in two tests.

Once the sample from test MGR22 was dismantled, its physical state was checked by determining the water content, dry density and pore size distribution at different positions. The final appearance of the clay was homogeneous, with no discernible pellets. There was a slight decrease of water content from the hydration surface to the top of the sample (from 35 to 30%), while the dry density increased in this sense (from 1.39 to 1.46 g/cm^3). The average dry density of the bentonite block considerably decreased as a consequence of saturation and that of the pellets part increased. The degree of saturation was close to 100% in every position. The pore size distribution significantly changed with respect to the original samples: the macroporosity of the pellets decreased, whereas the microporosity of both the pellets and of the block increased.

6. WP5 Testing verification and validation of models

One of the objectives of Beacon project is to improve models to simulate bentonite component evolution along the repository life. In this context, a specific work package is dedicated to verification and validation of models.

Based on an inventory performed within the project identifying experiments in link with mechanical evolution of repository bentonite barrier materials, a selection of test cases has been made. The test cases are based on experiments performed at several scales: from lab tests (cm) to field tests (scale 1) which are relevant in regards of the BEACON objectives.

Partners involved in WP5 make simulations on the chosen test cases and produce specified results. The objective of those simulations is not only to reproduce the experimental results which most of the time could be done by identifying some relevant parameters but also to detect where the difficulties in terms of modelling are. The aim is to be able to improve our capacities of prediction of long-term behaviour for bentonite-based components. Comparisons of results and analyses of the differences will lead to an improvement of the physical and numerical models creating a strong link with WP3 (model development) and should give a feedback to the experimentalists involved in the dedicated work package (WP4).

The strategy was to select tests at laboratory scale where homogenization processes have been highlighted, and which will constitute elementary bricks to tackle bentonite evolution modelling at a larger scale. The selected tests are:

- Swelling pressure tests for compacted plugs with free volume available TEST B1.7 from Clay Technology AB;
- Swelling pressure tests for pellets mixture TEST B1.16 from CEA, Andra;
- Swelling pressure tests for block and pellets structure TEST B1.6 from Posiva.

The first test modelled during this exercise concerns a pure MX-80 bentonite at an initial dry density of 1655 kg/m^3 and have two successive phases (Fig. 7). It consists first in a classical swelling pressure test at constant volume. When the swelling pressure is stabilized, the upper piston is moved upwards and fixed with spacers admitting a certain volume for the swelling. A second stage of swelling starts, bentonite filling the created void.

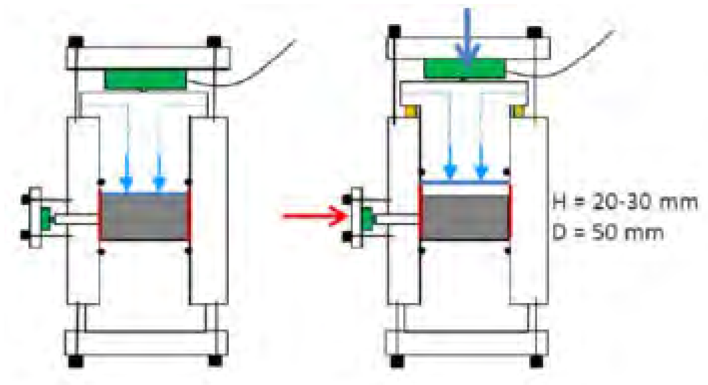

FIG. 7. Set-up used for the axial swelling tests. The red lines represent the lubricated surfaces and the blue lines represent filters and water supply. The radial pressure transducer is placed 10 mm from the bottom end of the specimen.

After finished swelling and homogenization, i.e. when no or negligibly small changes are noticed in the swelling pressure with time, the specimen is dismantled and cut in slices for determination of the water content and density distribution in the direction of swelling.

Several partners modelled the test obtaining results in good agreement with the measurements at the end of the first stage for the axial swelling pressure (Fig. 8). The exercise shows the difficulties of the models to represent the transient phase that is constituted mainly by water saturation and development of swelling pressure.

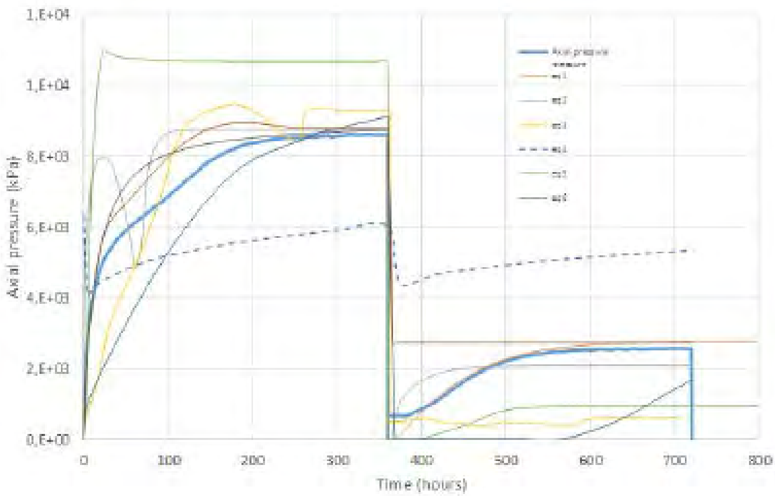

FIG. 8. Axial pressure evolution – comparison between the experiment and the models.

At the top of the sample, dry density and water content at the end of the test are higher due to the introduced void during the test. The water content obtained at the end of the test when the sample was dismantled is compared to the numerical results (Fig. 9) showing that the general trend for water content is well reproduced. Models seem able to reproduce the final heterogeneity of properties observed at the end of the test.

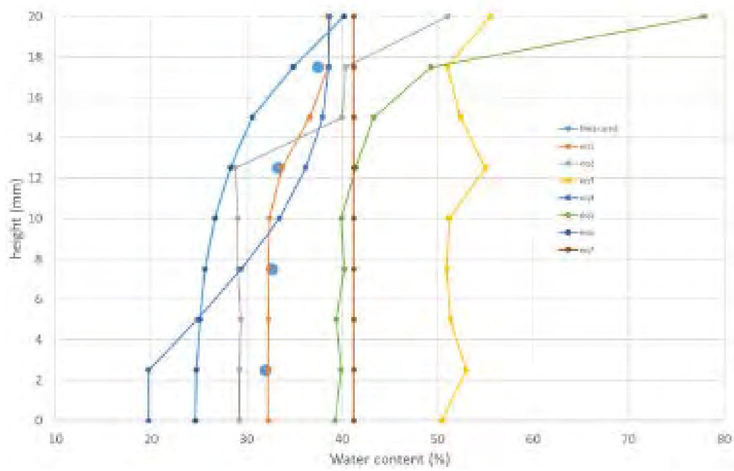

FIG. 9. Water content at the end of the test – comparison between the experiment and the models.

The first analysis was very useful to identify some specific points that need to be investigated and on what the model evolutions should be focused. The second test, in the list above, performed on pellets highlighted the same kind of conclusions. The hydration phase is always difficult to capture with the models.

The next task will be to model large scale field tests to show the capacity of the models to reproduce in situ experiments. Three experiments have been selected:

- EB - Engineered Barrier Emplacement Experiment (Mont Terri),
- FEBEX - Full-scale Engineered Barrier Experiment in Crystalline Host Rock (Grimsel),
- CRT - Canister Retrieval Test (Äspö).

7. Civil society interaction, dissemination and coordination

The overall aim of WP6 is to give civil society the opportunity to follow, discuss and give feedback on the research conducted in the project by the development, using previous experience, of a relevant interaction framework.

The work package will facilitate the translation of scientific results and other output from WP1-5 to the public and create the conditions for civil society local and national representatives to interpret, discuss and give feedback on the research results and other information made available by the project. This will enhance the possibilities of civil society participation in future situations where there are consultation processes as a part of safety case review.

The BEACON project has arranged one specific training course during the project, within WP7. The course took place at the Universitat Politècnica de Catalunya (Spain). The course aimed to give an overview of the current approaches and capabilities concerning the constitutive and numerical modelling of the hydro-mechanical behaviour of bentonite and other swelling clays. The context of the course was the field of nuclear waste management; however, the concepts and methods that were presented have a much wider scope of application. The topics of the course were:

- The fundamental science behind the mechanical and hydraulic properties of bentonite;
- Current constitutive modelling approaches;
- Numerical modelling and examples of application;
- The issues around the mechanical evolution of bentonite in nuclear waste management;
- Hands-on training with a computer code.

The course had 36 participants and was addressed to the nuclear waste management community as well as to students in areas of soil and material science and civil, environmental and mechanical engineering.

8. Conclusions

BEACON is now about half way into the project. So far the work has been both focused and according to plan. The State of Art reports from WP2 and WP3 are important summaries of the knowledge that never has been collected in a similar manner before. They will both be an important foundation for current and future mechanical assessments of bentonite. The benchmark tests in WP5 have also been very successful: they have pointed out that there are real challenges, but also have shown that there are model concepts available that should be able to meet those challenges.

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MICROBIOLOGY IN NUCLEAR WASTE DISPOSAL

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Abstract. Microbiology in Nuclear waste Disposal (MIND) is an interdisciplinary project consisting of two experimental work packages and a third one that handles integration of society and policy-oriented studies.

Work package 1 is focusing on the influence of microbial processes on organic containing long-lived Intermediate Level Waste (L/ILW) forms e.g. waste solidified with cement or bitumen. In work package 2 the influence of microbial processes on high level waste (HLW) and spent fuel geological disposal are studied. The emphasis is on quantifying specific measurable impacts of microbial activity on processes and the long-term performance of the system with its barriers under repository-relevant conditions to be considered in safety cases. The remaining uncertainties concerning the release of chemicals, gases and radionuclides that are important to the safety case for L/ILW disposal and near-field safety issues related to the engineered barriers in HLW disposal, are addressed respectively. Work package 3 is oriented towards interaction within (by e.g. sharing experience and results with other experts) and between different groups including both experts and the lay community through education and communication and thereby improving the general awareness of microbial issues.

Microbial activity may have a significant impact on the physical and chemical evolution of repositories for radioactive waste. Therefore, what controls their activity under repository conditions must be well understood.

1. Introduction

The MIND project is a project addressing key technical issues that must be tackled to support the implementation of planned geological disposal projects for higher-level radioactive wastes across the EU. Geological disposal is a challenge as social and technical aspects blend and input from social science with regard to the design, implementation and post-construction management of the installation is required. In this respect the impact of the inclusion of microbiology on expert conceptualisation and public perception of geological disposal have been considered as well. Our current understanding of the impact of microbial metabolism on the safety of geological repositories remains tenuous, even though microorganisms may have controlling influences on organic waste (e.g. solidified with cement or bitumen) evolution in situ, multi-barrier integrity and ultimately radionuclide migration from the repository. The project brings together, for the first time, 15 European groups from 8 countries working on the impact of microbial processes on the evolution/performance of the repository system and its barrier elements to be considered in safety cases for geological repositories across the EU, focusing on key questions posed by waste management organisations. The emphasis has been on quantifying specific measureable impacts of microbial activity on barrier evolution under repository-relevant conditions. The knowledge obtained will be considered when choosing design and materials when constructing repositories for radioactive waste. The MIND project has thus contributed to that microbial processes in repositories are now being taken into account to greater extent than previously leading to significant refinements of safety case models currently being implemented to evaluate the long-term evolution of radioactive waste repositories. The project consists of two experimental work packages, WP1 and WP2 and the third one WP3 handles distribution of knowledge obtained in WP1 and 2 including dissemination and education. WP4 handles project management.

1.1. Work package 1

The overall objective of WP1 is to reduce uncertainty of safety relevant microbial processes controlling radionuclide, chemical and gas release from long-lived intermediate level wastes (ILW) containing organics. Development of gas in a repository for L/ILW has been studied previously by e.g. Wiborgh et al., [1] and more recently by Small et al., [2] who performed experimental and modelling investigations of the biogeochemistry of gas production from low and intermediate level radioactive waste in the GGE (gas generation experiment) in Olkiluoto. Organic waste materials present in ILW include a variety of natural (cellulose, bitumen) and anthropogenic polymers including: polyvinylchloride (PVC), polyethylene (PE) and ion exchange resins (D1.1). Effects resulting from the combined effects of hydrolysis, radiolysis and biodegradation of such organic wastes have been studied under the physical and chemical conditions relevant to organic ILW solidified with cement (waste forms) and disposal concepts. The range of microbial processes that can be fuelled by these organic wastes has been examined to assess the effect on processes of gas generation and radionuclide complexation. Laboratory and in situ large-scale experiments have been performed examining alkaline, cement buffered (pH 10-12.5) conditions and including actual organic waste materials to determine the types of microbially mediated chemical and gas generation processes that may proceed in heterogeneous cementitious waste forms with organic waste. Microbial processes, affecting gas generation (CH_4) and consumption (H_2) have been examined that have relevance to the pressurisation of the repository system and which are also important to the migration of gaseous radionuclides such as ^{14}C. Models of the microbiological, geochemical and transport processes have been developed to assist in the interpretation of the in situ experiments.

The main safety issues concerning radionuclide, chemical and gas release from ILW that are addressed by the work package are summarised as:

1. The degradation of anthropogenic polymers (PVC and ion exchange resins) and hence their contribution gas generation and release of soluble organic species.
2. The biodegradation of cellulose hydrolysis products (e.g. ISA) and the overall effect on radionuclide complexation and transport.

3. Microbial gas generation (CH_4) and consumption (H_2) studied under in situ conditions.
4. The effect of high pH on limiting the above microbial processes in cementitious ILW.

1.2. Work package 2

In WP2 the objectives are to better quantify the contribution of microbially produced sulfide in the geosphere and in buffers and backfill to the overall rate of canister corrosion. There is also a need to gain systematic information on the efficiency of specific bentonite buffer in inhibiting microbial activity. Already a few years before MIND started, it was shown that there would exist a threshold density over which sulfate reducers could not be active (e.g. Motamedi et al, [3], Stroes-Gascoyne et al. [4], Masurat et al.,[5]).

Remaining key issues for the geological disposal of HLW concern the factors controlling sulfide production in the geosphere, including man-made artefacts to what extent microorganisms can accelerate canister corrosion in the near-field either by hydrogen scavenging or by sulfide and/or acetate production. Further, it is important to identify conditions more in detail (including buffer density) under which relevant bentonites inhibit microbial activity and to understand whether microorganisms can accelerate degradation of bentonite-based buffers and influence the long-term behaviour of plug systems and seals. To better understand the differences in behaviour between different bentonites.

Microbiology in work package 2 generally addresses near-field safety issues related to the engineered barriers canisters, bentonite clays and concrete. Three main safety issues can be postulated due to bacterial activity in the nearfield.

1. Bacterial sulfide production in buffer and backfill and the concomitant risk for sulfide corrosion of canisters.
2. 2. Bacterial acetate production in buffer and backfill and the concomitant risk for acetate induced stress corrosion cracking of canisters.
3. 3. Bacterial degradation of buffers and backfill, and of concrete constructions such as tunnel plugs.

1.3. Work package 3

The purpose with the third Work Package is to ensure that the output from WP1 and WP2 is well integrated. WP3 will evaluate and integrate microbial processes towards the conceptualization and performance assessment of geological repositories and in the respective state of the art knowledge base. The impact of the inclusion of microbiology on expert conceptualisation and public perception of geological disposal will be estimated. The proper contextualization of results will be ensured and remaining key topics within and beyond the MIND project will be extracted by maintaining an active dialogue with stakeholders.

In WP3 the outcome of the experimental work packages will also be distributed to a broad audience, including students, professionals, the scientific community, stakeholders and the lay community via e.g. Euratom Fission and Training Scheme programme PETRUSIII. Synergies of the MIND program and consortium will be identified and cultivated with ongoing research lines of European laboratories and institutes outside the MIND consortium, with special attention for those in the less advanced member states.

1.4. Work package 4

The project also organises an Implementers Review Board (IRB). The IRB consists of representatives of the Nuclear Waste Management organisations and regulators with interest in in MIND (SKB, Posiva, TVO, Andra, NWMO, Nagra, RWM, ONDRAF/NIRAS, NUMO, LANL, SURAO, CNSC, IRSN). During the course of the MIND project the IRB has advised the Technical Coordinator and the Executive Committee of MIND with critical evaluation concerning research quality and significance of outputs in relation to the implementers needs, highlighted opportunities for networking with other international research activities and raised awareness of our research programme where appropriate. Members of IRB have participated in the MIND Annual Meetings, participated in discussions and also produced written feedback at the end of each annual meeting.

2. Work package summaries

2.1. Work package 1

Outputs from laboratory and in situ experimental systems are reported in WP1 deliverables (D1.1- D1.8) and peer-reviewed journals, as discussed below.

The state of the art knowledge base concerning the biodegradation of organic polymers common in LLW/ILW was reviewed in D1.1, which includes a summary of information concerning the types of organic polymer present in ILW and some disposals of Low Level Waste (LLW) together with information concerning the European repository designs and concepts for their deep geological disposal. Deliverable D1.1 confirmed that the materials selected for study in the MIND project; bitumen, organic ion exchange resins and halogenated polymers (PVC), are present in significant amounts in the national inventories, but that biodegradation of these materials and their hydrolysis and radiolysis products was poorly understood. Cellulose is present in generally lower amounts in most inventories, but it is already established that it is of significance with regard to the strong complexation effect of its alkaline hydrolysis products. Recent findings concerning the biodegradation of the cellulose hydrolysis product isosaccharinic acid (ISA) using an alkaline inoculum from a high pH lime works [6,7] form the basis of further work within MIND WP1 using the inoculum to examine biodegradation of PVC (D1.2) and bitumen hydrolysis products (D1.3) at pH 10-11 conditions.

Deliverable D1.2 presents further studies of cellulose degradation following ^{60}Co Y irradiation (1 MGy) and hydrolysis at pH 12.7. Irradiation enhanced the rate of the abiotic alkaline hydrolysis of cellulose, which resulted in the production of higher concentrations of the radionuclide complexant ISA, compared to the unirradiated controls. Irradiation also led to an increase in the concentration of dissolved organic carbon, including ISA, and made the cellulose more bioavailable for microbial degradation at a starting pH value of 12.5. Fermentation of the cellulose degradation products at hyperalkaline pH (pH 12.5) led to the production of H_2, and acetate, while CH_4 was not detected. Fermentation at pH 12.5 is possibly due to the microbial activity in low pH niches associated with the cellulose tissue and which are further developed by acidity generated by fermentation. Characterisation, including 16S rRNA gene sequencing, of the bacteria (Anaerobacillus isosaccharinicus) isolated from the lime works inoculum establishes that it grew at pH 8.5–11, could utilise a number of organic substrates, and was able to reduce nitrate and arsenate (Bassil and Lloyd [8]). Deliverable D1.2 also presents studies of PVC biodegradation of pure PVC polymer (powder) and plasticised PVC sheet, following 1 MGy ^{60}Co Y irradiation in saturated Ca(OH)2. Batch microcosm experiments were set up to test the ability of a high pH-adapted lime works inoculum to use these irradiated materials as the sole source of carbon and electron donors for nitrate reduction at pH 10 (Nixon et al [9]). The results from this work demonstrate that PVC plasticiser and fire retardant additives present in the PVC sheet are able to fuel microbial metabolism at pH 10 conditions using nitrate as an electron acceptor. Irradiation of plasticised PVC renders the material less bioavailable at pH 10, but microbial metabolism appears to be supported. No nitrate reduction was observed with non-irradiated PVC powder, although irradiated powder supported minor nitrate reduction. Separate tests on phthalate, the breakdown product of phthalate esters under irradiating and high pH conditions, and a potential radionuclide complexant was not found to support the metabolism tested, although it is clear that other additives present in plasticised PVC were degraded. These results highlight the bioavailability of volumetrically significant plasticised PVC under conditions relevant to its geological disposal in cementitious intermediate level nuclear waste.

Results of studies of bitumen degradation are presented in D1.3. This study concerned the degradation of Eurobitum, which also includes nitrate salts, which have the potential to oxidise the Boom Clay that is being considered as a possible host rock for nuclear waste disposal in Belgium. The study compared the potential of a microbial inoculum from the Boom Clay to metabolise nitrate leached from thermally aged inactive Eurobitum in the presence or absence of known bitumen degradation products (acetate, formate, oxalate). The study examined denitrification at pH 9-12.5 conditions and also included experiments inoculated with the high pH adapted lime works inoculum used in other MIND studies (D1.2, [3,4]). The study demonstrated that the nitrate leaching from Eurobitum rapidly stimulated microbial nitrate reduction. Different rates were observed depending on the organic compounds that were used as the electron donor to fuel the nitrate reduction process. Microbes were also able to use the Eurobitum as an electron donor to reduce nitrate. Microbial nitrate reduction resulted in a significant production of nitrite, which has the potential to oxidise the Boom Clay and thus affect the mobility of some radionuclides. Enhanced rates and extent of nitrate reduction were observed for the high pH adapted inoculum at pH 10.5, but the Boom Clay inoculum was also capable of nitrate reduction up to pH 10.5, reflecting conditions at the interface of the Boom Clay and the concrete liner of the disposal gallery.

Studies of ion exchange resin degradation are in progress in the Czech Republic and Switzerland and interim results are provided in the year 3 synthesis report D3.5. Both studies involve irradiation of cationic and anionic polystyrene based bead resins. Swiss studies have studied irradiation in Opalinus Clay groundwater conditions (pH 8) and under alkaline conditions using an electron linear accelerator (50 kGy) and at higher dose (200 kGy) using a ^{60}Co Ɣ source. Analysis of the gas phase reveals the formation of H2 and a number of chlorinated aliphatics, such as bromomethane, chloromethane, dichloromethane, and chloroethane, as well as aromatic compounds, such as benzene and toluene; many of these compounds have potential to fuel microbial processes. Studies in the Czech Republic have undertaken microcosm experiments of irradiated resins in groundwater inoculated with sulfate reducing bacteria. In this case a higher total dose was examined (^{60}Co Ɣ, 1 MGy) and the proportion of resin to water varied. Degradation products of polystyrene resins detected in the liquid fraction mainly consisted of trimethylamine and dimethylaminacetatenitrile. Subsequent microbial microcosm experiments showed that the lowest concentration of irradiated anion exchangers (0.2 g/l) caused the highest relative increase in bacterial abundance (14 fold increase). At higher resin content microbial activity appears to have been inhibited by the low pH (3.1 - 3.4) following irradiation. The effect of Cs present in resins on microbial activity has also been examined, with no toxic effect being observed at 0.5 mM of Cs (stable) but with effects evident at higher concentrations of 1 mM and 5 mM Cs.

Deliverables D1.4, D1.5 and published journal papers [10], [11], [12] report specific studies of radionuclide interactions with cellulose degradation products and bio-reduction processes. Deliverable (D1.4) presents results of spectroscopic studies of uranyl (UO_2^{2+}) speciation with ISA and with acetate, the latter representing a typical fermentation product of cellulose and ISA as revealed by studies reported in (D1.2). Uranyl (UO_2^{2+}) - acetate (AcO^-) speciation is described by a 1:1 complex; $[UO_2AcO]^+$ and a 1:2 complex ; $[UO_2(AcO)_2]$, with no evidence for a previously proposed 1:3 complex (D1.4). Fundamental information about the interaction of UO_2^{2+} with ISA were gathered by a variety of spectroscopic techniques: (i) three dominant UO_2^{2+}-ISA-complexes were discovered; (ii) two of the three complexes are probably polynuclear; (iii) 5- and 6-membered rings are the dominant binding motifs; and (iv) the limiting metal to ligand ratio is 1:2 (D1.4).

Studies of Ni interaction and immobilisation with biogeochemical processes associated with the metabolism of cellulose degradation products (e.g. ISA) related to studies reported in [D1.2] have also been published by Kuippers et al [10]. Here it has been shown that in an applied experimental system examining the fate of Ni complexed with ISA that the biodegradation of ISA at neutral pH resulted in the removal of complexed Ni from solution and incorporation in iron sulfide phases that were formed as a consequence of the microbial activity (sulfate reduction) that was stimulated.

High resolution electron microscopy studies have been undertaken, along with detailed microbial studies to characterise new species of bacteria from bentonites that are able to reduce selenate (SeO_4^{2-}) to less soluble forms (D1.5). Ruiz-Fresneda et al. [11] and Sanchez-Castro et al. [12] report about the bacteria Stenotrophomonas bentonitica, that is capable of reducing Se(VI) and Se(IV) to Se(0) forming nanoparticles, which with time crystallise to more insoluble forms morphologies (D1.5).

Methanogenesis has been studied under in situ conditions at the Mont Terri rock laboratory and through the long term LLW gas generation experiment (GGE) at Olkiluoto (D1.6, D1.7, D1.8, Small et al [13]). Studies at the Mont Terri Underground Rock Laboratory (URL) have examined the potential for methanogenesis to develop in Opalinus Clay as a consequence of reaction of H2 with inorganic carbon (CO_2, HCO_3^-). This experiment relates to a scenario where H2 is generated by anaerobic corrosion and radiolysis processes associated with the disposal of ILW and is relevant to consumption of H2 as well as furthering the understanding of methanogenesis. Results of the in situ borehole experiments show that methanogens and acetogens are found at very low abundance (<0.1%) as part of the microbial community, however no change to the relative proportion of these microorganisms was detected throughout the duration of the experiment. Although the sulfate concentration was successfully reduced from 12 mM to less than 4 mM during the in situ experiment no evidence for methanogenesis and acetogenesis was recorded. Microcosm experiments were also setup to examine conditions with lower sulfate concentration. However these microcosms also show no evidence for the onset of methanogenesis. Methane concentrations were measured for the duration of the experiment however no increase in concentration was recorded. There was also no significant increase in the acetate concentration over time suggesting that acetogens were not active in the community. The microbial composition after the incubation period supports these conclusions as it is dominated by one family (Desulfobulbaceae), which accounts for over 98% of the total reads. No methanogenic or acetogenic microorganisms were identified. Further investigation suggests that the onset of methanogenesis is also controlled by the bicarbonate (HCO_3^-) concentration, which was too low in the in situ and microcosm experiments so methanogenesis remained thermodynamically unfavourable.

In situ study of methanogenesis from cellulose containing LLW under initial alkaline conditions has been studied through further microbiological characterisation and modelling studies of an 18 year gas generation experiment (GGE) at the VLJ Repository, Olkiluoto, Finland (D1.6, D1.8,[13]). The GGE was originally set up in 1997 as part of a previous EU project (PROGRESS) and is operated by Teollisuuden Voima Oyj (TVO) and examines microbial gas generation from 16 200 dm^3 drums of cellulose containing LLW from the Olkiluoto power plants, together with a 4 tonne concrete box in a 20 m^3 gas tight vessel initially filled with river water. Interpretation of the geochemical data and modelling (D1.7, D1.8) has shown that an observed decrease in pH of water present in the tank water in contact with the concrete from pH 10 to neutral occurred over a period of 8 years by cellulose degradation processes occurring within the waste drums. A biogeochemical model of the GGE (D1.8, [13]) represents the diffusion of alkali from the concrete and acidity from the waste drums generated by cellulose hydrolysis and fermentation processes. The model accurately represents the observed rate of CH_4 generation during the 18 years of operation (~ 0.5 to 1 m^3 CH_4 per year), including an observed doubling of gas generation that occurred after 8 years. Microbiological characterisation including genomic sequencing studies of samples from the GGE reveal that the increase in gas generation rate coincides with the presence of acetate utilizing Archaea from the family Methanosaeta; methanogens that consume organic carbon. Initially, the microbial community was characterised by sulfate reducers belonging to the order Desulfovibrionales and methanogens that utilise H_2 (Methanosarcinaceae). The increase in CH_4 gas generation rate also coincides with a decrease in concentrations of dissolved organic carbon (DOC) and volatile fatty acids in the tank water. Biogeochemical modelling ([13], D1.8) also simulated the effect of increased methanogenesis as being related to neutralisation of the initial alkaline tank water and delayed consumption of DOC. Consideration of concentrations of sulfide in the tank water [13] also raises the possibility that methanogenesis could be inhibited by sulfide, whose concentration was observed to decrease from 0.2 mM initially to < 3 x 10^{-6} M after 8 years as a result of slow equilibration with of iron sulfide (mackinawite).

Deliverable [D1.8] concerns modelling of microbial processes in in situ experiments such as the GGE and borehole experiments at the Mont Terri URL. Deliverable D1.8 describes the basis to represent the growth of anaerobic microbes through Monod kinetics and coupling to geochemical speciation and solute transport. Examples are provided using the open source geochemical code PHREEQC, for wider application to assist the interpretation of such biogeochemical experiments and to underpin performance assessment models.

2.2. Work package 2

This work package consists of 5 tasks.

1. Microbial production of sulfide in the geosphere;
2. Microbial induced corrosion of canisters;
3. Microbial activity in bentonite buffers;
4. Microbial degradation of bentonite buffers;
5. Microbial activity in backfill and influence on plugs and seals.

Microbial production of sulfide in the geosphere: In the context of microbiological risks related to radioactive waste disposal, the geochemistry of gases in deep groundwater is an integral part of the determination of geochemical constraints of biological activity at disposal depths. Data on gas compositions and concentrations do exist from several separate locations in Finland and two locations in Sweden (D2.1, D2.3). In laboratory experiments with deep groundwater populations, acetate was overall the most efficient activator of the studied microbial communities which indicates acetate's important role as an electron donor for different Olkiluoto deep subsurface groundwater communities. However, there were also activation effects from H_2, CH_4 and NO_3^- (D2.5). The deliverable D2.17 "Sulfide production" will be delivered M45. This deliverable aims at defining the boundary conditions constraining the availability of sulfide in deep geological disposal conditions. Critical process to be analysed is the sulfate reduction to sulfide, which is constrained by the sulfate source and the availability of possible electron donors (e.g., H_2, CH_4 and Fe^{2+}).

Microbial influenced corrosion (MIC) of canisters: This task has produced one deliverable, D2.13 "Anaerobic microbial corrosion of canister material" and D2.18 "Rate of corrosion of carbon steel in bentonite under biotic and abiotic conditions" will be ready in M45. The D2.13 report includes a description of MIC and methods that can be used to study corrosion and microbiology. Anaerobic MIC were studied in experiments with stainless steel and carbon steel in three types of water, granitic water from the VITA source and HV1 source in Frans Josephs underground research facility together with synthetic bentonite porewater which was inoculated with VITA water. Corrosion was studied in inoculated samples and in sterile controls with a range of electro-chemical methods; electrochemical impedance spectroscopy (EIS), open circuit potential and polarization curves. Weight loss studies were done and two DNA-techniques for identification of microorganisms were used. Also surface analyses were performed. Two temperatures, lab temperature and 35°C were used in some studies. The duration of the experiments was from 111 days to 2 years. It was clearly shown that the corrosion rate of carbon steel in the presence of bacteria, SRB, was several times higher than in sterile controls. This was shown by weight loss experiments and illustrated with SEM.

Microbial activity in bentonite buffers: This task was scheduled for 4 deliverables, D2.4 "Threshold densities" (M36), D2.6 "Microbial diversity in bentonite buffer of aged bentonite buffer experiment" (M36), D2.14 "Role of bentonite density on the rate of corrosion of carbon steel" (M42) and D2.15 "Survival of microorganisms in bentonite subjected to different levels of irradiation and pressure" (M42).

The relation between water saturated clays at varying wet density and bacterial sulfide-producing activity is well studied (D2.4). However, wet density is just a value of the total amount of clay and water. That value does not reflect the conditions in compacted clay where several variables of importance for bacterial life can be of importance, such as clay type, pH, temperature, transport conditions, water content, pressure, pore space and pore water composition. These variables need further attention for a full understanding of what conditions control bacterial activity in compacted bentonite clays. Significant acetate formation from natural organic matter present in the clays was detected in the studied bentonites. This production occurred at all wet densities and suggests that bacterial activity, per see, was possible also at densities where sulfide-production could not be detected. Acetate is known to induce stress-corrosion cracking of copper and other metals and the possible formation of acetate should, therefore, be further investigated.

The presence of living microbes on bentonite and on copper surfaces could not be demonstrated in the D2.6 study but microscopy studies revealed living microbial cells in the external water surrounding copper cylinders. According to the IonTorrent sequencing, SRB and IRB were detected in the bentonite matrix, water and the copper surface. SRBs can produce corrosive sulfide and IRBs can have a role in processes that could be linked to the loss of swelling properties in bentonite. Fungal conidia and hyphae were detected by SEM in water and several groups of Ascomycetes and Basidiomycetes were identified by sequencing from bentonite samples. Many of the fungal genera detected are able to produce organic or inorganic acids that help fungi in solubilisation of minerals from rock substrates.

The current results obtained from the in situ experiments in the Opalinus clay in Switzerland, offer a partial view on the microbial activity, and thus the potential impact of microbial processes on canister corrosion, under repository relevant conditions. Continued monitoring of the ongoing experiments may provide further evidence of the role of microbes in sulfide production and steel corrosion and the results will be presented in D2.14.

BaM bentonite is currently being tested at high temperature and pressure for D2.14. Two DNA extraction methods were compared (based on protocols obtained from HZDR and SCK•CEN), another method involving ultrasonic disintegration of the material was also tested. Experiments with inoculated bentonite suspension under pressure 1, 2, 3 and 5 MPa together with atmospheric pressure control were performed. Experimental setup of temperature/pressure experiments is being finalised and the experiments started. Influence of radiation on microorganism's survivability in the bentonite suspension and water is also studied. Experiments are still ongoing; they will be finished in 2019.

Microbial degradation of bentonite buffers: This task comprises 6 deliverables, D2.2 "Design, set up and operation of experimental equipment" (M18), D2.7 "Microbial diversity in aged bentonite" (M36), D2.8 "Long-term stability of bentonite in the presence of microorganisms" (M36), D2.9 "Evolution of stress in biotic and abiotic clay flow cells" (M36), D2.10 "Microbial mobility in saturated bentonites of different density" and D2.16 "Microbial activity and the physical-chemical and transport properties of bentonite buffer" (M44).

Sulfide has been found to reduce ferric iron in bentonites denoted Asha, MX-80 and Calcigel under the formation of elemental sulphur, ferrous iron and iron sulfide. This immobilisation effect can reduce the mass of sulfide that corrode metal canisters over repository life times, but the concomitant reduction of ferric iron may be problematic due to the destabilizing effect of ferrous iron on dioctahedral smectites such as montmorillonites.

The results of the D2.7 analyses showed that there were bacteria present in all of the bentonite samples studied. Surprisingly, the microbial communities detected in the bentonite samples showed a high level of similarity. The bacterial profiles were characterised by the dominance of heterotrophs, aerobes or facultative anaerobes capable of respiring oxygen or nitrates. The majority of detected bacteria belong to common soil microorganisms or ubiquitous microorganisms with wide ecological amplitude enabling them to survive under various conditions. The results suggest that microorganisms found in the bentonite samples in this study were most probably present in the bentonite already before the start of the experiment.

The aim of the laboratory scale D2.2/D2.8 MX-80 bentonite storage experiment was to simulate bentonite behaviour in circumstances that can take place in the interfaces of bentonite, host rock fractures and water flow in nuclear waste geological disposal. After one year, microcosms in MX-80 bentonite initiated both at aerobic and anaerobic conditions, no essential changes in bentonite mineralogy were found compared to the initiation of experiment. However, clear microbial activity in terms of ongoing sulfate reduction and sulfide formation as well as high number of sulphite reductase genes (dsrB) were detected in anaerobic samples. Microbial activity also affected bentonite water-phase chemistry and bentonite cation exchange capacity. These effects were not detected in sterile controls, demonstrating the microbial origin of these changes. The experiment is planned to continue for some years further as potential changes in bentonite mineralogy caused by microbial activity happens slowly in the studied conditions.

Given the limited duration of the D2.2/D2.8 tests, it is not surprising that the alteration of the bentonite was limited to a small zone adjacent to the iron. From a ‘flow perspective’ this will have little impact, as the bulk of the clay, and therefore the flowing porosity, remains unchanged. To understand the full impact of microbial action on the hydraulic properties of the clay, test durations would need to be increased substantially, or the iron should be dispersed within the entire clay matric to increase reaction rates. Given these findings, the question of whether microbial activity alters the hydraulic behaviour of bentonite remains unanswered. Further work is required beyond the lifetime of this project to fully assess the impact of microbial induced changes on the hydraulic integrity of the clay.

The D2.10 study fulfilled important goals. First, a reliable method for direct detection of bacterial presence (both viable and dead cells) in the bentonite was developed, which has been missing. This method is based on the extraction of bacteria from bentonite using density gradient centrifugation and their subsequent Live/Dead fluorescence staining. Although the method needs further optimization and testing of its general functionality on different bentonite types, it is believed the method will be very useful for future research of bacterial presence in various clay materials.

The D2.16 work is progressing according to the plans. The experimental equipment that is being assembled and tested begins to generate the data needed. Collating data on the evolution of stress in biotic and abiotic flow cells is ongoing. The first two experiments have been dismantled, samples have been taken for DNA analysis, and culture-based enumeration has been set up. Culture-based analysis and DNA analysis is ongoing and assessment of physical, chemical and transport is ongoing as well.

Microbial activity in backfill and influence on plugs and seals: This task comprises 2 deliverables, D2.11 “Cement deterioration boundaries” (M36) and D2.12 “Concrete stability” (M36). The D2.11 study demonstrated that the high pH conditions imposed by the OPC CEM I inhibited microbial sulfate and nitrate reduction. However, SEM analysis indicated the presence of intact cells in the suspension on top of cement and putative biofilm structures on the cement. This suggests that the high pH environment does not completely eliminate the microbial population. Interestingly, in sulfate reducing conditions, a pH decrease from > 12 to pH 10 was observed in one replicate harbouring clearly a larger microbial community in the suspension on top of the cementitious material compared to the other samples. Further studies to confirm this observation and to elucidate the precise mechanism are necessary.

The conclusion of the D2.12 results was that the alkaline solution, leached from the concrete, lead to a deviation in wet density and increased the pH in the bentonite clay. However, the inhibition of microbial activity was dependent of the added carbon source. Induced microbial activity in MX-80 with glucose led to a decrease in pH. A reason might be that natural occurring acetogenic bacteria produced organic acids from the added carbon source. In the future bentonite clay samples should be analysed for acetate and cultivatable acetogenic bacteria to confirm this hypothesis.

2.3. Work package 3

This work package includes 3 tasks:

1. Synthesis, evaluation, abstraction and integration of experimental and computational output;
2. The impact of the inclusion of microbiology on expert conceptualization and public perception of geological disposal;
3. Knowledge and information exchange.

Synthesis, evaluation, abstraction and integration of experimental and computational output:

Within this task of work package 3, all experimental work obtained within WP1 and WP2 was synthesized on a yearly basis and reported in two deliverables: D3.4 and D3.5. The first year, an evaluation of the initial state of the art knowledge base was reported as deliverable D3.1.

In addition, next generation sequencing based on the 16S rRNA amplicon, a technique that is frequently used by most partners to identify the present microbial community was compared and evaluated among different partners. This because it is known that the analysis of microbial communities via next generation sequencing based on the 16S rRNA amplicon can be biased due to the DNA extraction protocol, primer design, PCR amplification, sequencing artefacts and bioinformatics analysis procedures. Therefore, care should be taken in comparing results obtained using different methods. Also within MIND, DNA extraction procedures, sequencing processes and bioformatics pipelines are highly diverse among the different partners. In order to evaluate the impact of the different strategies on the identified microbial community, a commercial microbial community standard of ZymoBiomics, consisting of eight different bacterial species was used (note that all data were analyzed blind i.e. involved partners didn't know the composition of the mock community).

In first instance, the sequencing process and bioinformatics pipelines were compared and evaluated. To this end, the DNA of the mock community was sent around to eight different microbiology laboratories involved in the MIND project. The different laboratories processed these samples with their own sequencing and data analysis tools. In total, five laboratories had sent in their sequencing data. Two different sequencing technologies were used i.e. Illumina MiSeq and IonTorrent, and the V3-V4 or V4 region of the 16S rRNA gene was selected as amplicon. If different labs analyzed their own data and predicted the mock community, variation was observed in the amount of Operational Taxonomic Units (OTUs) between the different research groups, ranging between 10 and more than thousand OTUs. However, the majority of this variation could be explained by the bioinformatics pipeline used, rather than the amplicon region, the quality of the sequencing data or the type of sequencing technology (Illumina MiSeq versus IonTorrent). This could be confirmed by applying the same 16S rRNA gene amplicon sequencing analysis pipelines on the five different datasets as comparable results were obtained from the different datasets. It was also observed that longer amplicons (e.g. V3-V4) returned a higher sequencing error rate than the approaches focusing on one region (e.g. V4). Additionally, most artefacts in the sequencing data originated from the presence of chimeric sequences, even for the best performing bioinformatics pipeline. Overall, it was clear that the different state-off-the-art sequencing and data analysis approaches used by the different partners in the MIND community are adequate and comparable, providing high quality scientific data. Chimera removal should be a point of attention whenever analyzing sequencing data. Knowledge and experience on how to address and process such samples and data was shared among the partners.

In a next step, an experiment was carried out to compare different DNA extraction protocols to recover DNA from a clay-rich environment. This matrix – although hampers the efficiency of DNA extraction – was selected as it is essential to have robust DNA extraction techniques from relevant host rock formations to assess the microbial impact on the safety of deep geological radioactive waste repositories. Seven laboratories received a 10 g aliquot of Opalinus Clay rock collected from the Mont Terri Underground Rock Laboratory in St. Ursanne, Switzerland spiked with the Zymobomics cell mock. Every participating laboratory extracted DNA using their own method. Afterwards, DNA amplification (16S rRNA gene V4 region) was performed by a single laboratory and Illumina MiSeq sequencing was carried out by a single commercial laboratory. In addition, the same bioinformatics pipeline was used to process and compare the DNA sequences obtained. Highly different results were obtained with the different DNA extraction methods. The amount of extracted DNA ranged from 0.66 ng to 418 ng, while in theory ~ 4.5 µg DNA could be obtained. In addition, there was one method outstanding in reassembling the mock community, while for other methods, an over-and underrepresentation of different OTUs was observed. The results of this study will be further elaborated on in future work. Nevertheless, these results indicate that care should be taken with comparison of data obtained with different methods and that testing the efficiency of the used DNA extraction protocol is essential.

The impact of the inclusion of microbiology on expert conceptualization and public perception of geological disposal: In order to understand how MIND experts (MIND researchers, members of the MIND Implementer Review Board) and experts outside the project (e.g. geologists, waste management regulators, policy makers) conceptualize the role of microbes in radioactive waste disposal, social scientists conducted semi-structured interviews with MIND members, participated as observers and presenters at MIND meetings, and analyzed guiding RWM documents within the MIND project. Elicited findings served as inputs for communication with project participants and civil society. To this end, group discussions, interviews and an interactive workshop with implementers, project participants and civil society were organized.

Recurrent issues concerned the possibility and scope of interdisciplinary collaboration within and outside the MIND research community, the importance of public communication (particularly the communication of uncertainty), and the institutional recognition for microbiology in radioactive waste governance at large. In a concluding interactive workshop, members of civil society reproduced and reiterated these issues, while also shedding new light on them, by stressing that communicating uncertainty can generate (rather than erode) public trust in science, and by probing the relationship between MIND research and public safety. These observations should sensitize MIND stakeholders to their own research concepts and practices, including the value all stakeholders, without exception, ascribe to public communication – as research on the role of microbes in radioactive waste is characterized by a considerable degree of exoticness, uncertainty, and ambiguity. Although communication has been recognised as a challenge due to multidisciplinarity, trandisciplinarity, diverse risk perceptions and complexity, the new communication tools and opportunities offer a lot of possibilities to reach out with scientific results and to enable stakeholders to make informed decisions.

Knowledge and information exchange

Education and training activities were initiated (D3.3) to cultivate awareness of the relevance of microbial issues in otherwise typically abiotic fields of expertise, and to dissipate the knowledge gained in the MIND project beyond the known geomicrobiology expert circles. To this end, two courses related to microbiology in nuclear waste disposal were organized during the project, an exchange program for Master and PhD students has been developed and focused communication on these initiatives has been undertaken.

2.4. Work package 4

IRB has developed a table listing potential research gaps regarding Microbiology in Nuclear Waste Disposal. This table is a collation of FEPs on different microbial processes of potential relevance to waste disposal and also addresses to what extent these "FEPs" were addressed in MIND. As a final product the IRB has produced an Evaluation Report (D4.6) where the contributions of MIND are assessed with respect to microbial issues, processes and conditions of relevance to Post Closure Safety of Nuclear Waste repositories.

3. Conclusions

The MIND project was one of the first projects, investigating the impact of microbial processes on organic material in cementitious waste forms and their behaviour, on the technical feasibility and on long-term performance of repository components including clay and canister materials. Research focussed on key questions posed by waste management organisations. Overall, many experiments have been conducted providing further insights into different microbial processes that can be expected during the geological disposal of radioactive waste. Chemical conditions that may limit methanogenesis and hydrogen consumption in LLW/ILW repositories were elaborated on in more detail. The research related to H_2 consumption by sulfate reduction processes is also of relevance to microbial induced corrosion of metal canisters. In addition, the knowledge base concerning the range of organic polymers and additives that may contribute to gas generation from LLW/ILW including the combined effects of irradiation and biodegradation under alkaline conditions was increased. Further knowledge has also been obtained regarding the biodegradation of potential radionuclide complexants, including ISA under alkaline conditions. Furthermore, several experiments showed that enhanced microbial activity could result in solid partitioning of radionuclides, which could affect their mobility in ground water. Furthermore, different experiments resulted a more detailed understanding of microbial activity in backfill material and bentonite buffers. In addition to the experimental work, the MIND project took a lot of time on education and communication. All the expertise gathered within the project is summarized in yearly synthesis reports deliverables [D3.1, D3.4, D3.5] which can be valuable for waste management organizations to define further knowledge gaps that could be elaborated on in future projects.

The evaluation report (D4.6) by the IRB concludes that MIND has been invaluable to assemble the competence on microbiological issues of relevance to repository safety and has helped to clarify what issues are of potential importance and what that mere has scientific interest. Thereby MIND forms an essential platform for how further efforts in the areas should be prioritized.

The findings in the MIND project has contributed to that microbial processes in repository environments are now being considered e.g. when setting the requirements on engineered barriers such as buffer and backfill leading to significant refinements of safety case models currently being implemented.

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References

[1] Wiborgh M, Höglund L O, Pers K, 1986. Gas Formation in a L/ILW Repository and Gas Transport in the Host Rock. Nagra Technical Report 85-17.

[2] Small, J.S., Nykyri, M., Helin, M., Hovi, U., Sarlin, T., Itävaara, M., 2008. Experimental and modelling investigations of the biogeochemistry of gas production from low and intermediate level radioactive waste Applied Geochemistry 23: 1383-1418.

[3] Motamedi et al., 1996 Motamedi M, Karnland O, Pedersen K, 1996. Survival of sulfate reducing bacteria at different water activities in compacted bentonite. FEMS Microbiology Letters 141, 83–87.

[4] Stroes-Gascoyne 2010 The effects of the physical properties of highly compacted smectitic clay (bentonite) on the culturability of indigenous microorganisms Appllied Clay Science 47:155-162

[5] Masurat P, Eriksson S, Pedersen K, 2010. Microbial sulphide production in compacted Wyoming bentonite MX-80 under in situ conditions relevant to a repository for high-level radioactive waste. Applied Clay Science 47, 58–64.

[6] Bassil, N.M., Bryan, N., Lloyd, J.R., 2015. Microbial degradation of isosaccharinic acid at high pH. ISME J. 9, 310e320. https://doi.org/10.1038/ismej.2014.125

[7] Rout, S.P., Charles, C.J., Garratt, E.J., Laws, A.P., Gunn, J., Humphreys, P.N., 2015. Evidence of the generation of isosaccharinic acids and their subsequent degradation by local microbial consortia within hyper-alkaline contaminated soils, with relevance to intermediate level radioactive waste disposal. PLoS One 10 (3), e0119164. https://doi.org/10.1371/journal.pone.0119164

[8] Bassil, N.M., and Lloyd, J.R., 2017. Anaerobacillus isosaccharinicus sp. nov., an alkaliphilic bacterium which degrades isosaccharinic acid. International Journal of Systematic and Evolutionary Microbiology. https://doi.org/10.1099/ijsem.0.002721

[9] Nixon S.L., van Dongen B.E., Boothman C., Small J.S. and Lloyd J.R. 2018. Additives in Plasticised Polyvinyl Chloride Fuel Microbial Nitrate Reduction at High pH: Implications for Nuclear Waste Disposal. Frontiers in Environmental Science. 6:97. https://doi.org/10.3389/fenvs.2018.00097

[10] Kuippers, G., Boothman, C. Bagshaw, H. Ward, M., Beard, R., Bryan, N. and Lloyd, J.R. 2018. The biogeochemical fate of nickel during microbial ISA degradation; implications for nuclear waste disposal. Scientific Reports Volume 8, Article number: 8753. https://doi.org/10.1038/s41598-018-26963-8

[11] Ruiz-Fresneda, M.A. et al 2018. Green synthesis and Biotransformation of amorphous Se nanospheres to trigonal 1D Se nanostructures: impact on Se mobility within the concept of radioactive wastes disposal. Environmental Science: Nano https://doi.org/10.1039/c8en00221e

[12] Sanchez-Castro, I., Ruiz-Fresneda, M.A., Bakkali, M., Kämpfer, P., Glaeser, S.P., Busse, H.J., López-Fernández, M., Martínez-Rodríguez, P., Merroun, M.L., 2017. Stenotrophomonas bentonitica sp. nov., isolated from bentonite formations. International Journal of Systematic and Evolutionary Microbiology 67:2779–2786. https://doi.org/10.1099/ijsem.0.002016

[13] Small, J.S., Nykyri, M., Vikman, M., Itävaara, M., Heikinheimo, L. 2017. The biogeochemistry of gas generation from low-level nuclear waste: Modelling after 18 years

study under in situ conditions. Applied Geochemistry, 84, 360-372. https://doi.org/10.1016/j.apgeochem.2017.07.012

List of cited deliverables (www.mind15.eu)

D.1.1 Abrahamsen et al. (NNL) "A Review of Anthropogenic Organic Wastes and Their Degradation Behaviour", 2015.

D1.2 Nixon et al. (UNIMAN) "Report of effects of radiation and microbial degradation of ILW organic polymers". 2017.

D1.3 Mijnendonckx et al. (SCK•CEN) "Report on radiation and microbial degradation of bitumen" 2018.

D1.4 Brinkmann et al. (HZDR) "Report of radionuclide speciation associated with degraded organic ILW", 2018.

D1.5 Merroun et al. (UGR) "Microscopy and element mapping characterization studies of radionuclide microbe organic interactions", 2015.

D1.6 Vikman et al. (VTT) "Report on relevant microbial metabolic processes and limits on chemical conditions leading to methane generation in LLW and ILW", 2018.

D1.7 Bernier-Latmani et al. (EPFL) "Report on methane generation in the Mt Terri URL and the underlying microbial processes", 2018.

D1.8, Small et al (NNL) "Report on modelling of microbial processes relevant to ILW disposal", 2018.

D2.1 Kietäväinen et al. (GTK) "Inventory of reducing gases", 2016.

D2.2 Miettinen et al (VTT) "Design, set up and operation of experimental equipment", 2016.

D2.3 Kietäväinen et al. (GTK) "Interim report on deep gases and sulphur compounds as biogeochemical energy sources in crystalline rock", 2017.

D2.4 Pedersen et al (Micans) "Bacterial activity in compacted bentonites", 2017. D2.6, Vikman, et al (VTT), "Microbial diversity in bentonite buffer of aged bentonite buffer experiment", 2018.

D2.7 Ševců, et al. (TUL)"Microbial diversity in aged bentonites", 2015.

D2.8 Matschiavelli, et al (HZDR). "Long-term stability of bentonite in the presence of microorganisms", 2015.

D2.10 Černá, et al. (TUL) "Microbial mobility in saturated bentonites of different density", 2015.

D2.11 Mijnendonckx et al. (SCK•CEN) "Microbial cement deterioration boundaries", 2018.

D2.12 Taborowski, et al. (Micans) "Microbial activity in a concrete-bentonite clay interface", 2017.

D2.13 Černoušek et al (TUL) "Anaerobic microbial corrosion of canister material", 2019.

D2.14 EPFL in prep "Role of bentonite density on the rate of corrosion of carbon steel"

D2.15 Černá et al (CVREZ) "Survival of microorganisms in bentonite subjected to different levels of irradiation and pressure", 2019.

D2.16 UKRI (NERC) in prep "Microbial activity and the physical chemical and transport properties of bentonite buffer"

D2.17 GTK in prep "Sulphide production"

D2.18 EPFL in prep "Rate of corrosion of carbon steel in bentonite under biotic and abiotic conditions"

D3.1 Ahonen, et al (GTK) " Year one evaluation report", 2016.

D3.3 SCK•CEN, Micans, "Modular microbiology education and training", 2016.

D3.4 Mijnendonckx et al. (SCK CEN), "Year two synthesis report", 2017.

D3.5 Mijnendonckx et al (SCK CEN) "Year three synthesis report", 2018.

D4.6 Andersson et al (SKB) "Implementers' review board. Evaluation report", 2019

Session Three - Networking of research communities, Joint Programming of national programmes and integration of Radioactive waste producers

Chair: Piet Zuidema (Zuidema Consult GmbH, CH)
Co-chair: Ian Gordon (IAEA, AT)
Rapporteur: Jacques Delay (ANDRA, FR), Expert

FISA 2019
EURADWASTE '19

4-7 June, 2019
Pitesti, Romania

Session Three Summary

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Context and content of Session III

Providing that the EURAD - European Joint Programme on Radioactive Waste Management sets-off and performs adequately, the European Joint Programming (EJP) instrument is expected to be continued in the next Euratom FP and would be the main instrument for EURATOM support for research and training on Radioactive Waste management (RWM). In the meantime, in order to reinforce the R&D on pre-disposal and gradually include the waste producers in the EJP concept, the Commission has opened a topic on pre-disposal as part of WP2019-2020 on:

- #10, developing pre-disposal activities identified in the scope of the European Joint Programme in Radioactive Waste Management.

Session III was comprised of presentations from the three main structured actors in European RWM, i.e. Waste Management Organisations (WMOs), Technical Support Organisations (TSOs), and Research Entities (REs) which decided to merge their efforts and resources.

This session included a presentation of the result of the integration of their selected R&D activities in a single European Joint Programme (EJP) called EURAD. In addition, another presentation highlighted the needs of countries with longer timescale for deep geological repository implementation and in particular the need for cooperation and assistance. Besides the needs expressed, recall was made of the view of some of the Central and Eastern European countries, operating one to six reactors and dealing with small inventory, which follow the so-called ‘dual track approach’, meaning that they are considering the possibility of shared solutions for disposal either as a preferred or as an alternative option.

Finally, waste producers presented their views on predisposal R&D and their views on the possibility of their integration into the EJP on waste disposal.

Prior to the panel discussion, the synergies between EURAD and the IAEA and OECD/NEA programmes on the state of knowledge, Guidance on R&D and training and mobility were presented.

Ten years of effort in structuring the RWM community

Structuring networking and support to collaborative research across European countries has been the «raison d’être» of the EURATOM programme for at least two decades. As stated by Alan Hooper in EURADWASTE 13’ report, ”the organisational structures established through EURATOM, notably ENSREG, ENEF and the IGD-TP was clearly shown to be contributing strongly to the progress towards the safe and, long-term management of Spent fuel and heat generating and long-lives RW in Europe.” Furthermore, the JOPRAD Project engaged within the RWM community led to the possibility and now the start of a European Joint programming.

In 2009, the first step of integration of activities was the support to the Implementing Geological Disposal – Technology Platform (IGD-TP) that provided a coherent roadmap for collaborative R&D in view of the licensing of disposal facility. In addition, IGD-TP organised "Exchanged Fora" that proved to be an efficient tool to initiate collaborative projects. After the WMOs, the TSOs produced their own Strategic Research Agenda (SRA) in the framework of SITEXII project. Emphasis was put on the development of the independent expertise function as well as the means to involve the Civil Society in the process. More recently, the REs have established in the framework of JOPRAD their own SRA.

Today, the EURAD programme gathers mandated actors, i.e. mandated by their government to take part in the work in the RWM domain. The mandated actors are limited to WMOs, TSOs and REs. In addition, EURAD includes observers and non-technical participants who do not have a formal national mandate for research in RWM but who are considered as key interest groups and may benefit from or provide their view on the direction of specific activities undertaken. This includes Civil Society Experts, Nuclear Owners/Operators (waste producers), International Organisations and countries not part of the EU

Nuclear Owners/Operators Waste producers and those with a pre-disposal waste management remit are engaged via the Nuclear Generation II & III Association (NUGENIA). Although not direct contributors or participants of the EURAD initiative Joint Programme, NUGENIA will set a foundation for future collaboration in projects influencing the waste form for final disposal.

Waste producers and implementers at a national level are well-connected and have existing cooperation activities that should support the integration of waste producers RD&D needs (that impact disposal), via the WMOs.

Waste producers are often responsible for contributing to financing of disposal facilities. Thus, they are involved in the R&D in order to ensure the acceptance of the waste in the future disposal.

The Horizon 2020 R&D projects already linked to predisposal activities through calls on waste management are: CHANCE on characterization of conditioned nuclear waste; THERAMIN on thermal treatment for radioactive waste minimisation and hazard reduction, and INSIDER on methodology for characterization to minimize waste and to develop new methodologies for more accurate initial estimation of contaminated materials

Where do we stand?

One of the main achievements of the EURATOM continuous policy was to create at the EU level, discussion fora where project results are exchanged and future research development are initiated. Exchange Fora organised by IGD-TP, SITEX meetings, and JOPRAD/EURAD workshops have led to structure the communities and organise research priorities and topics.

Consequently, following the WMOs Strategic Research Agenda published in 2011, all the communities have expressed their priorities in their own documents. The methodology proved to be efficient to fulfil research objectives of real interest for the implementation of a Geological Disposal while avoiding duplication and making efficient use of the financial and human resources.

The methodology to set up of the research agendas and the programmes is mature and well understood. This work has to be renewed to take into account evolution in policies or improvement of knowledge. However, it should be acknowledged that the technical projects linked with safety or demonstration of a waste disposal are not the first priority for most of the European countries. They are dealing more with strategic issues and siting issues, which originally were out of the scope of the implementers for they were considered fundamentally a national issue.

EURAD is opening a new era with the possibility of embarking more activities that are predisposal and a spectrum of strategic studies.

Thus, for the first run of EURAD the SFC project is directly dealing with this activity. Spend Fuel Characterisation and evolution until Disposal (SFC) aims at reducing uncertainties in spent fuel properties in predisposal phases. This will study the properties, behaviour and associated uncertainties of spent nuclear fuel from the time when it is irradiated in the reactor up to the time of its final disposal in a geological disposal facility.

In addition, EURAD proposed strategic and horizontal Work Package (WP) studies in order to develop good practices, in particular, “uncertainties” and “routes”:

- To manage damaged waste packages and set the criteria and methods for reprocessing aged waste,
- To minimise radiological consequences in the event that packages have aged and require re-processing or have become damaged prior to transfer to a geological disposal facility,
- To support the safe management and safety assessment of existing storage facilities and design criteria for new storage facilities, and
- To establish and develop waste acceptance criteria.

Thus, for the first run of EURAD strategic studies, the two WPs are initiated in order to agree upon and define in some detail the needs for future activities, including further specific thematic studies or RD&D at the forefront of science. This may also be referred to as ‘think-tank’ or networking activities to determine if there is a RD&D need on an emerging issue, if there is a need of a position paper, or if it is considered mature and suitable for knowledge management activities.

In addition, Knowledge Management is enabled by three permanent WPs that derive directly from EURATOM expectations under WP2018 and that will be implemented through the Annual Work Plan:

- State of Knowledge - Activities under this WP consist of developing a systematic approach of preserving/capitalising on and providing open-access to knowledge generated in the field of RWM research.
- Methodological guidance - Activities under this WP consist of developing a comprehensive suite of instructional guidance documents that can be used by Member-States with RWM programmes that are at an early stage of development with respect to their national RWM programme. Such a WP shall pursue and complement the work initiated with the PLANDIS Guide.
- Training/mobility - Activities under this WP consist of developing a diverse portfolio of tailored basic and specialised training courses for the end-users within EURAD under the umbrella of a “School of Radioactive Waste Management,” taking stock

of and building upon already existing initiatives (i.e. IAEA and NEA) and creating new initiatives to bridge the identified gaps.

The way forward: NFRP 10 - Developing pre-disposal activities identified in the scope of the European Joint Programme in Radioactive Waste Management – potential technical topics

For EC, the aim is now to reinforce scope of pre-disposal of the EJP SRA by involving waste producers for preparation of future integration in an EJP waste that will follow EURAD. This Framework Programme appears to be dedicated to the waste producer community, although the connections with the RWM community are obvious.

Thus, the NFRP10 activity objective is to develop methods, processes, technologies and demonstrators for treatment and conditioning of wastes for which no or inadequate solutions are currently available. It should be noted that the dismantling is not included in the scope for these activities are the sole responsibility of the waste producers.

In a position letter published in March 19, the IGD-TP, presenting WMO's views, confirmed its strong interest in the project to be developed as the IGD-TP acts as the ultimate end-user of the pre-disposal activities. IGD-TP considered that the major aspect to consider is the development of the waste acceptance criteria (WAC). Based on a survey by the IGD-TP members, policy, treatment routes, and potential pre-disposal treatment techniques have to be developed in cooperation with waste producers. The first priority for the majority of the IGD-TP members lies in the treatment and conditioning of organic wastes, liquid, or solid such as bitumen, exchange resins, and polymers. Depending on IGD-TP members, graphite or metal treatment as well as conditioning of reactive metal could be developed in a shared proposal.

Civil Society involvement

Considering the long time for project design and development, interaction with Civil Society representatives will be enabled via their participation in the external advisory committee of EURAD. This should provide opportunity to CS to express their views on R&D proposed and scientific and technical questions to be solved. Participation of CS representatives in technical, strategic and horizontal Work Packages is possible whenever a clear task is identified and defined. Other beneficial roles of Civil Society can be in the strategy to be developed to allow the knowledge transmission amongst generations and European countries, and in contributing to education and training on technical and societal matters in consistent and efficient ways.

Possible ideas to develop and prepare a larger integration of waste producers needs in the EJP

According to EDF, the R&D that could be developed is two folds:

- A regulatory consideration, to foster a circular economy in materials management, including waste whatever they are radioactive or not, thanks to the appropriate definition of criteria and rules. In this domain, EC could support work, including coordination action, providing material, data, scientific, technical and economic impact of for example levels of acceptance criteria, in support of regulatory development on the topic.
- New treatment demonstrators or facility in order to reduce waste quantities and improve decommissioning techniques and waste management. The example given

is the use of arc melting furnace to decontaminate/homogenize metallic material in the frame of a recycling route. As part of its decommissioning strategy, EDF has launched a decommissioning demonstrator facility project to be in operation by 2022. Following a modular conception, and first envisaged to check the decommissioning operations of Graphite reactors.

Knowledge sharing

IAEA stressed on the knowledge tools and especially the documentation produced in the domain of R&D on RWM. In addition, Technical Cooperation programme including national and regional projects address global needs such as training and sharing knowledge in all steps of waste managements, and targets all types of waste management steps, scales and needs.

In complement, the OECD/NEA presented the objectives and means for competency management for regulators and implementers to ensure development of competences in specific domains as well as proper transmission of knowledge through generation.

Conclusion

- EURAD represent the achievement of ten years of integration of RWM community and the platform for further integration of R&D programmes with waste producers thanks to the continuous support of EURATOM programmes over a decade;
- For WMOs focus remains on geological disposal, but the missions are to be expanded to accommodate more upstream interests and a wider inventory coverage (e.g. sealed sources and borehole disposal). However, it is important to recognise that WMO RD&D programmes have a much wider scope of activities than the commonly-agreed EURAD strategic research agenda will address;
- For the SITEX community, the condition for participating to an EJP is to develop the high quality expertise function independent from WMOs as well as expanding interaction with Civil Society towards integration in R&D projects, meaning that CS may have a role on design of shared experiments;
- After decades of collaboration with WMOs and TSOs, European research organisations in radioactive waste management have organised themselves in a network, called EURADScience, with the vision of acting as an independent, cross-disciplinary, inclusive network providing scientific excellence and credibility to national radioactive waste management programmes. It aims at serving to build a European knowledge platform on RWM;
- The need to harmonization of regulation was emphasised in order to prepare predisposal activities. Actually, these activities could be minimized by better integrating waste management activities in the dismantling and decommissioning phases.
- Knowledge management programmes should lead to attract and train new competencies and new high level researchers to allow a cross fertilization of ideas and ensure that the competences will be present all along the duration of the disposal operation.

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EURATOM RESEARCH AND TRAINING PROGRAMME IN RADIOACTIVE WASTE MANAGEMENT: OVERVIEW STATUS AND VISION

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Extended abstract. Euratom Research and Training (R&T) on radioactive waste management began in 1975. It is one of the first, European Commission research programmes. The purpose of this extended abstract is to take stock of the evolution the Euratom (R&T) programme underpinning the strategic vision and plan of the European Commission for its continued role and support in the field of radioactive waste management.

Over the nine successive programmes, Euratom went through all the R&D phases needed to manage and dispose all types and categories of radioactive waste including decommissioning, pre-disposal (characterization, treatment, conditioning), fuel cycle (reprocessing, partitioning and transmutation-P&T) and disposal (basic science on key processes; performance assessment calculations; site, host rock and geological investigations plus natural analogues; underground research laboratory constructions and in situ testing for performance investigations, constructions and disposal concept feasibility and technology development); policy and waste management strategies; and social science and humanities (SSH) for public perception and acceptance.

R&D on dismantling was gradually stopped in the mid-2000's due to the industrial maturity of the dismantling projects. Working groups to maintain and exchange knowledge in this domain are operating at the two international organizations (OECD Nuclear Energy Agency and IAEA). At Euratom level, the need to re-open R&D on decommissioning for advanced and innovative techniques and technologies is being investigated in a Coordination & Support Actions (CSA), SHARE, to identify any need for a decommissioning R&D roadmap for activities of EU added-value.

Near-surface disposal of short-lived and intermediate level waste is being widely implemented across Europe, hence activities supported by Euratom in this field were discontinued during Framework Programme (FP7, 2007-2013). Support to characterization and waste treatment for these wastes was reopened during the Horizon 2020 FP as part of the Work Programme 2016-17.

R&D on P&T is conducted mostly by the research community close to reactor systems, hence in Euratom this domain of research is managed within the part of the programme on reactor safety.

In the early 2000's, after 25 years of R&D, there was still no scheduled date for start of operation of the first underground repositories in Europe and no country was still foreseeing a date of submission of an operation license application to its regulatory authority. Disposal of high-level and long-lived radioactive waste (HL&LL W) and spent fuel (SF) in deep underground repositories was and still is the most important challenge in all national programmes, which have to manage SF.

Being a priority in EU Member States (MS), Euratom gradually focused its support on this domain and lower priority was given to R&D on pre-disposal.

Geological Disposal (GD) is a complex multidisciplinary scientific, technical, organizational and societal issue. R&D in this domain being mostly non-commercial and open science the Commission started to advocate for increase and close collaboration and joint activities within the respective research communities involved in the safety case (SC) of GD. Although the principle for EU support is competitive project proposals, this principle had to be adapted to the specific situation of radioactive waste disposal, so that even if scientific excellence is the objective in R&D, collaboration instead of competition can bring more benefits to all MSs, which face the same challenges. This approach also avoids unnecessary duplication of research. The question has been and remains to which extent and scope collaboration in all domains of the SC for GD is of EU added-value as opposed to specific requirements in each MS national programme. And it is also necessary to identify which R&D has to be done in any case in each national programme.

Only competitive projects may not be the most effective working method both for the Commission and the research actors on GD. Evidence of unfruitful competition was exemplified by the failure, in 2007, of two large competitive project proposals on gas led on the one side by Technical Support Organizations (TSO) and the other side by Waste Management Organizations (WMO): GASCONI and GASMIG. Both proposals were rejected at the evaluation stage and both communities had lost time and effort. The underlying argument leading to this competition was that TSOs considered that they need to remain independent to draw conclusions on the outcome of the project. This argument was challenged during evaluation saying that the purpose of the projects was to develop scientific knowledge and understanding on the processes of gas in underground repositories and that the interpretation of the results for the performance of the repositories remains of the responsibility of the respective communities. Fortunately, a joint project (FORGE) was developed the year after with fruitful collaboration and did set the pace for future method of work of the different research communities for disposal.

In the mid-2000's, one of the steps taken by the EC to increase collaboration and joint activities within the respective research communities was to introduce new types of project contracts: Integrated Projects, Network of excellence and European Technology Platforms (TP), to help speed up industrialization of research outputs and to help establish the European Research Area (ERA). The first initiative in Euratom was the start of work towards integration / coordination of WMOs. A number of projects were conducted between 2002 and 2009 with the Network of excellence NET.EXCEL, then CARD, which eventually led to the establishment of IGD-TP, the Implementing Geological Disposal –Technology Platform, in 2009, between 11 WMOs.

In line with the strategy of ERA, the EC/Euratom aim is to provide EU-added value, leverage and benefit to all national programmes. Therefore, beyond collaboration within the research communities, EC policy to achieve this objective has been to gradually bring together the different research communities generating knowledge for the safety case of disposal with the end-users of the results, i.e. Waste Management Organizations (WMO), TSOs and academic and research organizations.

In the early 2010's, the context at the EU level and in the MSs continued to evolve in a way justifying, reinforcing EC strategy towards integration of the different research communities, but furthermore to develop Joint Programming activities between MSs at EU level.

In 2011 and 2012, the first two license applications for underground repositories were submitted in Sweden and Finland demonstrating maturity of knowledge for the SC in countries with advanced programmes for GD. This could have been understood that continued support from Euratom could be questioned. However, at the EC EURADWASTE '13 conference, two key conclusions provided evidence of the continued role for Euratom.

The first conclusion was that each underground repository is a first of the kind because of many different conditions including geological formations, disposal concept, etc.

The second conclusion was that knowledge underpinning the SC needs to be continuously improved in order to be in a position to update the operating license, respond to uncertainties in processes measured during operation and to regulatory questions, to optimize the repository concept and facility, to provide competence to next generations of scientists due to the long operational time of repositories (up to one hundred years), etc.

At the same time, the Council Directive 2011/70/Euratom establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste (the waste Directive) was adopted by the MSs.

The Directive requires each MS to establish and maintain national policy, and legislative, regulatory and organizational framework for managing all types of radioactive waste from generation to disposal. This includes establishing a national programme with significant milestones and clear timeframes, as well as RD&D activities needed in order to implement technical solutions. Therefore, a R&D programme is needed in each MS concerned with radioactive waste management.

The role of Euratom is considered as reinforced, when considering the different time scheduled between MSs on the start of their respective repositories. Advanced countries like Finland, Sweden and France plan operational starts in the next decade, while many other MSs have longer implementation timescales, i.e. commissioning dates of deep geological repositories planned around 2055-2065. These countries in early stage will need to go through all the research steps undertaken in advanced countries. Therefore, there is a central role for Euratom in organizing cooperation between all national programmes so that all countries can benefit from joint work.

In working together, as part of a European Joint Programme, advanced countries will be able to address specific cutting-edge science on very deep scientific topics, while less-advanced programmes will be able to plan, structure and implement the necessary R&D, with guidance, training and transfer of competence and knowledge from advanced programmes and not having to redo and duplicate R&D effort for which there is state of the art knowledge.

From a regulatory support point of view, given the on-going and forthcoming license applications Euratom began to support networking and R&D activities of TSOs for their necessary competence in the review of Safety Cases. The two SITEX projects, started in 2011, led to establishment of the SITEX Network in 2018.

Recently, the community of research entities (RE), taking into account the EURADWASTE ’13 key messages, also started to structure and coordinate at European level in order to contribute to the long-term R&D challenges of, in particular, GD as part of a European Joint Programme and to be in a position to provide a flowerbed for education and training of the needed scientists for the future. In 2018, this community launched its own network called EURADSCIENCE.

In response to the evolving context described above, the Commission initiated the process of integration of MSs’ national programmes in a Joint Programming at EU level via the use of the new contractual instrument: Joint Programme co-fund.

Preparatory work for a European Joint Programme was discussed intensively between IGD-TP and SITEX and eventually in effective cooperation within the JOPRAD project in the years 2015 to 2017. One important criterion for collaboration was preserving independence of the TSO. The three R&D communities took part and elaborated a common Strategic Research Agenda (SRA) for joint implementation at European level. The SRA is the basis for joint collaborative activities based on agreed prioritization and decisions of the Joint programme governing board. The SRA structure, being built to address research on scientific technical gaps, and on acquisition of basic science allows joint work between communities. This method is considered as respecting independence between implementers and reviewers, which can use separately the results obtained, to respectively develop their safety case and implement their review process. Non-technical stakeholders were also involved to provide input on their view of the needed R&D to be performed.

Integration of the actors of the disposal communities (WMO, TSO and RE) at European level, which have an official role in their respective national programme has delivered the EURAD European Joint Programme (EJP) to be launched in mid-2019 for five years.

One of the benefits of Joint Programming should be effective close collaboration and avoid undue competition on topics of common interest. The question will be whether R&D leading to industrial and commercial activities could be included in Joint Programming, which is mostly working on open science.

Regarding the national programmes with longer GD implementation timescales and those with small radioactive waste inventories, including those from central and eastern Europe, their participation in Euratom research projects has over the years been limited. Therefore, taking into account this situation, that of advanced knowledge on GD and that their R&D priorities could be, for the time being, on pre-disposal management of radioactive waste Euratom has reopened R&D topics on other categories than HL&LL W and SF. The scope of activities include, the development of methods, processes, technologies and demonstrators for characterization, quality control / checking, treatment and conditioning of unconventional, legacy waste, operational wastes, waste arising from repair or maintenance and decommissioning/dismantling waste or other waste streams for which there is currently no industrial pre-disposal and or disposal mature processes.

These activities are generally carried by waste producers and owners and the projects issued from this Euratom call domain are separate from the EURAD EJP. However, EC strategy is to gradually involve and integrate this community in future Joint Programming at EU level. The justification is that if characterization, treatment and conditioning processes are developed together with the disposal community based on co-developed waste acceptance criteria, there will be efficiency, optimization and benefits on both sides. The current limitation of the types of activities to be included in the EJP, considered by Euratom, is that decommissioning activities up to pre-treatment for stabilisation and packaging of dismantled waste are more of the responsibility of utilities. Also, dismantling are commercial and competitive markets, which does not seem compatible with the open-science approach in the EJP. This could be considered as an obstacle to open cooperation. Recent evidences can be found in project proposals received in the category Innovation actions (IA). A large numbers of technical reports were classified as confidential. Although an objective of the EC in the research programmes is to contribute to economic growth and employment, observation is made that when a project includes activities covering innovative products, processes or services and prototyping, testing, demonstrating, piloting, large-scale product validation and market replication of advanced and new technologies, the results are of direct benefit to a small number of organizations with IPR for commercial use.

The question for the EC is, whether these activities should be included in Joint Programming. In the domain of waste treatment, the current EC idea is to allow inclusion of development of new processes and technologies for waste types or streams common to several MSs or eventually for which there could be co-ownership of the process and possible common exploitation facilities. Otherwise, other research proposals based on existing technologies or new ones which are or would be property of a single company should be subject to competitive call for proposals.

Public acceptance and political decision to select a site to construct a repository or an underground research laboratory (URL) is a sensitive issue. Already early, a number of applications for site investigations and URLs had been refused due to local and public opposition. Euratom opened the domain of SSH to increase public perception and acceptance around 2000. A series of projects were supported to investigate communication, stakeholders' engagement, governance aspects and public involvement, mainly at local level: RISCOM2, TRUSTNET, COWAM series, OBRA, ARGONA, IPPA and InSOTEC. General principles and recommendations on communication and stakeholder involvement were produced by the projects.

The results are available for use in national programmes and in working groups of the OECD NEA, the Stakeholder Forum for Confidence (SFC). Therefore, the need to continue social science on its own as part of Euratom did not appear as justified. Instead the Euratom programme on radioactive waste management proposed, in some way an innovative approach for public participation by suggesting to involve public non-technical stakeholders in scientific / technical R&D projects when a clear task/contribution can be identified for them. A series of projects implement this approach: MODERN 2020, SITEX II, JOPRAD, MIND and Beacon. Lessons learnt from these projects need to be drawn and a number of questions need to be addressed to clarify which role and task could public and non-technical stakeholders play in future Euratom research activities.

The future involvement of public, non-technical stakeholders in R&D projects and Joint Programming at European level thus needs analysis. Civil Society Organizations (CSO) and Non-Governmental Organizations (NGO) have defined their role as interaction with civil society in following the research to give civil society the opportunity to follow, discuss and give feedback on the research conducted in the projects and to create the conditions for civil society local and national representatives to interpret, discuss and give feedback on the research result and other information made available by the projects. CS experts also wish to perform social science (SC) activities within scientific technical projects.

On the role of CSOs and NGOs to follow the projects to discuss and give feedback on the research conducted, trials have been tested in on-going projects. Scientific experts have been used to comment of the work performed by the projects. The content of the deliverable is similar as that requested from the external advisory boards composed of end-users (WMOs and TSOs). Therefore, the EC considers that if CSOs and NGOs wish to make scientific comments on the projects work, this should be carried jointly with the other external experts in the advisory boards.

On the role to create the conditions for civil society local and national representatives to use the project results and other information in future situations where there are consultation processes as a part of safety case reviews and licensing decisions, this could be considered as training and performed as such in the form of deliverables presenting the project results in understandable way for the public.

Social science activities are performed extensively as part of the OECD NEA SFC forum, therefore SC as individual projects in the field of RWM are not justified also because such activities on their own usually address strategic issues as nuclear energy and radioactive waste management policies, which are not part of the Euratom R&T programme scope.

Summary :

- The European Commission via the Euratom R&T programme on radioactive waste management has a role in fostering close cooperation and joint implementation of R&D on radioactive waste management,
- The criteria for supporting research is cutting-edge science on issues of common EU added-value for Member States. However, the wide gaps in the status of the national programmes towards implementation of geological repositories for high-level and long-lived radioactive waste (HL&LL W) and spent fuel implies a central role for Euratom in the management of scientific and technical knowledge on RWM for exchange between organisations across the MSs and to transfer to new generations of scientists to ensure the long-term safety of disposal,
- The European Joint Programme tool for R&D at EU level appears to be the most effective way to jointly prioritise and implement R&D at the European level between the main actors of the disposal community (WMO, TSO and RE) representing their official MS national programme,
- Public non-technical stakeholders may contribute in R&D activities at Euratom level whenever a clear and genuine task can be identified and does not diverge from the programme of their country of origin,
- The needs for R&D on pre-disposal at EU level may be justified as long as the criteria for cooperation are clear and that benefit is acknowledged for several MSs as opposed to activities leading to competitive and commercial markets of benefit to single entities.

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THE IMPLEMENTING GEOLOGICAL DISPOSAL OF RADIOACTIVE WASTE TECHNOLOGY PLATFORM (IGD-TP) – EVOLVING INTO OUR SECOND DECADE

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Abstract. The IGD-TP was established in 2009 to initiate joint RD&D activities that support implementation of geological disposal. Our vision is to have the first European geological disposal facilities operational by 2025.

Realization of this vision has been supported by establishing common, needs driven RD&D activities.

A robust knowledgebase now exists that underpins progression towards geological disposal facility licensing and construction. It is however important that we maintain and enhanced this throughout step-wise implementation.

Recently, the European community has been working to establish a European Joint Programme on Radioactive Waste Management (EURAD).

Whilst IGD-TP is supportive of EURAD, it is important to recognize that Waste Management Organization (WMO) RD&D programmes have a wider scope of activities than the commonly agreed EURAD strategic research agenda. IGD-TP therefore also sees value in expanding our remit to co-ordinate aspects of RD&D programmes where WMO collaboration is beneficial. This paper describes the evolution of the IGD-TP as we move into our second decade.

1. Introduction and background

The Implementing Geological Disposal of Radioactive Waste Technology Platform (IGD-TP) was established in 2009 to initiate joint technical activities to facilitate stepwise implementation of safe geological disposal. There are currently 120+ different member organisations and over 600+ individual members. The group was established by the European Commission (EC), but is now led and funded by an Executive Group (EG) comprising representatives from 11 European Waste Management Organisations (WMOs) and organisations responsible for implementation-related research, development and demonstration (RD&D). The IGD-TP's original vision on launch was to have the first European geological disposal facilities (GDF) for spent fuel (SF), high-level waste (HLW) and other long-lived radioactive waste in operation by 2025 (Vision 2025).

The IGD-TP has worked for the last ten years to support delivery of this vision, by steering the development of responses to EURATOM calls in the radioactive waste management and disposal area and in doing so helped to ensure proposals were aligned with implementation and safety case needs. In this time, we have led scope development and needs driven alignment of 17 successful EURATOM programme projects, totalling around €100M (€59M EC funding). In addition, the IGD-TP has worked to build confidence in the policy of geological disposal, minimised duplication, delivered savings and helped to make better use of existing European competence and research infrastructures.

2. Underpinning scientific and technical knowledgebase

The scientific and technical knowledgebase that has been acquired from more than 40 years of collaborative RD&D is considerable and is now sufficient to underpin progression towards licensing and construction of GDFs. For example, Posiva received a construction licence in 2015 and plan to submit their operating licence in 2021, SKB submitted their construction licence in 2011 and Andra are expected to follow in the near future. Significant progress has therefore been achieved. However, it is important that this technical knowledgebase is maintained, enhanced and shared, throughout the step-wise design, development, operation and closure of facilities.

A significant proportion of the underpinning scientific knowledge was developed with EURATOM funding. Recently the EC called for a ‘step change’ in RD&D cooperation involving all parties (e.g. Waste Producers, Waste Management Organisations (WMO), regulatory Technical Support Organisations (TSO), Research Entities (RE) and Civil Society Organisations (CSO)). To achieve this, the European community has been working together to establish a European Joint Programme on Radioactive Waste Management (called EURAD), founded on agreed common objectives. EURAD aims to deliver an ambitious, cohesive and co-ordinated joint programme.

This paper presents the IGD-TP Executive Group’s view that a sustained, co-ordinated and collaborative RD&D programme in the area of radioactive waste management and disposal is vital to ensure that all European countries, at various stages of advancement, continue to progress towards implementation. The main proportion of these RD&D programmes should ideally comprise national programme activities, with a selection of WMO jointly funded activities or international consortia interactions (on topics where it is sensible to cooperate), and finally a programme of activities of common interest co-funded by EURATOM (i.e. the EURAD Joint Programme). IGD-TP will act to identify RD&D work of common interest. Some of these topics might be taken up within EURAD (if they are aligned to the shared Strategic Research Agenda (SRA) [1] and consistent with the established joint programme ground rules). If, however, the topics of WMO interest are not suitable for progression within EURAD, IGD-TP will increasingly take the lead to co-ordinate and deliver these tasks as WMO funded initiatives that are parallel and complimentary to EURAD RD&D. This operational model is illustrated in Fig. 1.

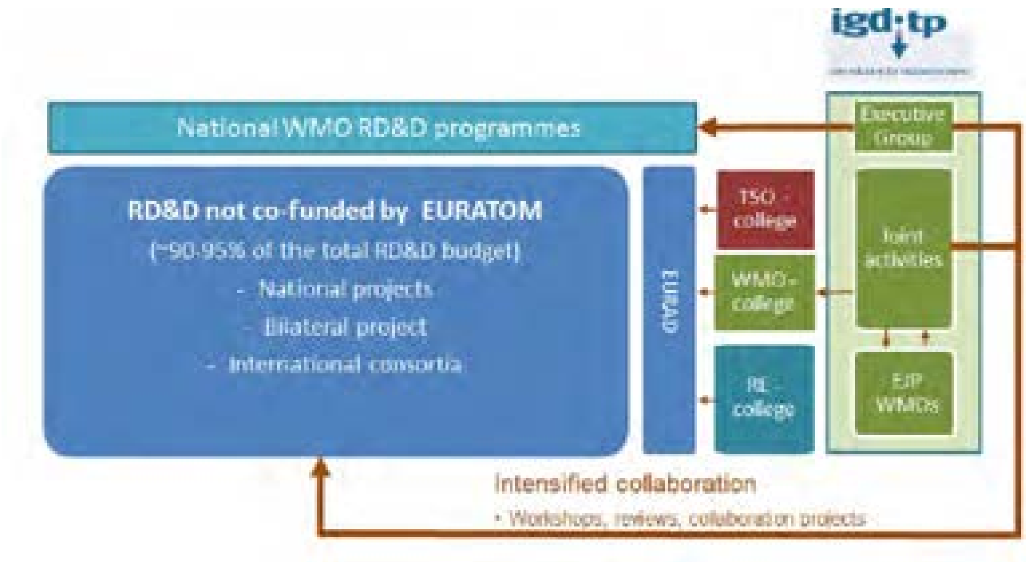

FIG. 1. Illustration of how the IGD-TP inputs to European RD&D programmes (both EURATOM and non-EURATOM funded activities).

The exact mix of RD&D that an individual WMO is involved in will largely depend on the stage of advancement of their national programme. The differing needs for and focus of RD&D at different stages of programme advancement is briefly discussed below. Following this, this paper seeks to explain the IGD-TPs input to EURAD and our intended future activities outside of and in parallel to the EURAD programme.

3. Need for and focus of RD&D at different stages of programme advancement

Geological disposal RD&D serves several purposes. It provides input to system design and optimisation and makes an essential contribution to siting of GDFs. Furthermore, it helps to achieve a sufficient level of system understanding to allow an adequate evaluation of safety. The RD&D priorities depend upon the stage of the programme lifecycle and change as the programme progresses. The current stage of advancement towards HLW/SF disposal facilities for each of the European waste management organisations that comprise the IGD-TP EG is depicted in Fig. 2, along with a broad indication of their RD&D focus, which is closely related to their stage of advancement.

In the early generic/site-selection phases the emphasis is on the development of basic concepts, combined with an evaluation of safety and of technological feasibility. These early phases are followed by a site-specific phase where the focus turns towards system optimisation, with an emphasis on post-closure safety and on site-specific geology and design concepts. The system of engineered barriers is increasingly tailored to the specific geological conditions. In the later stages (i.e. construction phase onwards), when moving towards implementation, practical issues become increasingly important, such as construction procedures, operational safety and optimisation of technology (including 'industrialisation' of repository operations). RD&D does not stop following the commencement of facility construction. It will need to continue throughout the construction and early operational phases. RD&D efforts are therefore necessary throughout the entire lifecycle of radioactive waste management and disposal programmes in order to ensure optimisation of management routes in general and of disposal solutions in particular, as well as to comply with Waste Directive obligations. RD&D must also continue in order to address evolving societal and regulatory concerns.

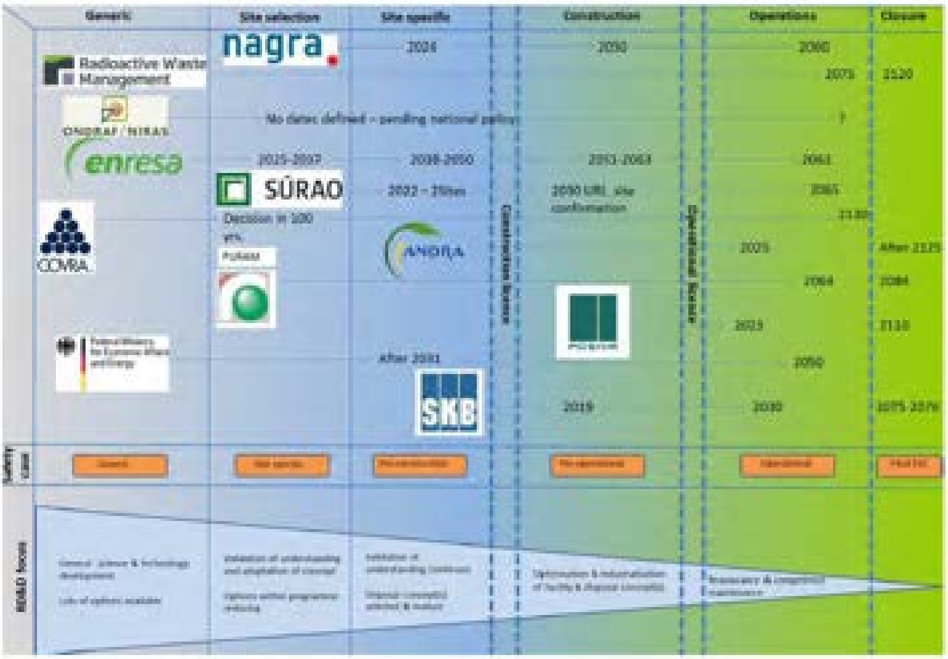

FIG. 2. Overview of European geological disposal facility maturity (for SF/HLW disposal programmes) and associated RD&D focus for IGD-TP member organisations, as of 2017.

4. IGD-TP input to EURAD – inclusive and unified

For almost a decade the IGD-TP EG has been functioning as a successful and enduring WMO RD&D platform. The group has already acted on behalf of all of the European WMOs when it input consolidated WMO comments into the JOPRAD-developed common SRA [2] and latterly the EURAD SRA [1]. The IGD-TP EG also acted to efficiently co-ordinate WMO review comments on the developing EURAD proposal. Based on this positive track record and well-established structure, the IGD-TP EG has offered to support EURAD more formally by co-ordinating the 'WMO College' within the proposed EURAD governance structure. The role of the IGD-TP/WMO College within the governance of EURAD is shown in Fig. 3.

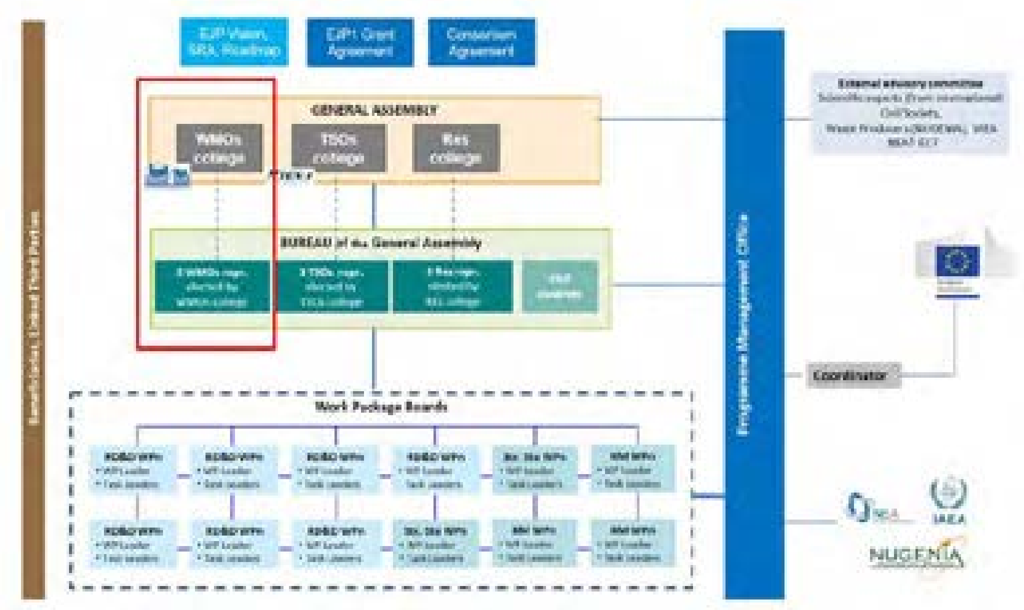

FIG. 3. Overview of proposed EURAD governance structure with the IGD-TP’s input highlighted in red.

The proposed governance arrangement for EURAD includes three colleges, one each to represent the mandated WMOs, research entities and regulatory technical support organisations participating in EURAD. The WMO College should represent all 19 of the current mandated WMOs participating in the programme; it is noted that 10 of these WMOs are members of the IGD-TP EG. The IGD-TP EG has acted to ensure inclusivity by inviting all non-IGD-TP EG WMOs who are mandated within EURAD to either join the EG or, alternatively, to reinforce our mandate as the co-ordinator of the proposed WMO college (by supplying their views via a less formal observer/associate member status).

To facilitate the inclusion of further European WMOs, the EG has proposed that the IGD-TP remains focused on geological disposal, with some interest in upstream activities, but progressively expands its remit to also include scope of greater relevance to nations with small programmes/inventories (e.g. disposal of sealed sources etc.). It is intended that this evolution of the IGD-TP remit will allow the group to more adequately represent all European WMOs and in doing so facilitate the IGD-TP EG to also act as an inclusive WMO College within the EURAD joint programme. This will mean that the IGD-TP EG/WMO College will be able to speak with one strong, unified WMO implementer’s voice.

5. IGD-TP activities outside of EURAD

The IGD-TP is fully supportive of EURAD. However, it is important to recognise that WMO RD&D programmes have a much wider scope of activities than the commonly-agreed EURAD strategic research agenda will address. This is also the case for our RE and TSO colleagues. This distribution of RD&D needs is nicely depicted by Fig. 4, which was developed as part of the JOPRAD project to represent common areas of interest for Joint Programming. It also serves to highlight the significant RD&D areas that joint programming cannot and in some cases should not seek to address. For example, this could be because:

- the scope is such that it would be inappropriate to collaborate with regulatory bodies (TSOs) due to a perceived conflict of interest;
- the topic area and scope of interest did not gain consensus with other EURAD actor groups (i.e. not of sufficient common interest);
- or the work is of WMO interest/significance, but is not deemed to be sufficiently cutting edge for inclusion within EURAD.

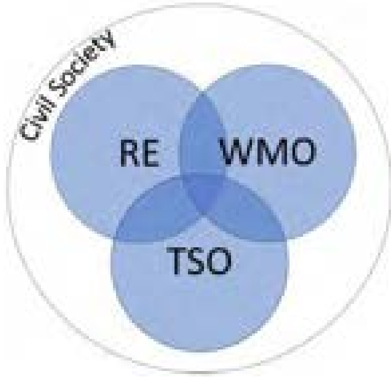

FIG. 4. Representation of common areas of interest for Joint Programming [2].

WMOs publish RD&D programmes at regular intervals, typically 3-5 years. Activities included in national programmes normally require a strict timeline for delivery, are very specific (and therefore would only be relevant to one or a small number of WMOs) and are applied topics that are interlinked with decision making. They almost always have a clear licence-driven purpose (reducing uncertainties, optimisation, robustness, stakeholder requests etc.).

Typical candidates are developing a common WMO view on how to integrate climate modelling in our safety assessments, sharing of the current state-of-the-art on retrievability, canister development aspects, interfaces between operational phase and post-closure phase, etc. These illustrative WMO joint activities could be delivered through, for example, shared RD&D activities, knowledge transfer workshops or the production of IGD-TP position papers.

Therefore, the IGD-TP also sees value in expanding the group's activities to co-ordinate aspects of these RD&D programmes where WMO collaboration is beneficial and sensible. We intend to do this in parallel with ongoing involvement in EURAD, as is highlighted in Fig. 1.

6. Update of the IGD-TP remit, vision and Strategic Research Agenda

In July 2011 the IGD-TP published a SRA [3]. This document identified the main RD&D issues that required a co-ordinated effort over the coming years in order to realise Vision 2025. Key Topics were identified in relation to their priorities, which were established collectively through discussions among numerous European WMOs. The SRA proved to be a good instrument for creating synergies, co-operation and co-ordination, both internally between the IGD-TP participants and with external activities. Because the SRA identified the key topics of RD&D that had the greatest potential to support repository implementation through enhanced cooperation, it provided valuable input to identifying topics for calls in the EURATOM Frameworks. Several of the priorities in the SRA have been addressed in the last 10 years. It further served as a significant element for the development of the shared JOPRAD [2] and subsequent EURAD SRAs [1].

Now that EURAD is a reality and the IGD-TP has decided to expand our remit to facilitate wider membership, it is an opportune time to revisit and revise our common WMO SRA [3]. Furthermore, taking into account the fact that the Vision 2025 is approaching realisation, an updated vision offering a longer term perspective up to 2040 is currently being developed and will be announced on the 10-year anniversary of the IGD-TP in November 2019.

In February 2019, the IGD-TP established a subgroup that was tasked with updating the IGD-TP's SRA and, in effect, producing the first IGD-TP SRA that also takes account of the EURAD SRA responding to the new vision. This task is currently underway, the original IGD-TP SRA structure will be used as a basis and the priorities will be re-assessed, also to take into account the progress that has been achieved in the last 10 years. Then, the areas in the EURAD SRA will be mapped on this update. We will then assign a WMO level of importance, significance and urgency (a prioritisation exercise) to each area. An additional step may well then be to identify any missing research needs and again conduct a prioritisation exercise. By engaging with all European WMOs (i.e. both those represented within the current IGD-TP EG and also all of the others mandated within EURAD) in the end we will be able to ensure inclusion of all WMO research needs, not just those related to deep geological disposal of spent fuel, high level waste and long-lived intermediate level waste.

7. Concluding remarks

The IGD-TP is approaching its second decade and is in a good position to realise its Vision 2025. The IGD-TP SRA proved instrumental in this realisation and fostering international collaboration. The IGD-TP welcomes the EURAD Joint Programme. EURAD will address a range of important WMO needs, but not all of them. The IGD-TP EG will therefore co-ordinate and develop collaborative research activities and deliver them in parallel to EURAD involvement (e.g. via multilateral WMO collaborations). The IGD-TP EG has offered to co-ordinate the views of mandated WMOs within the WMO College, so WMOs can speak with one unified implementer's voice. To achieve this in an inclusive manner the IGD-TP will adapt and evolve as we move into our second decade. We have been openly engaging on this issue for over a year and have now developed an appropriate role within and outside of the EURAD Joint Programme. This process will result in an update of our vision, to be announced at our 10-year anniversary in November 2019 and the publication of the second version of the IGD-TP's SRA soon after.

REFERENCES

[1] Vision, Strategic Research Agenda (SRA), Roadmap, Implementation Plan and Governance Scheme: European Joint Programme on Radioactive Waste Management (EURAD), Issue 1, 2018.

[2] JOPRAD, Programme Document – The Scientific and Technical Basis of a Future Joint Programme on Radioactive Waste Management and Disposal, Work Package 4, Issue 3, 2017.

[3] Implementing Geological Disposal of Radioactive Waste Technology Platform, Strategic Research Agenda, ISBN 978-91-979786-0-6, 2011

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THE SITEX INITIATIVE

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Abstract: The SITEX_Network is an association whose purpose is to foster cooperation at international level in order to achieve and maintain a high quality independent Expertise Function, in support of National Regulatory Authorities (NRAs), as well as Civil Society (CS), in the safety of radioactive waste management, with particular reference to the disposal of high and intermediate level waste in geological disposal facilities. Its particular value lies in bringing together different contributors to the Expertise Function, including Technical Safety Organisations (TSOs), Research Entities (REs), NRAs and CS groups. The SITEX_Network addresses activities related to research, safety case review methodology and practice, as well as training and effective interaction with CS and institutional experts. It has contributed to establishing the European Joint Programme on Radioactive Waste Management EURAD providing inputs that include its Strategic Research Agenda, possible CS Interaction modes and coordinated review mechanisms. The paper presents a background to the SITEX_Network, a summary of its work to date and future visions.

1. Settings

One of the internationally accepted principles of nuclear safety requires an independent regulatory function to be in place to ensure a high level of safety. Such independence refers to both avoiding conflicting of interest in the management and control of the regulatory function and also for an independent technical capability to undertake the regulatory review and assessment functions. This principle is written into the international nuclear safety treaties and into European legislation, in particular for Radioactive Waste Management (RWM) EU Directive 2011/70/Euratom of 19 July 2011 [1]. In this context, and with the support of the European Commission (EC), a number of Technical Safety Organisations

(TSOs) launched the initiative named SITEX ("Sustainable Independent Technical Expertise") with the purpose to enhance and foster cooperation at the international level in order to achieve a high-quality independent Expertise Function in the safety of geological disposal of radioactive waste. The Expertise Function needs to be independent from organizations responsible for the implementation of RWM programmes and aiming to supporting Nuclear Regulatory Authorities (NRAs), as well as broader Civil Society (CS). The EC coordination and support projects SITEX (2012-2013) and SITEX-II (2015-2017) (http://sitexproject.eu/) addressed a number of topics, in particular the orientations for research, safety case review methodology and practice for geological disposal of radioactive waste, the conditions and means of interactions between institutional bodies and CS, as well as training needs related to the reviewing of safety cases by the regulatory function. The SITEX projects were well supported, attracting organisations from within and outside of Europe and made substantial achievements. Building on these achievements, the SITEX_Network (https://www.sitex.network/) was created in 2018 to ensure the perennial development of its activities and to engage all the different interested categories of stakeholders, i.e. TSOs, Research Entities (REs) with an Expertise Function, NRAs and CS groups.

2. Context and rationale for the SITEX initiative

In the context of geological disposal, the role of the Expertise Function is to support the regulatory function in ensuring that the disposal facility is developed, constructed, operated and closed in a safe manner, that will not impose undue burdens on future generations i.e. people and the environment are protected against the hazards of ionising radiations arising from the disposed radioactive waste. This involves several types of activities, such as participating in the establishment of regulatory requirements, developing guidance for meeting these requirements at the different stages of the licensing process, undertaking research and evaluating the safety case developed by the operator throughout. Article 6-2 of the EU Directive 2011/70/Euratom of 19 July 2011 [1], requires the regulatory function has to be independent of the implementing function fulfilled by the operator. Accordingly, the independence of the regulatory function requires an independent Expertise Function that has the necessary know-how and skills in the field of safety of RWM and the resources to provide the necessary support. This involves a range of complex technical and scientific issues related to demonstrating operational and long-term safety of waste disposal facilities, including performing and/or overseeing research activities in support of safety analyses together with knowledge and information exchange on practice, establishing state of the art positions and knowledge transfer. These activities are important for developing the technical expertise of organizations with an Expertise Function and are necessary to build the credibility of their technical competences integrity and judgement vis-a-vis the various stakeholder and broad CS. Moreover, the need for such activities is clearly identified in international recommendations and requirements such as Article 8 of the 2011/70/EURATOM Directive that requires all parties, including the Expertise Function, to carry out education, training and research activities. It is also stressed in international safety standards of the IAEA that the Regulatory Body, and thus its supporting organisations may need to conduct or commission research in support of regulatory decisions (see IAEA GS-G-1.1 [2] (§3.33) and IAEA GS-G-1.2 [3] (§3.68)). The role of the Expertise Function and its linkage to the other main parties involved is illustrated in Figure 1.

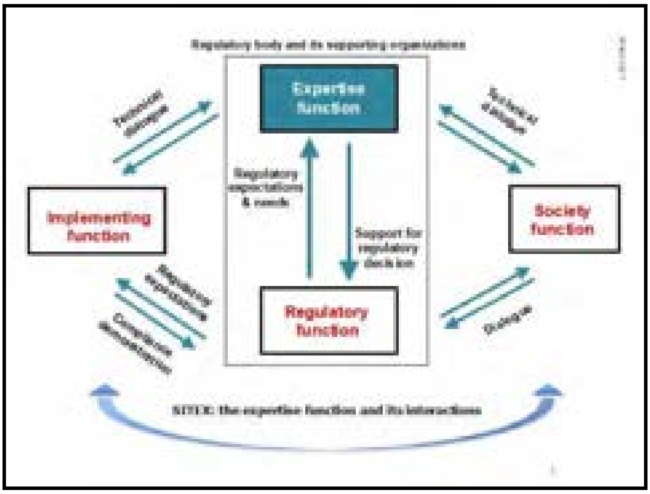

Figure_1: The Expertise Function and its interactions (SITEX D6.1 [4])

The EC has extensively supported collaborative R&D projects involving TSOs, notably through the EURATOM programme on RWM. At present, the EC supports implementation of a Joint Programme (JP) on RWM, including disposal, between the European Member States, considering the priorities of their national programmes. The approach of the EC in this regard is to promote and co-fund larger more ambitious joint programmes, bringing together entities from EU Member-States and associated countries rather than smaller individual projects. The SITEX_Network is well placed to play an important role in such programmes, bringing together the collective knowledge and experience of the largest TSO organisations in Europe together with the broader international dimension of TSOs from countries with advanced and less advanced nuclear programmes around the world. It also brings continuity from the former EC sponsored SITEX projects and the invaluable experience gained in the interactions with CS related organisations.

3. SITEX Network overview

The coordination action SITEX-II was initiated in 2015 within the EC programme Horizon 2020, aiming at practical implementation of the activities defined by the EURATOM FP7 SITEX project (2012–2013), using the interaction modes identified by that project. SITEX-II gathered different types of actors - Technical Safety Organisations (TSOs), National Regulatory Authorities (NRAs), Research Entities (REs) and Civil Society (CS) - involved in four types of tasks prefiguring the activities of the future network:

- **R&D** - defining the Strategic Research Agenda (SRA) based on the common R&D orientations agreed within SITEX, elaborating the ToR for the implementation of specific topics from the SRA, and interacting with IGD-TP and other external entities mandated through the JOPRAD EU project to implement research on radioactive waste disposal regarding the potential setting up of an European Joint Programme on radioactive waste disposal;
- **Safety review** - producing guidance on the technical review of the safety case at its different phases of development, fostering a common understanding on the interpretation and proper implementation of safety requirements for developing, operating and closing a geological disposal and on the verification of compliance

with these requirements; such activity was carried out in connection with other international entities or projects;

- **Training and tutoring** - developing a training module for generalist experts involved in the safety case review process, including the implementation of a pilot training session; this activity accounted for the existing training programs performed at national and international levels;
- **Interaction with CS** - developing interactions between institutional experts and CS, in the framework of R&D and review related tasks mentioned above, and more globally in the definition of governance patterns including CS in the framework of RWM including geological disposal.

In addition, SITEX-II prepared the "administrative" framework for a sustainable network, by addressing the legal, organisational and management aspects for launching such an association. The Final Project Report [5] presented a synthesis of the results achieved within all the working group of SITEX-II together with an Action Plan for establishing the SITEX network, that provided the contents and practical modalities of the future network for independent technical expertise of radioactive waste disposal.

Regarding R&D programming, SITEX-II developed the SRA of the Expertise Function [6], accounting for the concerns of the CS representatives. The R&D topics were ranked with regard to their level of interest and priority, leading to 7 "Main topics" associated to 35 specific issues. This SRA was an input to the European JOPRAD project aimed at assessing the feasibility of a Joint Programming (JP) in the field of RWM including geological disposal, involving Waste Management Organisations (WMOs), TSOs and REs [7]. All the SRA topics were acknowledged to be eligible for such a JP if the conditions identified by SITEX-II and documented in its SRA for preserving the independence of the organizations fulfilling an Expertise Function are met. The JOPRAD Programme Document globally well considers the needs of the Expertise Function identified in the SITEX-II SRA. Further SITEX-II has developed first Terms of Reference for its SRA implementation [8], considering three options for each topic: i) deploy activities through the first wave of European Joint Programming (EJP) in the field of RWM, ii) develop these activities through a future SITEX network or iii) consider the results of on-going European projects before deciding to start new activities.

For the safety case review activities, the SITEX-II partners shared national experience and prospective views on the interpretation and implementation of safety requirements on four topics: optimization of protection, waste acceptance criteria, site characterization and operational issues with regard to post closure safety. Position papers were developed on each of these topics [9]. In addition, SITEX-II partners continued developing the guidance on reviewing a safety case initiated during the former SITEX project, notably through the construction of grids for addressing the successive phases of a geological repository lifecycle [10].

Regarding training and tutoring, an overview of existing training and tutoring practices used by SITEX-II partners located in Europe and Canada was issued, as well as recommendations for competence building of independent technical experts (safety case reviewers) [11]. On this basis and thanks to the extensive practice of the involved SITEX-II partners and their effective collaboration, a training module at a generalist level with emphasis on the technical review of the safety case was developed and implemented in June 2017 in Lithuania, with 18 trainees from different SITEX related countries. The feedback provided by trainees and lecturers was thoroughly analysed and improvements were identified [12]. This experience provided a valuable basis for further developing the training and tutoring services to be provided by the SITEX_Network.

Interactions between institutional experts and representatives of CS organisations within SITEX-II took place on three thematic tasks, namely R&D, safety culture/review and governance [13]. This was undertaken both internally with SITEX-II CS representatives and externally through workshops with other CS organisations, as well as through interviews of various representatives of non-institutional (NGOs) and institutional actors in Europe (NRAs, TSOs, REs). Regarding R&D, a concept of CS knowledge interaction in international research projects on RWM was developed that is meant relevant for joint programming of future regional research work. The main communalities and differences in the vision of safety culture were investigated as well as the expectations regarding the engagement of CS in the safety case review. Regarding intergenerational governance of geological disposal, recommendations were written out on the basis of a literature review and a questionnaire. An innovative multi-stakeholders approach of interactions was also developed, entitled Pathway Evaluation Process (PEP), presented as a serious game and conceptualized as an exercise of participative and comparative assessment of different parallel alternative scenarios on long-term management of radioactive waste.

This work undertaken in SITEX-II, together with the Action Plan dealing with statutes and rules established for a future SITEX network [14], provided all the provisions to make the SITEX initiative sustainable. The relevance of the SITEX initiative being widely recognized by its participants and beyond, this consequently led to the launching of the SITEX_Network at the beginning of January 2018.

Establishment of the SITEX_Network was a logical evolution from the highly successful SITEX and SITEX-II projects. The invaluable role of the EC in establishing and supporting these projects is well recognised, but also is the need to provide for an ongoing self-standing association to take forward the role of interaction between the various expertise functions both within Europe and globally. Around 15 European countries, namely those with nuclear power programmes, have initiated or plan to launch programmes for the development and implementation of national programmes for deep geological disposal of spent nuclear fuel and high-level radioactive waste. The R&D efforts of Waste Management Organizations responsible for the implementation of these programmes are coordinated at the European level by the voluntary initiative on 'Implementing Geological Disposal of Radioactive Waste Technology Platform' (IGD-TP). Disposal facility developers run extensive multilateral national and international projects aimed at providing evidence that their facilities will be built and operated respecting international safety requirements and in compliance with national regulations. This evidence, documented in the safety case, must be independently reviewed and assessed by national regulatory authorities making use of Expertise Function (so-called technical safety/support organisation (TSOs) or research entities (REs)) that have the necessary capacities and capabilities to independently and effectively review the documentation submitted by operators or contribute to such reviews. Whilst review and assessment of the safety case is the core technical function of the regulatory process, regulatory activities are broader including the setting down of safety requirements, formulating regulatory procedures, and may include expressing informal (i.e. not required as a part of the licensing process) views and statements regarding the operator's plans and activities.

The SITEX_Network aims to enhance and foster cooperation at the international level in order to achieve the necessary high-quality Expertise Function needed in RWM including disposal and to facilitate dialogue and communication with the important stakeholders, in particular CS. This objective is being achieved through close cooperation of members organisations with a plurality of views and competencies, involved or willing to be involved in different waste management programmes in different states of their development: NRAs, TSOs, REs supporting the Expertise Function and CS stakeholders. Whilst the CS stakeholders do not have any formal regulatory or Expertise Functions, their views and concerns are nevertheless to be considered while developing a disposal facility, with respect to the Aarhus convention. The Societal Function (carried out by non-institutional experts, CS groups and the public) also exerts vigilance and provides additional inputs (CS expertise and expectations) that give a complementary contribution to safety case review.

Continuing the work from the SITEX projects, the SITEX_Network will continue to focus on research relevant to developing an independent position on key scientific and technical elements of the safety case. It will also give a high profile to the safety case review and assessment process and how this should be applied in the different stages of the development and licensing of geological disposal facilities. Training and exchange of knowledge and experience are being pursued in order to increase national skills and competencies, seeking mutual understanding of key concepts of regulatory review and to foster harmonization or common positions where needed in order to enhance confidence in the national decision making process. The SITEX_Network intends to maintain and further develop common positions of the Expertise Function within the international R&D scene, as initiated by the SITEX projects.

4. Contributions to the EJP EURAD

4.1. SITEX SRA

One of the major challenges of the SITEX-II project was to turn the R&D orientations for which future collaboration and sharing of resources would be potentially useful as defined in the SITEX project (2012-2013) into an SRA, defining and prioritizing R&D topics in line with these preliminary orientations. The SRA [6] was developed by applying a transparent methodology to address the needs associated with the different states of advancement of geological disposal programmes and to take into consideration the concerns of CS.

The scope of the SRA covered all the topics relevant to the Expertise Function to assess whether geological disposal facilities are developed and will be constructed, operated and closed in a safe manner. Therefore, topics related to pre and post-closure safety as well as to the technical feasibility of geological disposal were considered. The scope encompassed all topics relevant to any waste type and spent fuel for which geological disposal is envisaged as a solution for its long-term management. Actions dedicated to pre-treatment, treatment, conditioning, as well as transport and storage of radioactive waste having an impact on the safety of geological disposal facilities were also be considered. Furthermore, activities related to management options other than geological disposal were considered by the SITEX_Network if relevant to several national programmes. However, the first version of the SRA was specifically focused on disposal in underground facilities.

The SRA is not an exhaustive list of all the potential topics that could enter into the scope above. It covers topics for which a sufficient level of common interest has been expressed amongst the SITEX-II members (see below for the applied methodology). It considered a variety of interests at different stages of development of the geological disposal programme: conceptualization for Belgium, Bulgaria, Lithuania as well as for the HLW and SNF disposal facility in Germany; siting for Czech Republic, Switzerland and for spent fuel disposal facility in Canada, reference design for France and for low and intermediate level waste in Canada, construction for KONRAD disposal facility in Germany, operation for ERAM disposal facility in Germany. The concepts (waste forms and containers, engineered barriers systems, host rocks, reversibility) are also slightly different from one country (or type of waste) to another. The SRA was developed in three steps:

- identification of possible topics, following a preliminary list notably based on “R&D orientations for TSOs” of the former SITEX project;
- appraisal of the common level of interest for the possible topics; for each topic of the previous list, partners indicated the types of common activities in which they are interested (1- R&D; 2- sharing, exchanging or consolidating knowledge and expertise; 3- developing states of the art; 4- transferring knowledge) and ranked their level of interest (“H” for High, “M” for Medium or “N” for Not Interested);
- identification of the main topics (i.e., in which a high level of common interest could exist) and specific issues that will be included in the SRA.

The methodology allowed the concerns of the CS about the R&D needs of the Expertise Function to be considered and for review by the Associated Group members of SITEX-II and by all the SITEX-II partners. Based on the methodology presented above, seven main topics associated to three specific issues and activities of common interest for the Expertise Function were identified and included into the SRA. These main topics are:

1. Waste inventory and source term;
2. Transient Thermal-Hydraulic-Mechanical- Bacterial- Chemical (THMBC) conditions in the near-field;
3. Evolution of Engineered Barrier System (EBS) material properties;
4. Radionuclide behaviour in disturbed EBS and Host Rock;
5. Safety-relevant operational aspects;
6. Managing uncertainties and the safety assessment;
7. Lifecycle of a disposal programme and its safety case.

In addition to R&D activities, the needs for knowledge transfer (e.g. training or tutoring), for developing state of the art and for exchanging on practices and developing common positions were also identified in the SRA. Figure 2 illustrates the associated issues and activities of common interest for Main Topic 1.

SRA Main Topic and associated issues	Research activities (experiment and/or modelling works)	Horizontal activities		
		Exchange on practices, develop common positions	Develop states of the art	Transfer of knowledge (e.g. training)
Main Topic 1: Waste inventory and source term				
#1. Uncertainty about databases and methodologies used for defining waste inventories(including historical waste)				

#2.	Evolution of the waste inventory due to possible neutron activation				
#3.	Understanding of the release processes and speciation of the radionuclides for spent fuel, vitrified and cemented waste				
#4.	Waste acceptance criteria				

Figure 2: Associated issues and activities for Main Topic 1 of the Expertise Function SRA.

One particularly innovative development of the SRA related to the introduction in the main topic 7 of several holistic (complex) topics, for which both technical and societal aspects need to be investigated in an integrated manner, using specific interdisciplinary methodologies and involving CS participation (e.g., safety culture, site selection process, license of disposal operation, intergenerational governance of such phase, conditions for closure…). Also, regarding the other main topics, that are mainly technical, it came out essential to embed CS participation through the involvement of trained individuals, therefore offering the public the possibility to follow the development of this technical research, and to perform Knowledge Sharing and Interpretation activities along the development of R&D results.

In the frame of the European H2020 JOPRAD project [7], the TSO working group of JOPRAD had identified key RD&D aspects that the Expertise Function could share with other actors and conditions for sharing, notably based on SRA of the Expertise Function developed within SITEX-II. The WMO and RE working groups of JOPRAD have performed a similar work. This led to set the conditions for developing the JOPRAD Programme Document, a key conclusion of the SITEX-II and of the TSO working group of JOPRAD is that, if the conditions identified by SITEX and documented in its SRA for preserving the independence of the organizations fulfilling an Expertise Function were met, then all the activities and topics of the SITEX-II SRA could be implemented in the framework of a JP. These conditions are mainly:

- When shared experiments are developed in a joint project, all participants have a say on their design;
- There should be a transparency of the codes/data/results obtained: all parties have access to acquired data, codes, information… (i.e. for codes, this means that benchmark could at least be possible);
- Organizations fulfilling an Expertise Function should perform an independent analysis of the results from the one of WMOs. It is of crucial importance that Implementing and Expertise Functions can use separately the results obtained with respect to their own function within their national programme. However, this condition depends on the nature of the results and does not apply when the scope of the analysis is limited to a phenomenological understanding of specific processes;
- The objective of the activities "exchanging on practices" is fostering a mutual understanding on important issues and principles and not necessarily reaching common positions;

- Impartiality has to be ensured in the process of establishing states of the art and training activities.

The following possible EJP1 Work Packages were identified by the Core Group facilitating and coordinating the EJP1 proposal development in December 2017, considering the views of WMOs, TSOs and REs:

- RD&D activities:
    1. Modelling of process couplings and numerical tools applied to Performance Assessment
    2. Assessment of chemical evolution of ILW and HLW disposal cells
    3. Mechanistic understanding of gas migration (mainly in clay-based materials)
    4. Influence of temperature on clay-based material behaviour
    5. Cement-Organics-Radionuclide-Interactions
    6. Fundamental understanding of radionuclide mobility
    7. Spent Fuel characterization and evolution until disposal
- Networking activities:
    1. Waste management routes in Europe from cradle to grave
    2. Understanding of uncertainty, risk and safety by different actors

Based on this information, SITEX-II has developed a deployment plan for its SRA [8].

4.2. Interactions with civil society

The SITEX project approached a few selected CS organisations (CSO) to explore the possible modes of interaction between TSOs and CS in the SITEX-II project. This endeavour was successful and in the SITEX-II project there was a special work package on CS interaction involving three tasks: i) formulating key technical and socio-technical issues that from a CS perspective could be interesting to be included in European R&D on RWM, ii) investigating how safety culture for RWM can be shared through different interested parties and what the concrete conditions and means necessary for efficient public engagement are, as well as iii) issues involving intergenerational governance in RWM [13]. The CS experts involved as research partners in the tasks were from Mutadis and Symlog in France, REC in Slovenia, Energiaklub in Hungary and MKG in Sweden. The small group of research partners interacted all along the project with a larger group of CSO representatives co-ordinated by the Brussels-based organisation Nuclear Transparency Watch (NTW). In all there were 35 environmental non-governmental organisations (NGOs) from 18 countries in Europe making an input into the work done, reflecting a variety of partly very specific situations at national level.

The first task formulated R&D key technical and socio-technical issues that CS expects to be developed in R&D programmes. CS contributed actively to the review of the SITEX SRA by trying to place the CS interests into the research matrix developed by the institutional experts community of the SITEX-II project, by discussing with them the possibility to include citizen and social science in the SRA and by developing a concept of “Knowledge Sharing and Interpretation” for allowing CS interaction in future EU research projects on RWM [13]. This concept is now first tested in the Euratom Horizon EU project Beacon [15]. The task also started thinking about new R&D topics, including the incorporation of citizen and social science that would allow European discussions on potential crosscutting areas, i.e. the discussion of uncertainties. These were to possibly be included in future European Joint Programming R&D in RWM.

The second task investigated how safety culture can be shared through different interested parties and what the concrete conditions and means necessary for efficient public engagement are [13]. Through a questionnaire and a set of 27 personal interviews of various representatives of non-institutional CSOs and institutional actors in Europe (regulators, TSOs, researchers), the task identified commonalities and differences in the vision on safety culture in RWM and investigated the expectations of non-institutional as well as institutional actors regarding the engagement of CS in the safety case review of GD facilities. Based on the performed analyses, conclusions on the conditions and means to involve CS along the safety case review process of GD facilities were drawn.

The third task was dedicated to intergenerational governance and performed desktop review and analyses of the literature of the past and existing research and on-going reflections of international projects related to the intergenerational aspect of RWM (EU projects MoDeRn, Insotec, SITEX…), as well as perception and ideas from CSOs (national, international) [13]. The task also developed a new approach, entitled Pathway Evaluation Process (PEP), conceptualized as an exercise of participative and comparative assessment of different parallel alternative scenarios on long-term management of radioactive waste. The method is presented as a board game that can be used by different stakeholders to support discussion and identification of possible strategies for RWM. In addition, the task moderated discussions to reflect on and challenge the provisions and requirements related to intergenerational aspects of RWM and spent nuclear fuel (SF) management, as set out in different international treaties/conventions and other EU binding legislation.

As a result of the work done in the SITEX-II project it was decided that CS interaction should also be part of the work carried out within the SITEX_Network, therefore a separate college that allows the membership of CS organisations was organised. Herewith SITEX_Network is able to do work on how to promote efficient interaction with CS and its experts: establishing principles and ways for the dialogue and transparent information between the Expertise Function and the CS, strengthening knowledge and skills, adapting culture and practices of the Expertise Function to accommodate the active contributions of CS and its experts, acting in complement to WMOs where public expects an independent view on its scientific and safety concerns and expectations. Therefore, there is also representation from the CS in the management board of SITEX_Network.

5. Other SITEX outcomes

As for all other nuclear facilities and activities, the overall goal of the regulatory review and assessment of the safety case is to confirm, with adequate confidence, that the geological disposal will not cause unacceptable adverse impact on safety, human health and on the environment, both now and in the future. SITEX-II addressed the review and assessment process in two tasks: developing a common understanding on the interpretation and implementation of safety requirements [9] and developing guidance on reviewing the safety case [10].

Regarding the technical capabilities of the regulatory body, their importance is underpinned in Article 8 of Directive 2011/70/Euratom [1], stating that Member States shall ensure that the national framework require all parties to make arrangements for education and training for their staff, as well as research and development activities to cover the needs of the national programme for spent fuel and RWM in order to obtain, maintain and to further develop necessary expertise and skills. This requirement, when applied to the regulatory body, is indeed a prerequisite for ensuring effective independence of the regulatory body, as required by Article 6-2 of the same directive. To this regard, SITEX-II developed a training course on regulatory review and assessment of the safety case for geological disposal [12].

The SITEX-II findings of these activities are summarized below.

5.1. Interpretation and implementation of safety requirements

Fulfilment of the safety requirements by WMOs requires not only a clear formulation of regulatory expectations but also technical guidance explaining how these requirements can be met in practice and how their fulfilment should be substantiated in the safety case. Aspects identified of particular importance were:

- Optimisation of protection,
- Waste Acceptance Criteria,
- Operational issues in regard to post-closure safety,
- Programme for site characterization.

The discussions allowed developing a common understanding by regulators and TSOs on these topics and were summarised in position papers that do not cover the issues exhaustively, but rather highlight topical issues the SITEX-II participants felt worth to be raised. They provide a reference to national regulatory bodies when they are developing their own technical guides and to WMOs when developing the safety case during the various phases. Interactions with IGSC (NEA), GEOSAF II (IAEA) and WENRA were also organised. Further, guidance on reviewing the safety case was developed with specific emphasis on practices implemented to verify that safety requirements are effectively and properly implemented throughout the different phases of the development and implementation of a geological disposal. This guidance describes the role of the regulatory body in the pre-licensing and in the licensing processes, identifies the needs for an efficient management system and for developing competences. It proposes also a tool for the regulatory body to analyse the safety cases through the different phases of the development of a geological disposal. The opportunities to involve CS in the different steps of the review process were also examined.

5.2. Training

Experts with a wide range of technical and scientific competencies are required for the review and assessment process. In SITEX (2012-2013), five types of experts were identified to be necessary for such technical review - generalist experts, environmental experts, numerical modellers, risk experts, experts in long-term safety - and the knowledge and skills required were compiled into “experts’ profiles”. SITEX-II further developed these ideas and a work package was devoted to the development of a training module for generalist experts and its implementation in practice to test the viability of the network to fulfil this mission. The work was organised in three tasks: Identification of the practices, experiences and prospective views on training and tutoring; Development of a training module for generalist experts in geological disposal; Implementation of a pilot training session for “common core module”, respectively described in the SITEX-II deliverables [11, 12] and summarized below.

A questionnaire was developed to collect information from SITEX-II partners on their strategies and practices on competence building of technical experts. A thorough analysis of the answers led to the following key conclusions and recommendations to be considered for developing the training module for the pilot training session:

- The importance and necessity of knowledge management and learning processes such as training, learning from experience and continual improvement is acknowledged. The strategy for knowledge management is more formalized and documented in the organisations having dedicated human resource or knowledge management departments or is incorporated into overall organisation's management systems;
- Different means of knowledge management and expert training are used: while some have dedicated departments, internal procedures or schools for expert training, others rely more on co-working of younger and senior experts, participation in research programmes on the national and international level. Usually, organizations have several parallel ways for knowledge management and training of experts in parallel;
- On-the-job training, participation in research projects and taking external courses were reported as the common ways for competence development. Considering this observation, the form of SITEX training could be recommended to be defined as a package of activities on a cycle of several years (lectures accompanied with practical exercises, visits, partial review of existing safety cases, etc.);
- To ensure effective competence building in the specialized areas for technical review of a safety case, a means to "equalize" the background of the participants needed to be considered.

The pilot training course was successfully implemented both technically and administratively and demonstrated that the necessary expertise is available within the SITEX member organisations to present such training events. Two options were contemplated for future training activities. One option is a training programme involving participants committing to a series of training courses, scientific visits and a review project. The programme suggested would be integrated within the activities of the future SITEX network. The second option is a series of discrete training courses over a defined period involving general courses similar to the pilot course and several specialist courses focussed on the topics previously identified by SITEX. The viability of either option depends on the numbers of participants anticipated to be interested and the funding model determined. Arrangements are being made to implement the first option in 2019.

6. Conclusion

The SITEX_Network has been created based on the valuable and successful experience gained in the two SITEX projects. It has a clear vision to enhance the capacities of the various organisations making up the Expertise Function that forms an indispensable component of the regulatory process in the field of safety of radioactive waste management and especially for licensing geological disposal.

The identification of the TSO views on the EURAD preparation was strongly facilitated by SITEX, thanks to the important cooperation between the TSOs, NRAs, REs and CS stakeholders within the Network. The SITEX_Network intends to maintain and further develop the position of the independent safety expertise on radioactive waste (Expertise Function) within the international RWM scene, including that of R&D in this field, advocating civil society involvement. Specifically concerning the EJP EURAD, SITEX_Network will continue exchanging with other organisations with an Expertise Function, NRAs and CS stakeholders on the implemented joint research and related horizontal activities and contribute to the development of high quality and balanced reviews as well as proposals promoting safety considerations in RWM. Thus, the SITEX_Network acknowledged the outmost importance of EURAD in the international RWM-related R&D scene and intends to engage with this EJP as a key network of experts to the benefit of knowledge and safe waste management solutions.

References

[1] European Commission, „Directive 2011/70/Euratom establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste,“ 19 July 2011.

[2] IAEA, „Safety guide GS-G-1.1 - Organization and staffing of the regulatory body for nuclear facilities,“ IAEA, Vienna, 2002.

[3] IAEA, „Safety guide GS-G-1.2- Review and assessment of nuclear facilities by the regulatory body,“ IAEA, Vienna, 2002.

[4] EC FP7 SITEX project, „D6.1 Conditions for establishing a sustainable expertise network“ 2014.

[5] EC H2020 SITEX-II Project, „Deliverable D5.4 - SITEX-II Final Project Report“, 2018, Available: http://sitexproject.eu/index_2.html#deliverables.

[6] EC H2020 SITEX-II Project, „Deliverable D1.1 - Strategic Research Agenda of the Expertise function in the field of geological disposal of radioactive waste“ 2016, Available: http://sitexproject.eu/index_2.html#deliverables.

[7] EC H2020 JOPRAD Project (Towards a Joint Programming on Radioactive Waste Disposal), [Online]. Available: www.joprad.eu.

[8] EC H2020 SITEX-II Project, „Deliverable D1.2 - Setting the Terms of References for the SRA implementation“ 2017, Available: http://sitexproject.eu/index_2.html#deliverables.

[9] EC H2020 SITEX-II Project, „Deliverable D2.1 - Developing a common understanding on the interpretation and implementation of safety requirements“ 2018, Available: http://sitexproject.eu/index_2.html#deliverables.

[10] EC H2020 SITEX-II Project, „Deliverable D2.2 - Technical guide on the review of safety case“ 2018, Available: http://sitexproject.eu/index_2.html#deliverables.

[11] EC H2020 SITEX-II Project, „Deliverable D3.1 - Synthesis of existing practices for training and tutoring of experts in geological disposal safety“ 2016, Available: http://sitexproject.eu/index_2.html#deliverables.

[12] EC H2020 SITEX-II Project, „Deliverable D3.2 - Lessons learnt from the pilot training session“ 2017, Available: http://sitexproject.eu/index_2.html#deliverables.

[13] EC H2020 SITEX-II Project, „Deliverable D4.1 - Conditions and means for developing interactions with Civil Society“ 2017, Available: http://sitexproject.eu/index_2.html#deliverables.

[14] EC H2020 SITEX-II Project, „Deliverable D5.5 - Action plan for establishing SITEX network“ 2018, Available: http://sitexproject.eu/index_2.html#deliverables.

[15] EC H2020 BEACON Project (Bentonite Mechanical Evolution), [Online]. Available: http://www.beacon-h2020.eu/

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"EURADSCIENCE", A NETWORK OF RESEARCH ORGANISATIONS FOR RADIOACTIVE WASTE MANAGEMENT SCIENCE WITHIN EUROPE

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Abstract. Founded in December 2018, EURADScience is an independent, cross-disciplinary, inclusive network with the aim of ensuring long-term scientific excellence and credibility in radioactive waste management. Among the 25 founding members are representatives of nationally funded research organisations, smaller consultancy firms, and academia. EURADScience's Vision is to maintain a holistic view of relevant scientific disciplines and provide scientific excellence to advance progress of national radioactive waste management programmes and establish credibility of waste management concepts.

EURADScience will work closely with complementary networks such as IGD-TP (the Implementing Geological Disposal Technology Platform, established and led by waste management organisations) and SITEX (a network of technical support organisations to national regulators). EURADScience will also cooperate closely with the new European Joint Programme on Radioactive Waste Management (termed EURAD), and will take a lead on developing new research proposals within its sphere of expertise.

1. Introduction

1.1. Context

Research on radioactive waste management and disposal has been ongoing for more than 40 years. Driven by the need to establish national solutions, international co-operation has been supported through the Euratom R&D co-funding programmes, focusing on the pooling of resources, competences and infrastructure to tackle diverse, cross-disciplinary scientific and technical challenges associated with storage and disposal solutions.

Over the past 10 years, this international cooperation has been further developed through the establishment of networks, bringing together, e.g., European waste management organisations (WMOs) and other bodies concerned with implementation of deep geological disposal within IGD-TP (Implementing Geological Disposal of radioactive waste Technology Platform, https://igdtp.eu/), or the technical support organisations (TSOs) fulfilling an expertise function in the field of safety of radioactive waste management, within the SITEX network (Sustainable network for Independent Technical Expertise on radioactive waste management, https://www.sitex.network/).

The next level in integrating the different actors involved in radioactive waste management science and technology on a European level was developed within the JOPRAD project (Towards a Joint Programming on Radioactive Waste Disposal, http://www.joprad.eu/) and the subsequent development of the EURAD proposal, the first European Joint Programme on radioactive waste management, including disposal.

The first geological disposal facility for high-level waste/spent fuel has obtained its construction licence (in Finland), and it is likely that others will follow in the next decade. Thereby, the role and long-term perspective of the associated science and technology is changing. Next to a long-term vision on how to continue development of the state-of-the-art in view of the many additional disposal projects to follow in the next several decades and their long operational lifetimes, a broader spectrum of pre-disposal activities feeding into the final disposal step needs more attention.

1.2. Background

When preparing for the European Joint Programming proposal EURAD during the JOPRAD project, the Research Entities (REs) input was requested in addition to that of the WMOs and the TSOs. However, unlike the WMOs and TSOs, the Research Entities had no representation structure. Thus, facilitated and coordinated by the CNRS (France), a number of research entities organised themselves and generated a Strategic Research Agenda (SRA) as input to the EURAD project. After several meetings (Brussels, June 2015; Paris, September 2015; Nantes, November 2015; Paris, March 2016), a final draft was produced in May 2016 by a working group comprising 22 partners from countries having both advanced and less advanced radioactive waste management programmes, and with both a traditionally strong nuclear research community or only a relatively small RD&D programme. Subsequently, the CNRS facilitated the translation of the Research Entities' SRA into the research organisations' priorities and concerns integrated into the central "Program Document", an important milestone and deliverable within JOPRAD

(http://www.joprad.eu/fileadmin/Documents/JOPRAD_Deliverables/JOPRAD_WP4_D4.4_Programme_Document_Final_-_Issue_4_30.05.18-.pdf). This document served as the scientific and technical basis for the development of the proposal for a Joint Programme on radioactive waste management, or EURAD.

During this exercise, but also throughout the development of the EURAD project proposal, it became apparent to many research organisations that their self-organisation through a network could provide added value in the implementation phase of EURAD, as well as contributing to the development of excellent and breakthrough science in the context of safe and sustainable radioactive waste management. Therefore, an initiative was launched in

June 2018 to bring together interested research organisations into such a network with a broader objective than only that driven by the need for EURAD implementation. After positive feedback, Research Entities were invited to a joint meeting in Berlin, Germany on 5 December 2018, where such a network was established under the name "EURADScience".

2. Vision and Mission of EURADScience

The key challenge identified is essentially the importance of continuously developing the scientific frontier in view of the extremely long timescales associated with the generation and storage of radioactive wastes, and the development, operating and closing of geological repositories. Correspondingly, and in view of the particular contribution required from the scientific community, EURADScience's Vision is to act as an **independent, cross-disciplinary, inclusive network ensuring scientific excellence and credibility** to radioactive waste management.

This vision is driven by the mission of the EURADScience network and its members, which can be summarised as follows:

- Research organisations are at the centre of developing a long-term vision for the scientific and technical challenges that are inherently linked to safe waste management and disposal, beyond national borders and implementation programmes:
    - Such a link is also addressed by the Council Directive 2011/70/Euratom of 19 July 2011 establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste.
    - Research organisations are in a unique position to provide scientific excellence and credibility to waste management concepts established and implemented within national programmes.
    - Research organisations are also key contributors for providing scientific solutions to meet implementation and safety-driven needs.
    - The organisation within a network facilitates engagement with the wider scientific community outside EURAD, including actors beyond Europe.
- Research organisations have a primary focus on long-term knowledge development and management and are key to maintaining competence and know-how. Research organisations are frequently providing the cradle in which the next generation of experts is trained, and are strongly positioned in providing education and training:
    - In order to attract this new generation of scientists, research organisations need to emphasise and promote important research.
    - Such research can only be sustained when maintaining and developing state-of-the-art infrastructure and expertise, which can be pooled and made available on a European level.
- Nationally funded research organisations identified as Mandated Actors within EURAD form the membership of the Research Entities college:
    - EURADScience can be used as supporting function for this college.
    - As such, EURADScience can be seen as complementary but independent to the existing IGD-TP and SITEX initiatives, with its own emphases and needs.

- By interaction between the Research Entities college and EURADScience, views of the larger research community (including also Third Parties linked to Mandated Actors within EURAD) can be promoted within EURAD.

3. Interest in EURADScience

Following the December 2018 inception meeting in Berlin, minutes together with accompanying material were distributed to research organisations across Europe in order to attract a sufficiently critical number endorsing the EURADScience vision and mission. As of March 2019, 25 research organisations from 15 countries (Fig. 1) have responded positively to this invitation.

These research organisations include nationally funded research centres, smaller specialist companies, and members of academia, and are located in countries having both larger and smaller waste management programmes. As such, the EURADScience founding membership is already considered to be representative of the range of research actors within the European landscape. Inclusiveness being at the heart of the EURADScience vision, the network is still open to accommodate new interested research organisations and will remain so in the future.

FIG. 1. Country map of organisations responding positively to EURADScience's invitation of endorsing the vision and mission (correct as of March 2019).

4. Organisation of EURADScience

The new EURADScience network needs a management structure with resources and experienced research personnel provided by member organisations. The aim is a lean structure with the potential for expansion, if required in the future. At the 2018 Berlin inception meeting, it was decided to establish an Executive Group responsible for preparing the work to be undertaken within the network, and for communicating with both the wider EURADScience membership and the outside world (including other networks). The tasks allocated to the Executive Group are as follows:

- To prepare processes, documents and meetings within and on behalf of the network, allowing and enabling progress.
- To safeguard the vision, mission and values endorsed by the network.
- To ensure communication between all members, with EURAD, and outside EURAD.

Participation in the Executive Group is on a voluntary basis. A limited number of committed organisations are needed in order to perform these tasks. The eight organisations (and their representatives) who answered positively to the call for becoming a member of the Executive Group are reflected in the author list of the current paper. Membership of the Executive Group is limited to 2.5 years, after which the position is opened again to all EURADScience members. EURADScience members are asked to formally approve the Executive Group membership.

The Executive Group members will chose a Chair to act as spokesperson for EURADScience, which will also be a rotating position.

5. Future of EURADScience

EURADScience plays a dual role (i) as actor and science-stakeholder on a European level, and (ii) as the platform in support of the Research Entities college within EURAD. For its functioning, EURADScience will communicate with all mandated Research Entities, as well as all research organisations who express interest in participating in the network.

The EURADScience network will therefore need to:

- develop and promote a joint vision on common interests, the scientific state-of-the-art, and research priorities of its members;
- effectively support the Mandated Actor group, with their Linked Third Parties, to fulfill their obligations within EURAD and, as such, act in a similar fashion as the already-existing IGD-TP and SITEX networks.

5.1. Roles within EURAD

The specific roles within EURAD will be specified by the forthcoming EC grant agreement, but are expected to include:

- Providing input to updating the EURAD work programme in view of the second wave of activities within the EJP EURAD phase 1 (mid-2019 – mid-2024).
- Providing input to updating the EURAD Strategic Research Agenda and Roadmap by consultation with the Mandated Actors and their Linked Third Parties.
- Assisting in the knowledge management activities within EURAD by suggesting, nominating and/or providing experts in the different research fields for which either the state-of-the-art needs to be established, or in which education and training activities are organised.

- Providing the Research Entities college for operation of the EJP EURAD.
- Electing three representatives of the Research Entities to the Bureau of the EURAD General Assembly.

5.2. Roles outside EURAD

EURADScience as a network will play a wider role within the European RD&D landscape on radioactive waste management. Activities will need to be undertaken to promote its visibility, such as investing in a webpage, and other activities to communicate more widely about its role and work (presentations, flyers, and papers such as this one). Furthermore, EURADScience also aims to promote networking activities such as joint meetings, and the organisation of working groups on certain scientific and/or technical themes. Within the Executive Group, discussions will have to be undertaken regarding the structure best suited to operate such activities, thereby ensuring the commitment of EURADScience and its membership to the founding vision and mission. In the longer term, a scientific secretariat might become desired.

The role as a science-stakeholder on a European level will include providing a forum for research organisations to exchange and develop ideas, strategies and joint R&D. Other aims and activities will need to be further developed.

As one of the first possibilities for establishing and promoting EURADScience as a network, it will provide the necessary support in developing a proposal for the 2019-2020 EURATOM work programme on pre-disposal management (NFRP-10).

The emphasis of EURADScience activities will be within the European Union. In addition, within the context of the implementation of EURAD, it will need to develop mechanisms for interaction with EU candidate and associated countries. With respect to collaboration beyond the EU, objectives, strategies and processes will be discussed within the network and implemented as jointly agreed.

6. Conclusion

For the first time, European research organisations in radioactive waste management have organised themselves in a network, called EURADScience, with the vision of acting as an independent, cross-disciplinary, inclusive network providing scientific excellence and credibility to national radioactive waste management programmes. Twenty-five organisations from 15 countries have already declared interest and have endorsed EURADScience's vision and mission as agreed during the inception meeting in December 2018.

EURADScience aims to play a complementary role to the already established IGD-TP and SITEX networks, both within and outside EURAD.

Acknowledgments

The EURADScience Executive Group acts on behalf of the EURADScience membership, and acknowledges all of the efforts, ideas and proposals developed by many organisations and individuals to reach the current state of the network.

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NEEDS OF COUNTRIES WITH LONGER TIMESCALE FOR DEEP GEOLOGICAL REPOSITORY IMPLEMENTATION

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Abstract. Countries operating nuclear power plants have to deal with the tasks connected to spent fuel and high-level radioactive waste management. There is international consensus that, at this time, deep geological disposal represents the safest and most sustainable option as the end point of the management of high-level waste and spent fuel considered as waste. There are countries with longer timescale for deep geological repository (DGR) implementation, meaning that the planned date of commissioning of their respective DGRs is around 2060. For these countries cooperation, knowledge transfer, participation in RD&D programmes (like EURAD) and adaptation of good international practice could help in implementing their own programmes. In the paper the challenges and needs of a country with longer implementation timescale for DGR will be introduced through the example of Hungary.

1. Introduction and background

1.1. Countries with longer implementation timescale

Nuclear Power Plants are operated since 1970's and 1980's in Central and Eastern European (CEE) countries. This means that these countries have to deal with spent fuel management, including the final disposal of high-level radioactive waste (HLW): spent nuclear fuel or vitrified HLW corresponding to the direct disposal or reprocessing option respectively for the back-end of the nuclear fuel cycle. As it is formulated in the Council Directive 2011/70/EURATOM (Directive) [1]: "it is broadly accepted at the technical level that, at this time, deep geological disposal represents the safest and most sustainable option as the end point of the management of high-level waste and spent fuel considered as waste".

Taking into account the above mentioned, most of the CEE countries have to face the challenge of implementing a deep geological repository, the programs for which are in an early stage, so these countries could be named as: 'countries with longer timescale for deep geological repository implementation' (countries with longer implementation timescale). Usually the planned commissioning date for deep geological repositories (DGRs) in these countries is around 2055-2065 (Fig. 1).

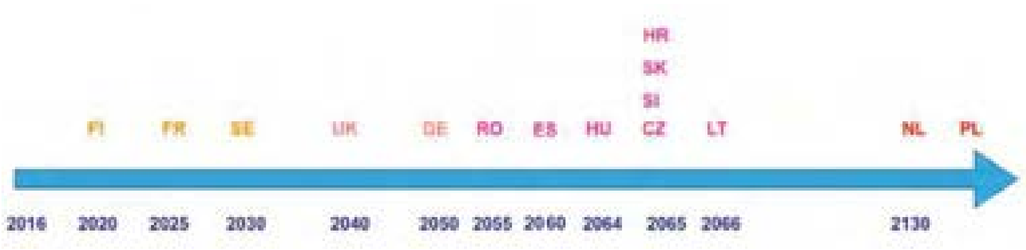

FIG. 1. Planned start of operation of deep geological facilities in the EU [2].

Nevertheless, when a country is in an early stage of implementation, it is essentially important from several aspects (and it is required by the Directive [1]), to develop a long-term programme – and an underpinning RD&D plan – for the implementation of a DGR. A long-term programme, with its technical contents and connected cost calculations is necessary to collect enough funding for the long-term liabilities, meeting the general principle, that requires not to leave undue burden on future generations.

1.2. The need for cooperation and assistance

Because of the small scale of the nuclear industry – including radioactive waste management – in CEE countries, providing the necessary resources (human, technical, financial, etc.) for deep geological repository implementation through decades could be more challenging. Very useful guidance documents exist to assist Member States in the development of their long-term programme and the connected RD&D plan.

The NAPRO working group of the European Nuclear Energy Forum has drafted a guide (NAPRO Guide [3]) with the aim of assisting the Member States in the establishment of their National Programmes, addressing among others guidance on how to develop a comprehensive programme for all waste streams, showing the management routes from the generation until the final disposal in dedicated repositories. From all waste streams, the biggest challenge is to find a management route and implement the programme for the disposal of HLW and spent nuclear fuel.

The Directive [1] prescribes that, “the National Programmes shall include (…) the research, development and demonstration activities that are needed in order to implement solutions for the management of spent fuel and radioactive waste”. The NAPRO Guide [3] contains some general guidance on how to meet this requirement. More specific assistance on RD&D planning can be found in the PLANDIS Guide [4], which was developed by the SecIGD2 Project. The PLANDIS Guide was intentionally focused on the needs of the countries with longer implementation timescale (or countries with less-advanced programmes).

Cooperation at the international level can assist these countries in facing some of these challenges. Some of the CEE countries follow the so-called ‘dual track approach’, meaning that they are considering the possibility of shared solutions for disposal either as a preferred or as an alternative option. From the technical and financial point of view, the shared disposal option is a rational idea to solve the problems, however, beside the technical issues, more complex legal, financial and political questions have to be answered.

Another important circumstance is the fact, that there are countries with mature, advanced DGR implementation programmes. These countries accumulated a vast amount of information and experience during the past few decades. This knowledge base could be adapted by countries with longer implementation timescale for their own situations, within their boundary conditions. In this respect, the EURAD project (European Joint Programme on Radioactive Waste Management) could play an important role in collecting the state of knowledge and developing training modules in different areas.

In the next chapters, the example of Hungary is used to illustrate the specific boundary conditions, current situation of a programme and R&D needs of a country with longer implementation timescale.

2. Programme boundary conditions

2.1. National policy

The Hungarian Parliament, in accordance with the requirements of the Directive, adopted the national policy document on the management of spent nuclear fuel and radioactive waste (national policy). The national policy summarizes the principles applicable to the management of spent nuclear fuel and radioactive waste. Most of these principles were promulgated in the Hungarian legal regulation - mainly in the Act CXVI of 1996 on nuclear energy (Atomic Act) and its implementing decrees - before the adoption of a national policy, but have also been recast according to the requirements of the Directive in a systematic manner. Some of the important principles from the national policy – which are relevant for the DGR implementation programme – are highlighted below:

- During the use of atomic energy, safety has priority over any other aspects.
- The Hungarian state shall assume ultimate responsibility for the management of spent fuel and radioactive waste generated in Hungary (with some special exemptions for spent sealed radiation sources and research reactor spent nuclear fuel).
- The primary responsibility for safety rests with the license holder of the facility or activity.
- During the use of atomic energy, the safe final disposal of the generated radioactive wastes and spent nuclear fuel shall be provided in line with the latest justified scientific results and the international recommendations and experience in such a way that no undue burden is transferred to future generations.

According to the national policy, the final decision concerning the back-end of the fuel cycle of power reactors is not yet necessary to be made, but it is important to state that the country must address the management of high-level radioactive waste regardless of the chosen back-end option. The most suitable and most widely accepted solution to this is final disposal in a deep geological disposal facility. The policy concerning the back-end of the fuel cycle follows the "do and see" principle, meaning that an open fuel cycle i.e. direct, domestic disposal of spent fuel originating from nuclear power plants has been determined as the reference scenario, which provides the basis of the relevant cost estimates concerning the currently operating four units. Domestic and international developments concerning the back-end of the fuel cycle must be followed ("see") and, if necessary, must be incorporated into the policy of the back-end of the fuel cycle, while at the same time progress must be made on the site selection of the domestic deep geological disposal facility ("do"). [5]

2.2. National framework

The Hungarian Atomic Energy Authority (HAEA) was established in Hungary, as an independent regulatory body, responsible for the supervision and licensing of nuclear facilities and radioactive waste repositories, from nuclear safety, radiation protection and physical protection point of view.

In accordance with the Atomic Act, the Hungarian government appoints an organization to carry out the tasks related to:

- the preparation of the national policy and national programme,
- the final disposal of radioactive waste,
- the interim storage of spent fuel and the back-end of the nuclear fuel cycle,
- the decommissioning of nuclear facilities.

In 1998, the legal predecessor of Public Limited Company for Radioactive Waste Management (PURAM) – the waste management organization of Hungary – was established to cover the above mentioned tasks and responsibilities.

On the basis of the Atomic Act, a segregated state financial fund, the Central Nuclear Financial Fund (Fund) was created in 1998. This provides funding for the management of radioactive waste and spent fuel, and for the tasks related to the decommissioning of nuclear facilities. The costs of managing spent fuel and radioactive waste are to be borne by those who produced these materials – through making payments into the Fund.

2.3. Main milestones of DGR implementation

The national programme of Hungary for spent nuclear fuel and radioactive waste management was adopted by the Hungarian government. At the level of the national programme, the coherence and interrelations between the management of the different waste streams were taken into account, and the main milestones of DGR implementation were set.

After consecutive phases of surface-based investigations (Fig. 2), the site is selected and an underground research laboratory is planned to be constructed from 2032 at that site. During the operation of the URL, the in-situ underground investigation, site confirmation activities will take place in the first period, while in the second period, the focus will move to the demonstration programs with the aim of preparing the construction and operation. The start of the construction of the DGR is scheduled for 2055 and the operation for 2064.

FIG. 2. Time schedule of the Hungarian DGR implementation programme.

The first conceptual plan [6] describing the disposal system of the DGR was developed in 2005. This plan contained the first cost calculations of the whole programme. In 2008, the technical and financial update of the long-term investigation programme of the Boda Claystone Formation [7] was compiled. In principle the time schedule of the implementation programme for the DGR and the cost estimate are based on this document. The long-term investigation programme was reviewed by the Swiss NAGRA, who had given useful comments on the document.

At this early stage of site selection, it is necessary also for countries with longer implementation timescale to develop a long-term implementation programme and a connected R&D plan, in order to have an idea about the technical content and the cost implications of the project. This is important, because on the basis of the cost calculations enough money has to be collected in the fund during the operation of the NPPs. In the Hungarian cost profile, the deep geological disposal project is the most expensive element, so the technical content of the programme has to be justified, and the cost estimates have to be defendable.

Due to the very long timescale of the implementation of deep geological disposal programme, maintaining the core competences within a waste management organization and keeping educated, skilled and experienced workforce for decades could be a challenge mainly for countries with longer implementation timescale. Participation in international R&D projects could be a good instrument to attract young people into the radioactive waste management business and this approach could be justified in those cases as well, when the results of a given R&D task will be used much later in the national programme of the interested country.

3. Development of a R&D framework programme

3.1. Introduction

In Hungary, the preparations for the disposal of spent nuclear fuel and HLW started in 1993. In 1994, an exploration tunnel was excavated in the Mecsek Uranium Mine, reaching the Boda Claystone Formation (BCF), and on-site underground data acquisition began at a depth of ~1050 m. The formation was explored underground by a tunnel extending into the claystone ~500 m. The tunnel was utilized as an Underground Research Laboratory (URL), and a large amount of on-site underground data was collected. During this programme, the Hungarian partners received technical assistance from the experts of the Canadian AECL company. In 1998, the mine was flooded, and the opportunity to perform underground investigations was terminated.

From 2000, based on desktop studies, a nationwide screening was carried out by evaluating the potential host rock formations in detail. Thirty-two lithological formations potentially suitable for a deep geological repository, within the territory of Hungary, were identified (Fig. 3). This comprehensive investigation in 2003 confirmed that the BCF has the highest potential among the suitable host rocks for hosting a DGR.

Between 2004 and 2017, there were two new starts for the investigations of the BCF, but both programmes were interrupted. This was a typical challenge of a small nuclear country: due to the lack of enough resources it was difficult to run three big programmes (continuous extension of the interim storage facility for spent fuel, construction of an underground repository for I/ILW and site selection activities for a DGR) in parallel.

In 2018, PURAM drafted a new site investigation framework programme for the BCF, based on the recently extended governmental decree, which now contains the requirements for the site selection phase. Both the modified regulation and the new framework programme seriously take into account the recommendations of the PLANDIS Guide [4].

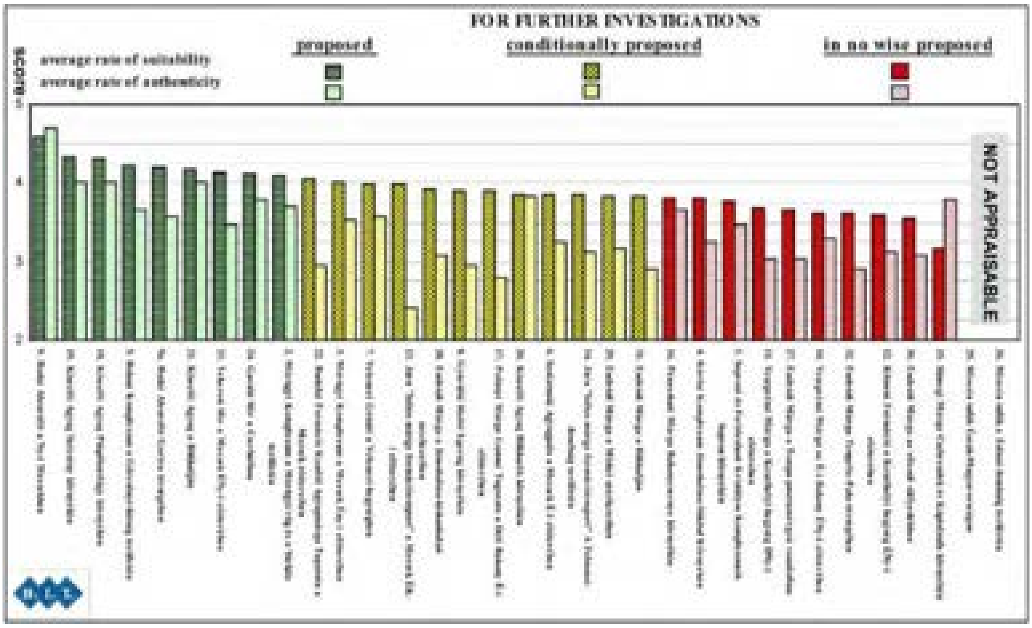

FIG. 3. Ranking of the formations in Hungary during the screening 2000-2003.

In the development of the site investigation framework programme, PURAM could effectively use the methodological advices of the French waste management organization, ANDRA, which were transferred in the frame of a cooperation agreement between the companies. The cooperation agreement focused on project development planning and functional analyses. It should be emphasized, that it was important for the colleagues of PURAM to understand the methodology, the rationale behind that and implement it within the Hungarian boundary conditions. The experts of ANDRA also promoted this kind of adaptation (instead of copying) and mentoring programme, which provided a real added value for PURAM from a country with longer implementation timescale.

3.2. Structure of the site investigation framework programme

The long-term safety of the disposal facility relies on multiple barriers (and multiple safety functions). In case of a deep geological repository, the host formation and the geological barrier play an extremely important role in meeting the post-closure safety targets. Accordingly, the site investigation framework programme has an independent annex for geological investigations. In the main text, meeting the regulatory requirements, the R&D activities are structured in the following areas:

- waste inventory - amount, activity content, physical-chemical form,
- waste package (waste form and package) - geometry, properties, long-term behaviour, compatibility with other elements of the disposal system,
- engineered barrier system (buffer, backfill, seals and plugs) - geometry, properties, long-term behaviour, compatibility with other elements of the disposal system,
- geological and natural environment of the facility – properties and long-term evolution of the geological barrier, external natural hazards relevant for the safety

of the facility (this area is elaborated in detail in the geological investigation programme, which is an independent annex of the framework programme),

- preliminary design and layout of the surface and underground part of the facility
- operation of the facility, transport and transfer of waste packages, ensuring retrievability / reversibility,
- methods for R&D investigations, models, evaluation,
- data management, and long-term information preservation.

3.3. Phases of the site investigation framework programme

The phases (Table 1) of the R&D activities for the surface-based investigation period (with site selection and preparations for the construction of the underground research laboratory) were defined based on the targets of the geological investigation program.

Table 1. Main goals and durations of the surface-based investigation phases

Surface-based investigation		
investigation phase I	**investigation phase II**	**investigation phase II**
2019-2023	2024-2029	2030-2032
general data acquisition in order to rank candidate areas	Site selection and characterization of chosen site	preparations of the URL

For each phase, a detailed site investigation plan has to be prepared by PURAM and has to be submitted for licensing to the regulatory body (HAEA). At the end of each phase, a final investigation report and on the basis of that a preliminary safety case has to be compiled, and the site investigation framework programme has to be reviewed and updated, if necessary, for the next phase(s). In this preliminary stage of the Hungarian Programme, the safety case is dominantly used (i) to help in understanding the main processes and how the elements of the systems could fulfil their safety functions; (ii) to identify the uncertainties and knowledge gaps, and (iii) through sensitivity analyses to prioritize the R&D needs.

3.4. Investigation area

An investigation area (86.7 km^2) was identified for the site investigation framework programme in such a way that this contains all relevant field investigation locations within its boundary (Fig. 4, green line). The surface projection of the potential disposal zone (32.6 km^2) – the area, where the Boda Claystone Formation can be found at the depth between 500 m and 1000 m – is also shown on this map (Fig. 4, brown line).

The investigation area is important from the public participation point of view as well. In the licensing procedure for the site investigation framework programme and site investigation plan, a public hearing is organized by the HAEA. All interested people can participate and those who own a property within the investigation area have a 'client right' in the licensing process.

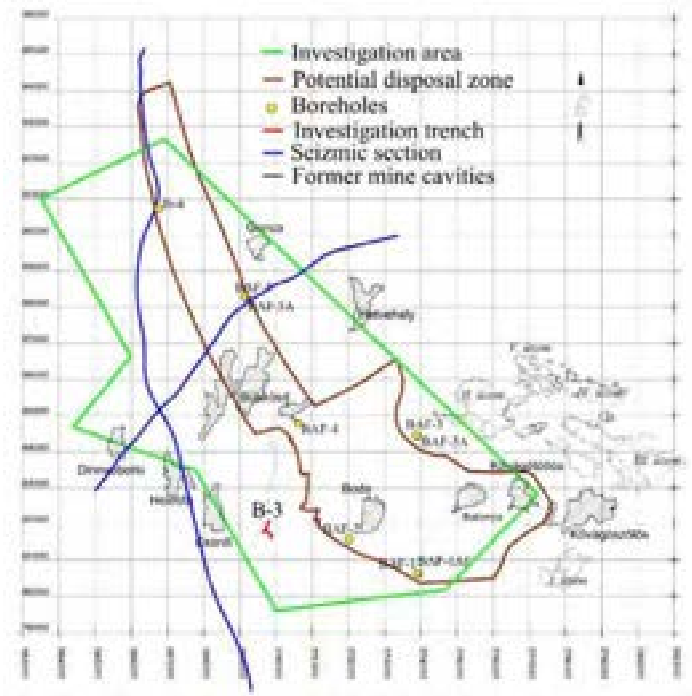

FIG. 4. Investigation area and potential disposal zone.

3.5. Goals of the investigation phases

The general aim of the investigation phase I is data acquisition for site characterization and ranking the candidate areas for phase II. Four special goals were identified for phase I:

- understanding of the geological environment in such detail, that the ranking of the candidate areas can be made;
- evaluation of unfavourable site properties and exclusion criteria and screening out of those;
- detailed investigation of the host formation;
- data acquisition for the preliminary safety case.

Phase II of the investigations will focus on a reduced 10 km^2 area. The general aim of investigation phase II is data acquisition for designating the location of the underground research laboratory. Special goals of investigation phase II are:

- designation and surface-based characterization of the site, confirmation of geological suitability;
- designation of the location of the surface and underground facilities and the underground research laboratory;
- data acquisition for the conceptual design of the facility;
- data acquisition for the preliminary safety case.

The general aim of investigation phase III is data acquisition and the preparation of the underground research laboratory and for the site licence application. Special goals of investigation phase III are:

- characterization of the geological environment of the previously designated location for the surface and underground parts of the facility in such details, that the site licence application could be compiled;
- preparation of the underground research laboratory and planning the investigation program to be conducted in it;
- evaluation of the reference state of the site for the environmental impact assessment;
- data acquisition for the safety case, substantiating the site licence application.

The field investigations of phase III are focused on a few km^2 area of the site.

During the three above mentioned phases, in parallel with the geoscientific investigations, the relevant R&D activities have to be carried out for the different elements of the disposal system: waste inventory, waste form, packaging, engineered barrier system (buffer, backfill, seals and plugs). The preliminary conceptual design of the underground and surface facilities has to be developed.

At the end of investigation phase III., an environmental protection licensing procedure (based on an environmental impact assessment) is considered for the construction and operation of the URL. From nuclear safety point of view, the site licensing procedure will be conducted. In the frame of this licensing step, mainly based on the safety case, the feasibility of the disposal concept is demonstrated. The decision in principle of the Hungarian Parliament – which is a requirement based on the Atomic Act – will be asked after the site licence is granted.

4. Summary

The execution of the implementation programme for a deep geological repository contains some challenges for countries with longer implementation timescale. There are a lot of preconditions for the success of implementation, like:

- high quality scientific and technical work
- sound political commitment and support;
- adequate funding and financing scheme;
- acceptance of the stakeholders (local people, general society);
- enough educated, skilled and experienced workforce with the necessary competencies covering several disciplines.

Nevertheless, for a country in the early stage of its programme, it is important to develop a long-term implementation programme, in which the milestones are set and clear decision points are defined. The technical content of the programme has to be justified, and the cost estimates have to be defendable. International benchmarking and validation can increase the credibility of the programme, which helps to gain acceptance of the stakeholders (public, regulatory body, politics, waste producers). International good practices can be adapted and incorporated within the given country's boundary conditions. At an early stage of the programme, lessons learned by advanced countries, the rationale (pro's and con's) behind strategical decisions (e.g. the URL is a part of the future DGR or not) and methodological recommendations have a real added value.

Participation in international RD&D programmes (e.g.: European Commission cofounded programmes, like EURAD) on the one hand can support the knowledge transfer from advanced countries to the countries with longer implementation timescale, on the other hand, it is a good instrument to attract young people into the radioactive waste management business, which is necessary to providing educated, skilled and experienced workforce for decades.

References

[1] Council Directive 2011/70/EURATOM of 19 July 2011 establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste.

[2] COM(2017) 236 final; Report from the Commission to the Council and the European Parliament on progress of implementation of Council Directive 2011/70/EURATOM and an inventory of radioactive waste and spent fuel present in the Community's territory and the future prospects; Brussels, 15.5.2017.

[3] European Nuclear Energy Forum (ENEF); Work Group Risk; Working Group (NAPRO, National Programmes): Guidelines under the Council Directive 2011/70/ EURATOM of 19 July 2011 on the responsible and safe management of spent fuel and radioactive waste for the establishment and notification of National Programmes.

[4] T. Beattie, R. Kowe, J. Delay, G. Buckau, D. Diaconu: RD&D Planning Towards Geological Disposal of Radioactive Waste DELIVERABLE (D-N°: 2.3) Guidance for less-advanced Programmes; 30th June 2015.

[5] Sixth National Report of Hungary prepared within the framework of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, 2017.

[6] F. Takáts et al.: Preliminary conceptual plan and cost estimate for the deep geological repository accommodating the high level and long-lived wastes and spent nuclear fuel generated in Hungary, TS(R)6/25rev2., 2005 (available in Hungarian only).

[7] L. Kovács et. al.: Technical and financial update of the long-term investigation program of the Boda Claystone Formation; 2008 (available in Hungarian only).

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EUROPEAN JOINT PROGRAMME ON RADIOACTIVE WASTE MANAGEMENT

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Abstract. For more than 40 years, considerable scientific and technical knowledge has been acquired in Europe in the field of radioactive waste management, both for near-surface disposal and geological disposal. RD&D will continue to be necessary to develop, maintain and consolidate knowledge throughout the stepwise development, operation and closure of disposal facilities, which will be spread over many decades and make this knowledge available to all end users. Recently, the EC has promoted a step-change in pan-European research cooperation between EU Member States' national programmes by promoting the setting-up of inclusive research joint programmes in Europe gathering those organisations with scientific and technical responsibilities and a national mandate for research in radioactive waste management. Based on the positive achievement of the JOPRAD project (2015-2017), the EC confirmed in 2017 its willingness to co-fund such a Joint Programme in the field of RWM. The RWM community therefore pursued the efforts to establish the Founding Documents (Vision, Strategic Research Agenda, Roadmap, Deployment) and a Work Plan for a first implementation phase of 5-years (2019-2024). In June 2019 the Joint Programme – EURAD – was accepted by the European Commission.

1. Introduction - Successful RD&D collaboration across Europe

For more than 40 years, considerable scientific and technical (S/T) knowledge has been acquired in Europe in the field of radioactive waste management (RWM), in particular for deep geological disposal. This has supported countries to progress towards licensing of geological disposal facilities (e.g. Finland, Sweden and France) and contributed to the progress of numerous Member States' disposal programmes. RD&D efforts in radioactive waste management, including disposal, will continue to be necessary to:

- develop, maintain and consolidate S/T knowledge throughout the stepwise development, operation and closure of disposal facilities, which will be spread over many decades and make this knowledge available to all end users;
- ensure optimisation of waste management routes and of disposal solutions;

- address evolving regulatory concerns;
- bridge the risk of shortage of the skilled, multidisciplinary human resources needed to develop, assess, license and operate facilities for RWM ; and
- help in gaining and maintaining public confidence.

The European Commission (EC) has supported the acquisition of knowledge at the European level by supporting collaborative RD&D projects through the EURATOM programme on RWM and has also enhanced coordination and networking activities by supporting the establishment of the IGD-TP platform - a network for European Waste Management Organisations and the SITEX Network for the regulatory expertise function undertaken by regulatory authorities, regulators, and their technical support organisations, which are both now independently funded.

Recently, the EC has promoted a step-change in pan-European research cooperation between EU Member States' national programmes by promoting the setting-up of inclusive research joint programmes in Europe, attracting and pooling a critical mass of national resources on specific objectives and challenges. The objective for the EC is therefore to promote and co-fund ambitious programmes rather than individual projects, bringing together those legal entities from EU Member-States and associated countries able to direct national funding and/or manage a national research and innovation programme.

2. A feasibility study towards a Joint Programme on RWM – JOPRAD project

The EURATOM JOPRAD project was launched in June 2015 with the objective to assess if the RWM community could be meaningfully integrated in such a Joint Programme, and if so, to prepare its establishment. By identifying those with key responsibility for directing RD&D in the field of RWM, and engaging them in the process of developing a shared Vision and identifying the S/T basis for shared research agenda, JOPRAD has demonstrated the feasibility and the added-value of creating such a Joint Programme in the field of RWM.

2.1. Identifying the categories of organisations

Across Europe, the organisation for how RD&D is managed and completed, in support of the safe management of radioactive waste, varies widely. At the highest level, most Member States have programme owners such as a ministry, national/regional authority or private organisation in charge of setting-up and managing a national programme. This is often followed by varying levels of 'programme managers', who have a formal mandate and delegated responsibility for technical RD&D activities associated with the national programme.

The JOPRAD project identified three distinct categories of organisations, from across 28 EU Member States, Switzerland and Ukraine, with S/T responsibilities and a national mandate for research in RWM, and that are willing to share a Strategic Research Agenda (SRA) for European collaborative RD&D:

- **Waste Management Organisations (WMOs)** having the ultimate responsibility for the implementation of geological disposal (which includes the management of a supporting RD&D programme), and for some other topics of RWM (e.g. waste characterisation, treatment and packaging, interim storage, etc.). WMOs from across Europe form a core part of the Joint Programme and provide a driving force for what is needed for successful and practical implementation from an industrial perspective. WMOs have established a network and coordination framework for

RD&D needs of the implementers of geological disposal at the European level via the Implementing Geological Disposal Technology Platform (IGD-TP);

- **Technical Support Organisations (TSOs)** carrying out activities aimed at providing the technical and scientific basis for supporting the work and decisions made by a national regulatory body. As safety cases for waste processing, storage and disposal develop, so too do the safety case reviews and independent scrutiny responsibility by regulatory organisations in the framework of the decision-making process. This requires specific skills (such as safety case review methodology) from the regulatory expertise function undertaken by safety authorities, regulators, and their TSOs. Several TSOs, together with other organisations fulfilling a regulatory expertise function and Civil Society Organisations have established the SITEX network to support independent technical expertise in the field of safety of geological disposal of radioactive waste; and
- **Research Entities (REs)** working to different degrees on the challenges of RWM including disposal (and sometime in direct support to implementers or WMOs or TSOs), under the responsibility of Member States. This includes national research centres, some research organisations and some universities that could also be funded by other sources. RE’s provide scientific excellence and leading-edge research on basic components and generic processes in relation to the management of radioactive waste, and therefore represent an important proportion of the contributions to the Joint Programme.

Furthermore, the following organisations were identified as key interest groups of cooperative research in the field of RWM:

- **Civil Society Organisations (CSOs)** having an interest in RWM.This includes local organisations (associations, local committees of information, local partnerships), national or European civil society organisations willing to take part in interactions with the nationally mandated actors in EURAD;
- **Waste Producers** and those with a pre-disposal waste management responsibility are engaged via the Nuclear Generation II & III Association (NUGENIA);
- **International Organisations** such as the International Atomic Energy Association (IAEA) and the Organisation for Economic Co-operation and Development – Nuclear Energy Agency (OECD-NEA).

2.2. Identifying the S/T basis for a Joint Programme

Each of these three categories of actors (WMOs, TSOs, REs) then identified S/T activities suggested as suitable for inclusion within a potential future Joint Programme and within the different activities considered, they indicated their preferences and priorities based on their own perceived needs.

The following step-wise process was then used to further define and prioritise the S/T domains of common interest of the different categories of actors:

1. Compiling Activities for Inclusion: Drafting a first compilation of combined activities suggested as suitable for inclusion within a potential future Joint Programme. A key part of this step was to organise and coalesce suggested activities (identified from WMO-, TSO- and RE-specific SRAs) into a suitable structure, considering the different types of activities suggested and the adoption of a common terminology and appropriate scope definition for a potential future Joint Programme. Once the first compilation was prepared, it was recognised that this did not represent an

exhaustive list of all the potential activities that could enter into the scope of a potential future Joint Programme. It simply indicated activities for which a sufficient level of common interest has been expressed among the JOPRAD contributors.

2. Surveying Representative Joint Programme Participant Views: Eliciting JOPRAD participants' opinions on their preferences and motivations for prioritising activities. This was completed by issuing a comprehensive questionnaire of suggested activities, allowing JOPRAD participants to comment and express views on activities suggested by all the represented groups for the first time;
3. Identifying Priorities and Activities of High Common Interest between WMOs, TSOs and REs: Analysing the questionnaire responses to identify the themes with high common interest, and the adoption of screening criteria used to prioritise what should be included in the Joint Programme. This step included development of a methodology to cross-check that all prioritised activities met with the established boundary conditions for the Joint Programme (See section 2.3) ;
4. 1st Draft SRA: Drafting a first compilation of the Joint Programme S/T scope with a clear description of prioritised RD&D activities agreed and supported by all JOPRAD participants;
5. SRA Consultation and Finalisation: Consultation of the draft S/T scope within the broader European RWM community. Obtaining feedback and end-user input to facilitate updating of the final Programme Document.

2.3. Defining the governing principles for a Joint Programme

The JOPRAD project has defined the following principles that shall be respected for joint programming.

Positive Participation – Contributors will work positively towards achievement of the Vision. All contributions will be valued. Work will be carried out considerately and respectfully by all, maintaining relationships that respect diversity, different roles and boundaries, and respect the knowledge, insight, experience and expertise of others.

Maintenance of Independence – It is possible for different organisations with different roles in their national programme to work together, without prejudice in relation to their own role in the national implementation process. Most important is the independence between the "expertise function" (fulfilled by TSOs and by some Research Entities) and the "implementer function" (fulfilled by WMOs). Different parties (WMOs and TSOs in particular) can have common agreement of what RD&D should be done and how, and Research Entities may furthermore have a long-term vision of general research needs. All can collaborate in doing the basic research; however, maintaining their independence in developing their own views on the interpretation of the generated research results and data is essential.

Transparent Governance – A transparent, balanced and efficient mode of governance is maintained, taking into account the role and independence of the Joint Programme participants with a national mandate for research in RWM.

Scientific Excellence – RD&D activities shall focus on achieving passive safety (safety of a disposal facility is provided for by means of passive features inherent in the characteristics of the site and the facility and the characteristics of the engineered barriers, together with certain institutional controls, particularly for surface facilities) and reducing uncertainties through excellence in science.

Balanced Programme – Recognising that different Member States have a wide variance in the status of their National Programme, the scope should support programmes at all stages of advancement;

Added Value – Ensuring that the Joint Programming provides real added value (e.g. enhanced coordination and improved information and knowledge transfer between national programs, improved financial arrangements, improved stakeholder understanding and acceptance of outputs, more robust RD&D outputs, etc.). Administration costs should represent a small proportion (including ongoing legal, EC admin., etc.) in comparison to the money spent on the technical and scientific scope;

Inclusiveness – Ensuring that the different categories of actors and groups of interest are involved in the definition and implementation of the Joint Programme;

Equitable Financing – Financial costs (financial/in-kind) should be equitable; participants should contribute what they can afford, or what they consider matches their interest in a project;

Complementary Participation – Participation in Joint Programme is complementary to RD&D activities which will continue to be undertaken nationally or jointly outside of the auspices of the Joint Programme where required; and

Tangible Results – The scope is appropriately prioritised and focused on the objective to achieve tangible results within a reasonable timeframe. A key aspect is that participants recognise that the Joint Programme is a distinct change from past work (and other collaborative working) on radioactive waste management. Translating the scientific, technical and societal challenge of RWM (including disposal) into operational reality requires the generation of new knowledge, combined with the consolidation, maintenance and transfer of existing knowledge.

3. Establishing the European Joint Programme on Radioactive Waste Management - EURAD

Based on the good progress and the positive achievements of JOPRAD, the EC confirmed in 2017 its willingness to co-fund such a Joint Programme in RWM with a dedicated topic included in the EURATOM WP2018 (indicative EC available budget for 5 years: 32.5M€). The RWM community composed of 52 organisations mandated by their Programme Owner (19 WMOs, 13 TSOs and 20 REs) and more than 100 associated research organisations from 23 countries pursued the efforts to establish a Joint Programme in order to be able to submit in September 2018 to the EC its Founding Documents (Vision, Strategic Research Agenda, Roadmap, Deployment mechanisms) and a Work Plan for a first implementation phase of 5-years.

3.1. Vision

A step change in European collaboration towards safe RWM, including disposal, through the development of a robust and sustained science, technology and knowledge management programme that supports timely implementation of RWM activities and serves to foster mutual understanding and trust between Joint Programme participants.

By step-change we mean a new era via a more effective and efficient public RD&D funding in Europe, and a deepening of research-cooperation between Member States. The aim is to implement a joint Strategic Programme of research and knowledge management activities at the European level, bringing together and complementing EU Member State programmes in order to ensure cutting-edge knowledge creation and preservation in view of delivering safe, sustainable and publicly acceptable solutions for the management of radioactive waste across Europe now and in the future.

The Joint Programme shall support the implementation of the Waste Directive in EU Member-States, taking into account the various stages of advancement of national programmes. National RWM programmes across Europe (Figure 1) cover a broad spectrum of stages of development and level of advancement, particularly with respect to their plans and national policy towards implementing geological disposal. Programmes differ significantly depending on the national waste inventory, with some member states only responsible for relatively small volumes of medical and research reactor wastes, compared to others that have comparatively large and /or complex waste inventories from large nuclear power (and fuel reprocessing) and defence programmes. Programmes also differ significantly in the way in which they are managed, particularly with respect to the national policy and socio-political landscape with respect to longer-term storage and geological disposal.

FIG. 1. Representation of countries involved in the joint programming

Across Europe, the terms 'Advanced Stage Programme', 'Early Stage Programme' (or programmes with longer time scales) and 'Small Inventory Programme' are typically adopted. Regardless of size and stage of implementation, all Member-States are responsible for the safe management of radioactive waste and are required to report periodically on the status of their national programme.

The EURAD therefore gathers Members-States:

- with no nuclear power programme operating, but with research, training or demonstration reactors, and/or other sources of radioactive waste;
- with a nuclear programme;
- with different amounts of radioactive waste to manage;
- at different stages of advancement in the implementation of their national RWM programme; and
- with plans for geological disposal for Spent Fuel, High-level Waste and long-lived intermediate level waste, with different host rocks and different disposal concepts and at different stages of implementation.

3.2. Strategic Research Agenda and Roadmap

The EURAD Strategic Research Agenda (SRA) provides a description of S/T Themes and Sub-Themes of common interest between the participants. These needs are grouped into a number of scientific themes and based upon the scope established by the JOPRAD project. The SRA is structured by seven Scientific Themes, as illustrated in Fig. 2 and should allow to capture all areas relevant for the implementation of waste management solutions. Although all technical in nature, Theme 1 is an overarching theme, Themes 2-5 are predominantly focussed on fundamental science, engineering, and technology, and Themes 6 and 7 include aspects more of an applied science and integration focus.

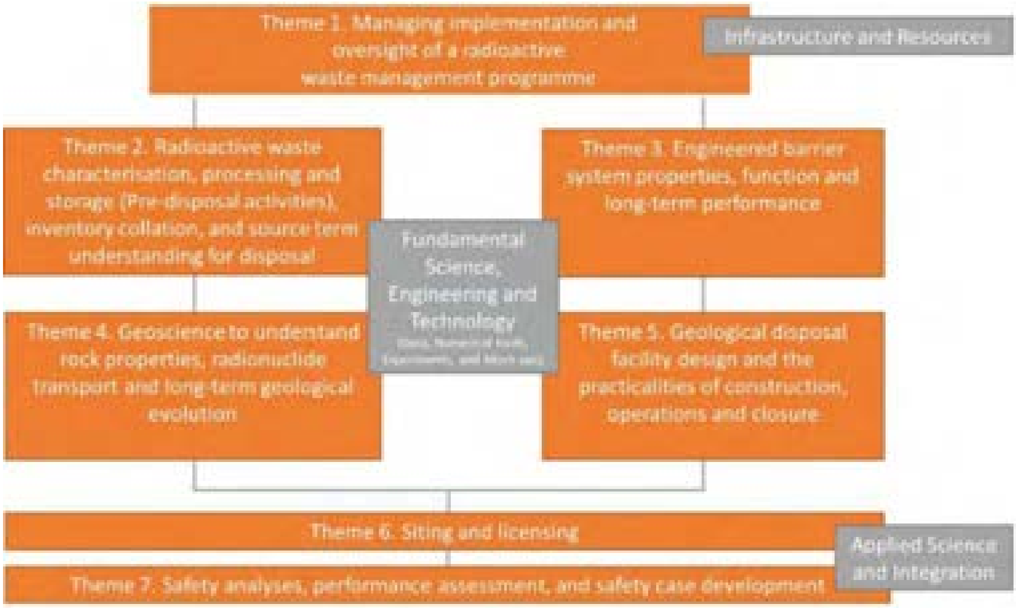

FIG. 2. Scientific Themes of the EURAD SRA.

The S/T scope in the SRA covers cutting-edge S/T activities on RWM from cradle to grave, including predisposal, interim storage and disposal solutions - mainly geological disposal of spent fuel, high level waste and intermediate level waste[2]. The EURAD SRA has been set up as a dynamic and living document that shall be updated periodically in order to integrate outcomes of RD&D activities as well as any emerging collaboration needs identified by the RWM community during the implementation phases of the Joint Programme.

Theme 1: Managing implementation and oversight of a RWM programme

Implementation of a national RWM programme, including geological disposal, requires a national policy reflected in the legal framework, a long-term vision based a sound scientific-technical foundation, appropriate regulatory oversight, funding, organisational infrastructure and sound management systems and processes and formally organized exchange among stakeholders. For programmes in the early phase of establishing national policy or

2

Specific RD&D required for near-surface or surface disposal and low-level waste (LLW), will be addressed, and is encompassed within the RD&D needs identified for waste characterisation and processing, interim storage and geological disposal of radioactive waste. Nuclear facility dismantling and decommissioning activities are however excluded, although interfaces, and particularly aspects that impact final disposal will be considered.

developing a waste management programme, support by international entities (IAEA, NEA) is available and EU-wide good practice and lessons learned can be used to facilitate implementation of suitable organisational structures and strategic decision making.

Theme 2: Radioactive waste characterisation, processing and storage (pre-disposal activities), and source term understanding for disposal.

This involves characterizing and documentation of the various waste types (requiring activation calculations, evaluation of contamination carry-over, development of waste treatment and packing technology, etc.), evolution of waste matrix properties during extended interim storage, developing waste acceptance criteria and developing model predictions about future waste. This also includes development of sufficient interim storage capacity. Source term and radionuclide release mechanisms need to be assessed for different waste forms/waste packages considering the interaction of the various interfaces with the disposal environment. In this broad area of work much information is already available or can be acquired through co-operation. The remaining issues are often site and design specific.

Theme 3: Engineered barrier system properties, functions and long-term performance.

Engineered barriers (overpack, buffer, backfill, seals, etc.) are in a broad sense comparable in many programmes and much basic information is already available today as there have been many European and international projects to-date. Existing needs can be further developed through continued co-operation, which includes the provision of utilising available Underground Research Laboratories (URL) to conduct large-scale demonstration and verification testing. However, at a National Programme level some specific development work is often necessary to improve the understanding of the system of engineered barriers, optimise it or adapt it to the specific situation at hand. Remaining research issues concern in particular cementitious and to a lesser degree clay-based materials.

Theme 4: Geoscience to understand rock properties, radionuclide transport and long-term geological evolution.

Geoscience focusses on host rocks representative for a broad range of geologies also to better understand long-term geological evolution (and stability), and on the detailed understanding of the relevant properties and behaviour of different types of host rocks. This includes the transport properties of radionuclides and fluids, redox phenomena, coupled phenomena to address facility-induced disturbances, and the impact of gases. This also includes the demonstration and verification that the important coupled geomechanical, thermal, hydrological and chemical phenomena are sufficiently well understood to allow for long term assessment of void space closure, fluid movement and behaviour of the material interfaces, in some cases through full scale experiments in an URL. The broad area of geoscience will require significant activities that are specific to each country (especially regional geology but also the details of specific rocks), but with respect to the properties of rocks, much can be learned from other programmes working on similar rocks and may involve co-operative projects in URLs.

Theme 5: Facility design and the practicalities of construction, operation and closure.

Facility design (covering early conceptual design during early programme phases, right through to detailed design for construction, operation and closure). In the area of geomechanics and excavation, much can be learned from the tunnelling and mining industries and the corresponding science and technology developments. The current focus is on the demonstration of waste and engineered barrier emplacement techniques, and to perform demonstration tests under real 1:1 scale and active conditions. URLs and/or rock characterisation facility experiments, incl. monitoring activities often focus on demonstrating that technical aspects of facility construction and operation are suited for their purpose.

Theme 6: Siting and licensing.

The selection of a site (or sites) and licensing of a geological disposal facility is clearly the most important challenge of the successful implementation of long-term management of radioactive wastes. Site characterisation (exploration of geometrical aspects such as rock layers and structures, and characterisation of key rock properties), acquiring site property parameters through the use of geophysical techniques, hydraulic and geochemical measurements in boreholes and seismic investigations will contribute to the selection of the site. As part of the full development of the selected site, underground testing will be required to allow detailed in-situ confirmation (and/or refinement) of some of the critical data on rock properties and state parameters before and during the construction of the repository. Site selection policies and procedures, regulatory arrangements and licensing requirements vary between member states, reflecting inter alia the socio-political context, geological factors, and the waste inventory. In this broad area of work a large part is of national focus but much can be learned from science and technology e.g. developed for hydrocarbon exploration, and also the wealth of information available from RWM programmes and from previously existing URLs should be considered. For URL-experiments, significant technology developments have been made (testing tools, sensors, etc.) that are essential for underground testing at repository sites. This area is very much suited for co-operation.

Theme 7: Performance assessment, safety analyses and safety case development.

For safety analyses (methodology, numerical tools, compiling all the information and data, drawing the conclusions), a wealth of information is already available. The development of the safety case and the task of integrating all the necessary information will always be specific to the system evaluated and thus, in this area, each country must develop its own capabilities. Nevertheless, information exchange and interaction with experienced experts is considered useful and includes e.g. the exchange on the treatment of uncertainties and development of arguments for confidence building.

There is a need to recognise the need for independence between those supporting and managing safety case development and those supporting or managing the regulatory review and scrutiny of a safety case, this applies to all the SRA Themes, but is especially relevant to Theme 7.

The EURAD SRA has been set up as a dynamic and living document that shall be updated periodically in order to integrate outcomes of RD&D activities as well as any emerging collaboration needs identified by the RWM community during the implementation phases of the Joint Programme.

3.3. Roadmap

The SRA is further complemented by a Roadmap with clear objectives, linking the SRA Themes and Sub-themes to milestones typical for the different phases of a RWM programme as drawn from the IAEA work - Site evaluation and site selection; Site characterisation; Facility construction; Facility operation and closure; Post-closure – to which a phase on Policy, framework and programme establishment has been added to recognise the needs of Members-States who are in the process of establishing a waste management programme.

The Roadmap covers the full scope of the Joint Programme and shows the relevance of the different themes for waste management and disposal programmes at different stages of maturity. The Roadmap effectively provides a framework upon which to organise the scientific priorities of the SRA, enabling users and programmes to 'click-in', and to access existing information and knowledge and active work or future plans. For each of the phases, the Joint Programme Roadmap explains how e.g. the aspects related to disposal facility design and safety case development (and supporting safety analyses) span across all phases. The Roadmap elaborates further on the how the emphasis of work on each of the themes differs and changes through successive Phases.

The Roadmap also provides a framework for future periodic assessment of the Joint Programme, and to evaluate future priorities as new knowledge is acquired or as new needs are identified, and to communicate completed, ongoing and future work activities to those interested in our work.

3.4. Deployment Activities

The following types of activities will be established within the Joint Programme:

RD&D activities - The main activities of EURAD will consist of RD&D activities aiming at developing and consolidating S/T knowledge of the EURAD Strategic research Agenda and Roadmap. There shall be a balance between operational RD&D in direct link with implementation of repository concepts as well as safety concerns and prospective RD&D such as short and long-term experiments and/or modelling work to demonstrate the robustness of the waste management concepts, to increase understanding and predictability of the impact of fundamental processes and their couplings or to maintain scientific excellence and competences throughout the stepwise long-term management of radioactive waste.

Strategic Studies - Complementary to RD&D activities and in support of the implementation of the Member States' national programmes, Strategic Studies shall give the opportunity to participants and expert contributors to network on methodological and strategic challenging issues that are common to various national programmes and in close link with scientific, technical and issues.

Knowledge management - Beyond RD&D and Strategic Studies, ambitious activities of EURAD are to consolidate efforts across Member-States on Knowledge Management – this includes access to existing Knowledge (State-of-Knowledge), guiding the planning and implementation of a RD&D plan of national RWM programme, and developing/ delivering training/mobility in line with core competencies.

Interaction with Civil Society - The successful implementation of RWM programmes relies on both S/T aspects for a sound safety strategy and scientific and engineering excellence and societal aspects. EURAD shall allow interactions between WMOs, TSOs and REs, and Civil Society Organisations (CSOs) in order to facilitate the translation of S/T results to allow effective interactions with CS and by extension to the public and create the conditions for CSOs to express their expectations and perspectives. Such interactions shall improve the mutual understanding of how and to what extent RD&D on RWM makes sense and contributes to improving decisions. It shall also contribute to developing ideas, propositions and methodologies on how to interact with Civil Society on S/T results, how to deal with uncertainties, and on how to promote mutual benefit of the available knowledge, based on cooperation and sharing.

EURAD 1 Work Packages (2019-2024)		Indicative Budget	EURAD Strategic Research Objectives	EURAD Beneficiaries		
		Total Cost (EC + Beneficiary Contributions)	How the Work Package will address objectives, priorities and activities of high common interest in the EURAD Strategic Research Agenda	WMOs	TSOs	REs
				◆ = Beneficiary Organisation; ◆ = Coordinating Beneficiary Organisation		
Programme Management Office		**7%**				
WP1	Administration, Scientific Coordination, Communication and Dissemination	€2.7 M		◆◆	◆	◆◆
Collaborative RD&D		**75%**				
WP2	Assessment of Chemical Evolution of ILW and HLW Disposal Cells (ACED)	€5.1 M	Multiscale approach and process integration to improve long-term modelling and assessments .	◆◆◆◆◆	◆◆◆◆◆	◆◆◆◆◆ ◆◆◆
WP3	Cement-Organics-Radionuclide-Interactions (CORI)	€4.7 M	Improved understanding of the role of organics (either naturally occurring or as introduced in the wastes) and their influence on radionuclide migration in cement based environments.	◆◆	◆◆◆	◆◆◆◆◆ ◆◆◆◆◆
WP4	Development and Improvement of Numerical Methods and Tools for Modelling Coupled Processes (DONUT)	€3.7 M	Improved understanding of the upscaling of THMC modelling for coupled hydro-mechanical-chemical processes in time and space.	◆◆◆◆	◆◆◆◆◆	◆◆◆◆◆ ◆◆◆
WP5	Fundamental Understanding of Radionuclide Retention (FUTURE)	€4.6 M	Quantification of long-term entrapment of key radionuclides in solid phases to inform reactive transport models and the influence of redox.	◆◆	◆◆◆◆◆	◆◆◆◆◆ ◆◆◆
WP6	Mechanistic Understanding of Gas Transport in Clay Materials (GAS)	€5.6 M	To increase understanding and predictability of gas migration in different host rocks.	◆◆◆◆◆ ◆◆	◆◆◆	◆◆◆◆◆ ◆◆◆◆
WP7	Influence of Temperature on Clay-based Material Behaviour (HITEC)	€5.3 M	Improved THM description of clay based materials at elevated temperatures.	◆◆◆◆◆ ◆◆◆◆◆	◆◆	◆◆◆◆◆◆
WP8	Spent Fuel Characterisation and Evolution Until Disposal (SFC)	€5.8 M	Reduce uncertainties in spent fuel properties in predisposal phase.	◆◆◆◆◆	◆◆◆◆◆	◆◆◆◆◆ ◆◆◆◆◆
Strategic Studies to Address Complex Issues and Expert Networking		**10%**				
WP9	Waste management routes in Europe from cradle to grave (ROUTES) *	€1.7 M	Waste Management Routes across Europe considering different waste types and their specified endpoints.	◆◆◆◆◆ ◆◆◆◆◆ ◆◆	◆◆◆◆◆ ◆◆◆◆◆ ◆◆◆	◆◆◆◆◆ ◆◆◆◆◆ ◆
WP10	Uncertainty Management multi-Actor Network (UMAN) *	€1.7 M	Further refinement of methods to make sensitivity and uncertainty analyses and the development of a multi-actor network for uncertainty management.	◆◆◆◆◆ ◆◆◆	◆◆◆◆◆ ◆◆◆◆◆ ◆	◆◆◆◆◆ ◆◆◆◆
Knowledge Management		**8%**				
WP11	KM State-of-Knowledge (SoK)	€1.4 M	To maintain information, knowledge and records over the long lead- and implementation-timelines of geological disposal programmes, from pre-licensing through to the post-operational phase.	◆◆	◆◆	◆◆
WP12	Guidance	€0.5 M	To identify RD&D and knowledge transfer needs in support of defining pre-licensing activities that can support success in the siting and licensing phase/process.	◆◆	◆◆◆	
WP13	Training & Mobility	€0.6 M	Training and competence maintenance of skills and expertise to support safe radioactive waste management including disposal.	◆◆	◆◆◆	◆◆

* Interactions with Civil Society

FIG. 3. EURAD first implementation phase (2019-2024).

4. EURAD first implementation phase (2019-2024)

Building on the initial work of the JOPRAD project, taking into account ongoing projects at the EU level, the RWM community has co-developed an initial five-year deployment plan (2019-2024) as illustrated in Fig. 3.

5. Conclusion - how EURAD will complement the National Programmes

The Joint Programme is not intended to replace National Programmes, rather it complements the national efforts and enables effective use of resources by sharing RD&D efforts and by making existing knowledge easily available to end-users. Member-States' Programmes are organised and funded independently, and their participation in the Joint Programme is the responsibility, and at the sole discretion, of each national programme owner. By mandating organisations to participate, Member States demonstrate that EURAD has an EU-added value beyond their National Programme. Overall, the following impacts can be expected:

- **Support compliance with European regulations** – by supporting Member States in implementing RD&D, developing skills and providing for transparency in order to develop solutions for their radioactive waste (see, Waste Directive articles 8, 10 and 12.1(f));
- **Support passive safety of radioactive waste management solutions** – by contributing to the responsible and safe management of radioactive waste in Europe, including the safe start of operation of the first geological disposal facilities for high-level and long-lived radioactive waste / spent nuclear fuel as well as improvement, innovation and development of science and technology for the management and disposal of other radioactive waste categories;
- **Help to gain or maintain public confidence and awareness in RWM** – by fostering transparency, credibility and scientific excellence;
- **Support RWM innovation and optimisation** – by supporting the development of solutions for different waste streams and types and continuously improving and optimising waste management routes and disposal solutions, including identifying needs specific to small inventory programmes with their particular challenges with respect to access to critical mass of expertise and developing appropriate disposal options;
- **Contribute to addressing S/T challenges and evolving regulatory concerns** – by prioritising activities of high common interest, and creating conditions for cross fertilization, interaction and mutual understanding between different Joint Programme contributors and participants;
- **Enhance knowledge transfer to early stage programmes** – by providing an opportunity for less advanced programmes, and in particular those in an early stage of geological disposal programme implementation, to benefit from the cross-European integration in radioactive waste management activities;
- **Foster efficient use of the RD&D resources at the EU level** – by sharing and advancing existing knowledge, facilities and infrastructure rather than repeating and duplicating efforts; and
- **Foster a better transfer of knowledge across generations of experts** – by helping to bridge the risk of shortage of the skilled, multidisciplinary human resources and critical infrastructure needed to develop, assess, license and operate RWM facilities, in view of the long lead-times and the intergenerational operational time-spans.

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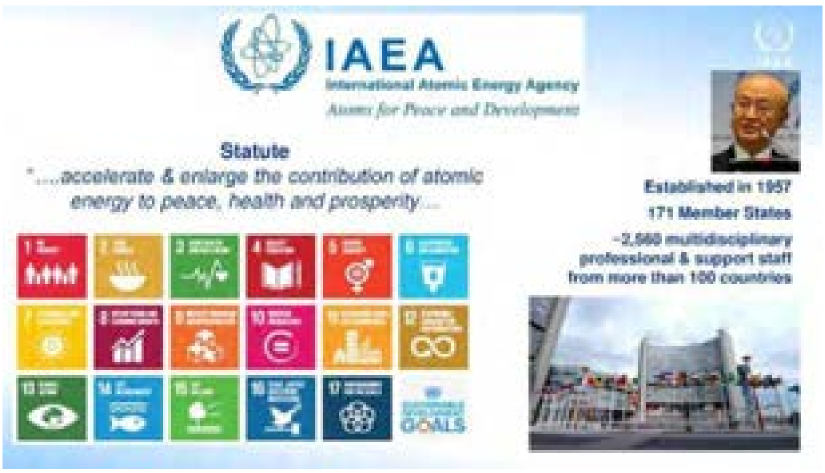
RADIOACTIVE WASTE MANAGEMENT: A NATIONAL RESPONSIBILITY AT A GLOBAL SCALE REQUIRING A LOCAL SOLUTION.AND SOME OTHER THINGS IAEA CAN DO TO HELP

Stefan Mayer

IAEA, Austria

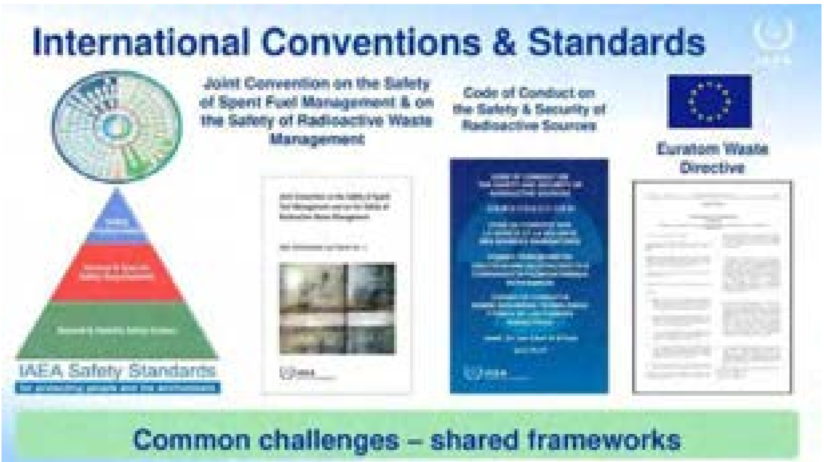



Radioactive Waste World-Wide

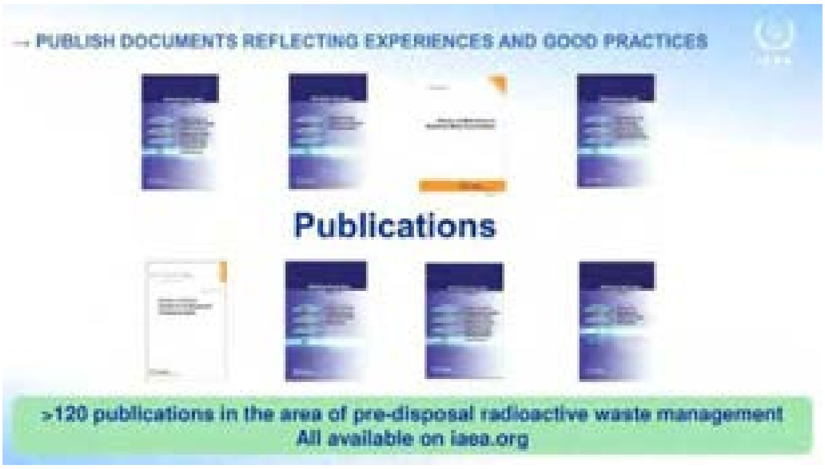

Radioactive Waste World-Wide
All MSs have radioactive waste arising from nuclear fuel cycle operations, nuclear power generation, research reactors, radiopharmaceutical production, and/or other uses of nuclear technologies in hospitals, for research, agriculture, industry etc… as well as from the associated decommissioning and environmental remediation needs.


Radioactive Waste World-Wide
All MSs have radioactive waste arising from nuclear fuel cycle operations, nuclear power generation, research reactors, radiopharmaceutical production, and/or other uses of nuclear technologies in hospitals, for research, agriculture, industry etc… as well as from the associated decommissioning and environmental remediation needs.
All countries are responsible to provide solutions for the safe, secure & safeguarded management of their national inventories. From generation to disposal.


Radioactive Waste & SF Inventory
SRIS – Waste Inventory Database
• SRIS is the agency's new waste inventory information tool Spent Fuel & Radioactive Waste Information System
• Developed in collaboration with EC
• SWIFT – an associated information tool that allows Member States to compile their national reports – EC Waste Directive, JC etc.
• Meeting to "beta-test" functionalities in June 2019 – Release planned 2019
Inventory data are reported once and can be used by MSs for several different purposes
Status and Trends in RWM & SF
• Provides an international overview of SF & RW inventories, global status and trends
• Prepared in collaboration with MSs, EC, OECD NEA & WNA
• The next update will be published in 2020
Provides visibility of shared challenges & proven solutions


International Conventions & Standards
Joint Convention on the Safety of Spent Fuel Management & on the Safety of Radioactive Waste Management
Code of Conduct on the Safety & Security of Radioactive Sources
Euratom Waste Directive
IAEA Safety Standards
Common challenges – shared frameworks


IAEA's Services & Products
→ Organize meetings and conferences
→ Provide the secretariat for international conventions
→ Develop Standards and Guides
→ Publish documents reflecting experiences and good practices
→ Manage Coordinated Research Projects
→ Provide the secretariat for communities of practices (Networks)
→ Manage databases (SRIS, Intl. Catalogue for Sources and Devices...)
→ Host the worlds largest nuclear information library (INIS)
→ Develop training material (Lectures, Workshops, eLearning)
→ Provide expert missions and training courses (Technical Cooperation)
→ Provide peer review services (Artemis...)
→ And through the Safeguards Department, we are also known as the "nuclear watchdog"
...always with Member States, for Member States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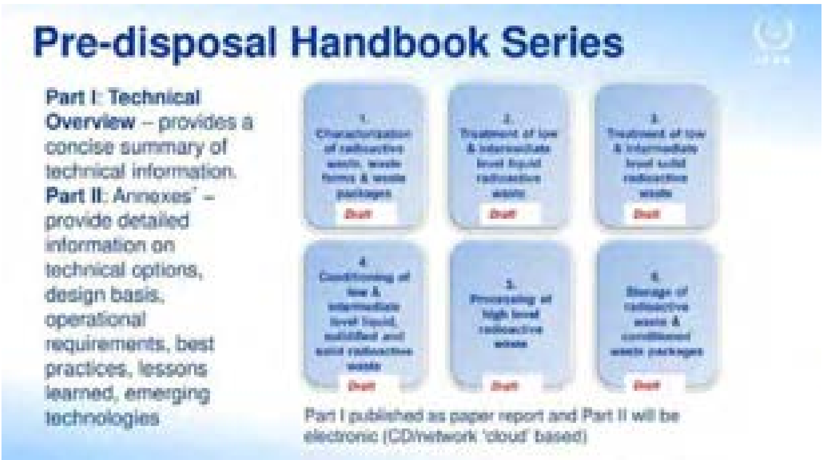
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Part I: Technical Overview – provides a concise summary of technical information.
Part II: Annexes' – provide detailed information on technical options, design basis, operational requirements, best practices, lessons learned, emerging technologies
1. Characterization of radioactive waste, waste forms & waste packages
Draft
2. Treatment of low & intermediate level liquid radioactive waste
Draft
3. Treatment of low & intermediate level solid radioactive waste
Draft
4. Conditioning of low & intermediate level liquid, solidified and solid radioactive waste
Draft
5. Processing of high level radioactive waste
Draft
6. Storage of radioactive waste & conditioned waste packages
Draft
Part I published as paper report and Part II will be electronic (CD/network 'cloud' based)


Implementing disposal programmes
Concepts - Overview
In Publication
Cost estimation method
In Publication
Stakeholder engagement
In Publication
VLLW and LLW - Near Surface
ILW - Geologic disposal at intermediate depths
HLW/SNF – Deep Geologic disposal
Generic DGR Roadmap
Draft
Site investigations
Draft
Post-accident waste
Draft
60 years URF Compendium
Draft

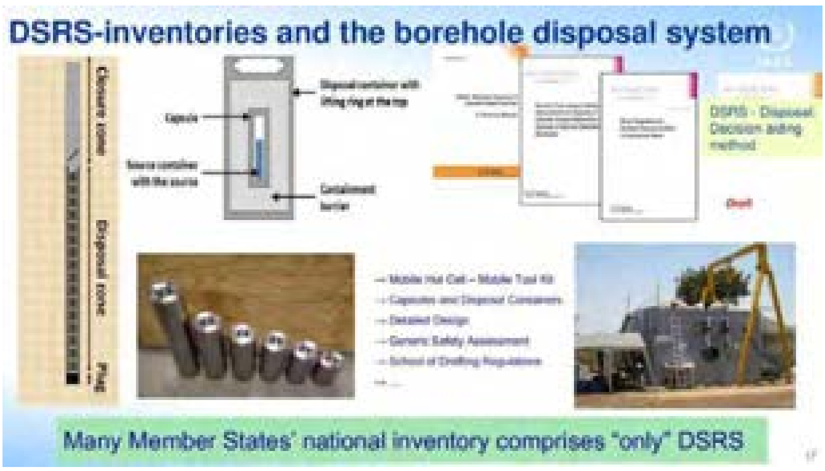

Building Capacities - Spent Fuel and Radioactive Waste Management eLearning
The IAEA has an online learning platform (former CLP4Net) available with eLearning materials, free of charge.
The materials on Spent Fuel and Radioactive Waste Management, Decommissioning and Environmental Remediation are organized by thematic areas and distributed into courses for better understanding and use. Altogether, there are currently 45 modules with a total of 93 lectures. Some are available in other languages as well. More are underway.
Access is possible also through the IAEA CONNECT platform, via the professional Networks.
Link to "walk-through" video here

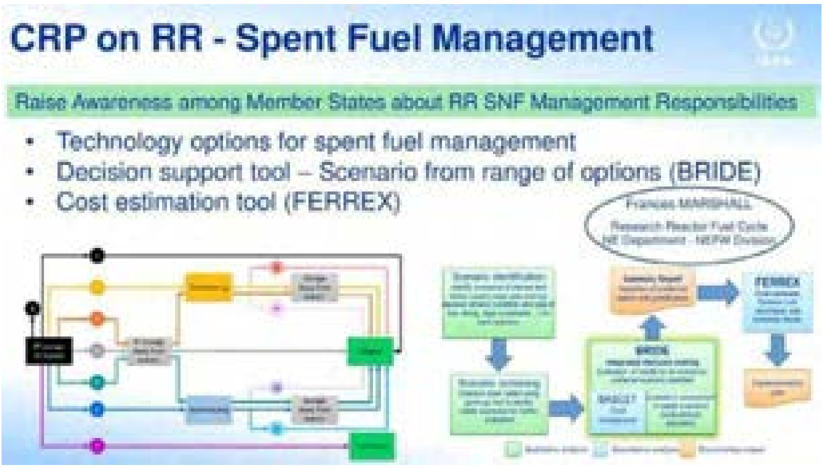

Building capacities - Technical Cooperation
Technical cooperation programme
The technical cooperation programme is the IAEA's primary mechanism for transferring nuclear technology to Member States, helping them to address key development priorities in areas such as health and nutrition, food and agriculture, water and the environment, industrial applications, and nuclear knowledge development and management.


Technical Cooperation in RWM/SFM
National Projects
(Pakistan, Croatia, Romania, Brazil, Egypt, Libya, Moldova, Georgia, Serbia, Ukraine ....)
Policy and strategy
Planning & siting for disposal
Waste management optimization
Characterization
Legacy waste management
Modular processing
Procurement of key equipment
Regional Projects
Latin America, Africa, Asia-Pacific, Europe
e.g. TC-RER 2020-23 addressing:
Life-cycle waste management
Strategy & planning
Integrated national RWM plans
Inventory to disposal
Inter-regional Projects
e.g.: Cradle-to-grave management of disused sealed sources
Nuclear power plants
Research reactors
Use of radioactive sources


Example: Capacity Building Workshops & Training Courses
Courses organized to transfer radioactive waste management knowledge and best practice usually on topics of common interest to MS
Workshop on Problematic Waste from Decommissioning
Expert lectures
Group exercises
Technical visit to FGUP RADON to observe different treatment technologies being applied in practice
Advanced Training on Management of Large Components with Complex Geometries
Provide decommissioning professionals with necessary theoretical and practical basis for the management of large components


Co-ordinated Research Projects (CRPs)
CRPs are tools to encourage information exchange/cooperation on on-going R&D activities in MS on selected topics of common interest
Usually participants from 10-15 countries
Periodic Research Coordination Meetings organized to facilitate exchange of progress, discussions
Results of CRP published as Agency Reports
In Publication
New Proposal
New Proposal
NEW
NEW

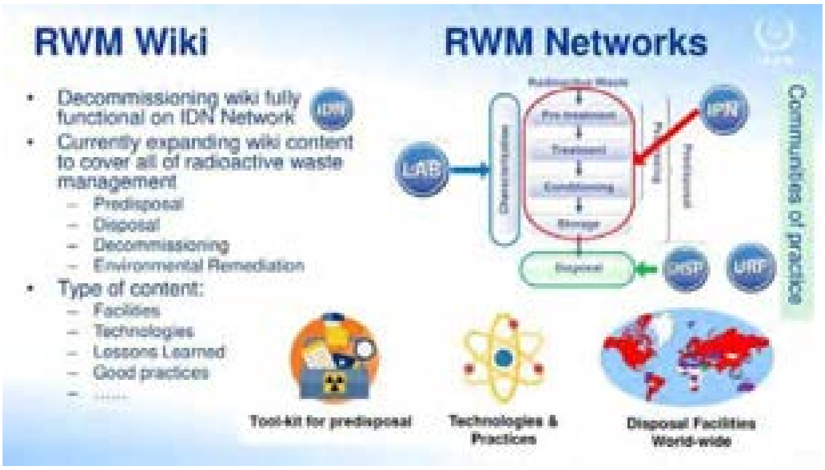

DSRS-inventories and the borehole disposal system
Closure zone
Disposal zone
Plug
Capsule
Source container with the source
Containment barrier
DSRS - Disposal Decision aiding method
Many Member States' national inventory comprises "only" DSRS


CRP on RR - Spent Fuel Management
Raise Awareness among Member States about RR SNF Management Responsibilities
• Technology options for spent fuel management
• Decision support tool – Scenario from range of options (BRIDE)
• Cost estimation tool (FERREX)
Frances MARSHALL
Research Reactor Fuel Cycle
NE Department - NEFW Division
FERREX
BRIDE


Small inventories of ILW or HLW
Exploring a portfolio of disposal concepts that show potential of providing a safe and effective disposal solution for small waste inventories.
DRAFT
Draft


Access to waste processing facilities - Mobile Processing Systems
Key benefits:
Lower capital cost
Alternative to centralized facilities
Easy replacement
Shared use
Useful for small volume streams
Potential to cross borders
Disposability
Ability to schedule processing campaigns
Common uses:
Smaller volume, problematic waste streams
Accident/urgent response situations
Decommissioning & remediation


Access to waste processing facilities
- Modular Designs for Small Volumes
Ideal for small waste quantities
Flexible size & configuration
11 pre-designed modules that can be assembled & factory-tested off-site before being transported to waste processing/storage site
Processing modules available for:
High & low volumes of liquid waste
All types of solid waste:
- compactable & non-compactable
Sludges, ion-exchange resins, DSRS
Can be combined to form an integrated process scheme
Storage modules are available for all types of LLW packages/DSRS and sizes of inventory


RWM Wiki
RWM Networks
Decommissioning wiki fully functional on IDN Network
IDN
Currently expanding wiki content to cover all of radioactive waste management
Predisposal
Disposal
Decommissioning
Environmental Remediation
Type of content:
Facilities
Technologies
Lessons Learned
Good practices
......
LAB
IPN
DISP
URF
Disposal
Communities of practice
Tool-kit for predisposal
Technologies & Practices
Disposal Facilities World-wide


Guidance, Tools & future developments
Waste
DSRSs
RR SF
Generation
Processing
Storage
Transport
Disposal
Synergies across organizations?
Synergies across organizations?
Pre-disposal technology handbook series
Optioneering for RR-SF management
Steps and components of a disposal program
Integrated Waste Management Plans
Strategies and tools for DSRS Management
Cradle-to-grave strategies for small inventories
Waste Inventory
Waste Acceptance Criteria
Continuous Improvements – Gap Analysis – RD&D Needs

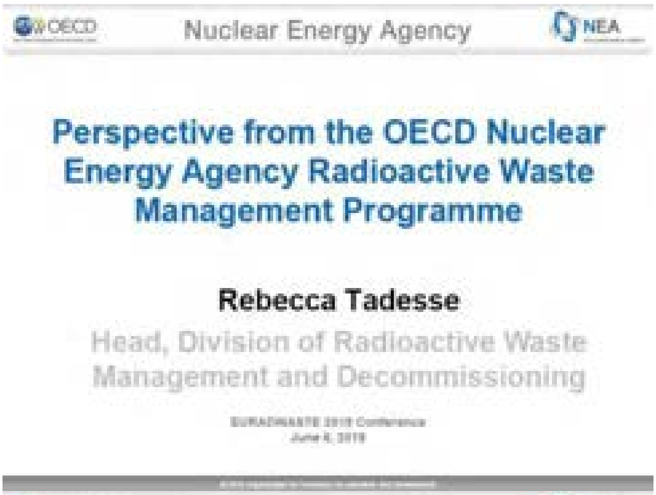

The future of RWM World-wide
Life-cycle radioactive waste management planning begins before any waste is generated
Waste hierarchy principles are adopted (avoid, minimize, recycle, reuse, dispose) to minimize waste going to disposal
End-of-life plans are in place for all new sealed sources (i.e. recycle, return, disposal)
All waste is characterized at the point of generation
A waste inventory is created and tracked at all life-cycle stages
Fit-for-purpose processing, storage and disposal solutions are selected and implemented in a timely manner
Adequate provision is made for radioactive waste management resources at all stages – financial, technical and human
Future RWM responsibilities can be planned and provided for.


Management of Waste from Advanced Reactors & Fuel Cycles
SMRs
EVOLUTIONARY
INNOVATIVE
LFR, GFR, SFR, SCWR, VHTR, MSR, ADS
New initiative to develop IAEA guidance regarding radioactive waste management considerations during the design phase of new reactors, fuel types and advanced fuel cycles


IAEA
Scientific Basis for Nuclear Waste Management
Thank you!

REBECCA TADESSE
OECD/NEA, France

PERSPECTIVE FROM THE OECD NUCLEAR ENERGY AGENCY RADIOACTIVE WASTE MANAGEMENT PROGRAMME

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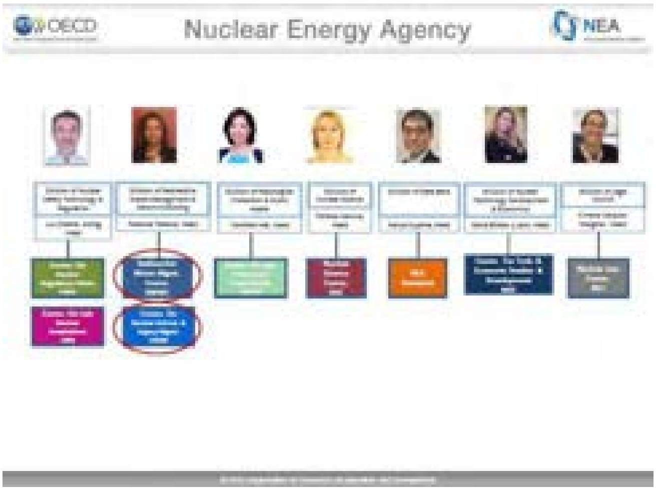
NEA Organizational Chart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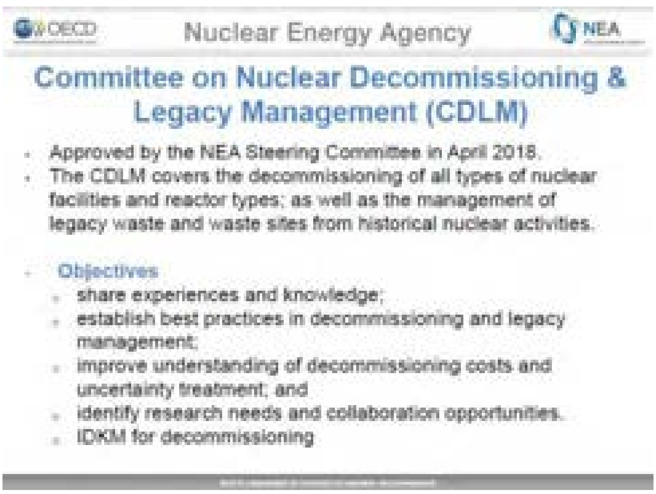
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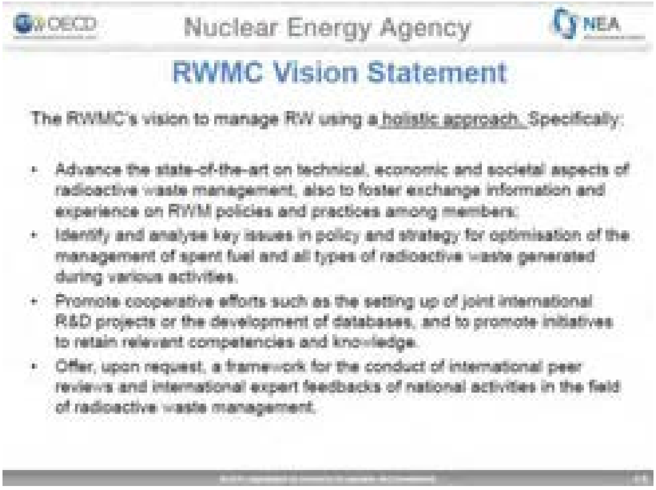
Committee on Nuclear Decommissioning & Legacy Management (CDLM)
Approved by the NEA Steering Committee in April 2018.
The CDLM covers the decommissioning of all types of nuclear facilities and reactor types; as well as the management of legacy waste and waste sites from historical nuclear activities.
Objectives
share experiences and knowledge;
establish best practices in decommissioning and legacy management;
improve understanding of decommissioning costs and uncertainty treatment; and
identify research needs and collaboration opportunities.
IDKM for decommissioning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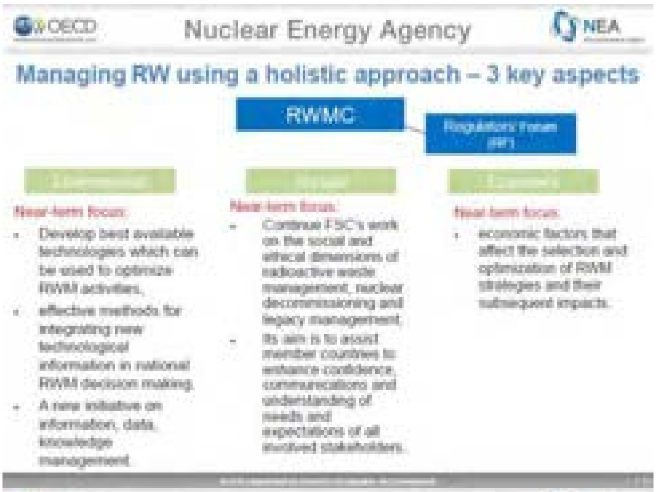
RWMC Vision Statement
The RWMC's vision to manage RW using a holistic approach. Specifically:
• Advance the state-of-the-art on technical, economic and societal aspects of radioactive waste management, also to foster exchange information and experience on RWM policies and practices among members;
• Identify and analyse key issues in policy and strategy for optimisation of the management of spent fuel and all types of radioactive waste generated during various activities.
• Promote cooperative efforts such as the setting up of joint international R&D projects or the development of databases, and to promote initiatives to retain relevant competencies and knowledge.
• Offer, upon request, a framework for the conduct of international peer reviews and international expert feedbacks of national activities in the field of radioactive waste management.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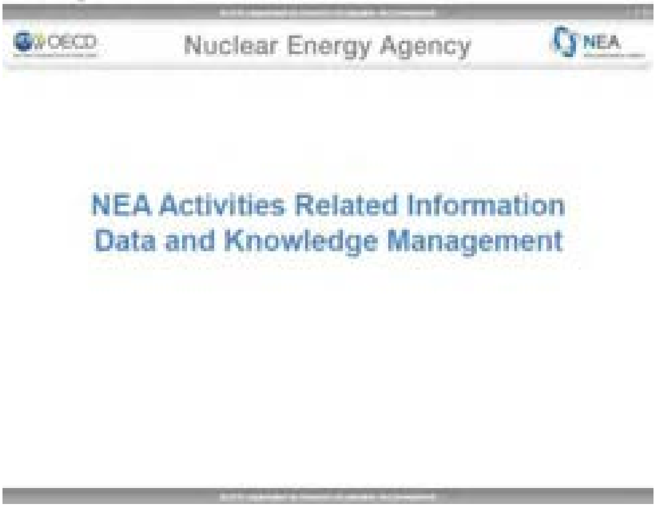
Managing RW using a holistic approach – 3 key aspects
RWMC
Regulators' Forum (RF)
Near-term focus:
• Develop best available technologies which can be used to optimize RWM activities,
• effective methods for integrating new technological information in national RWM decision making.
• A new initiative on information, data, knowledge management.
Near-term focus:
• Continue FSC's work on the social and ethical dimensions of radioactive waste management, nuclear decommissioning and legacy management.
• Its aim is to assist member countries to enhance confidence, communications and understanding of needs and expectations of all involved stakeholders.
Near-term focus:
• economic factors that affect the selection and optimization of RWM strategies and their subsequent impacts.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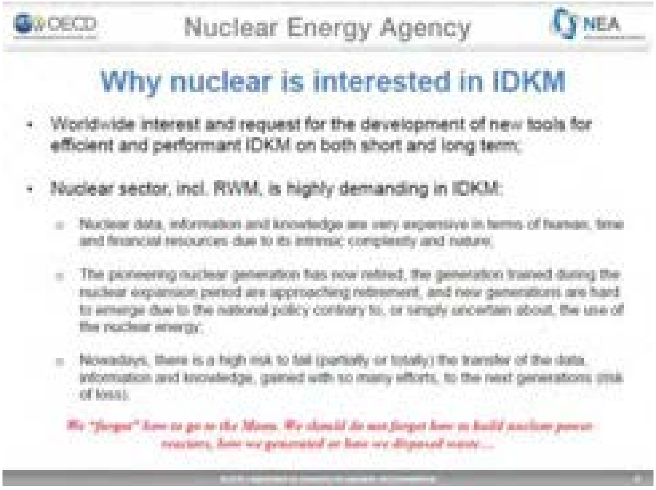
NEA Activities Related Information
Data and Knowledge Management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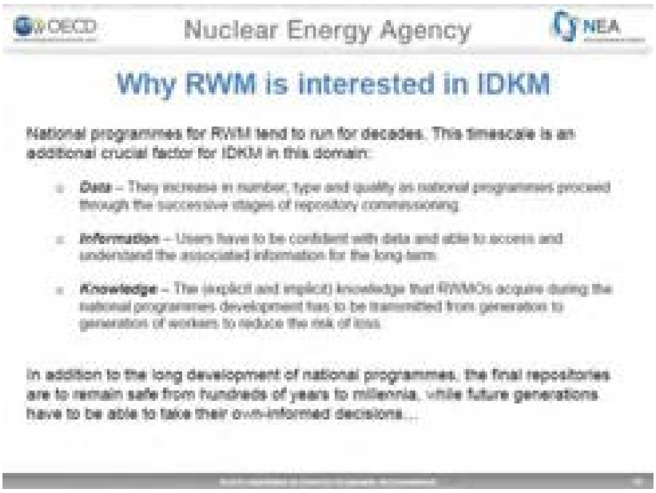
Why nuclear is interested in IDKM
Worldwide interest and request for the development of new tools for efficient and performant IDKM on both short and long term;
Nuclear sector, incl. RWM, is highly demanding in IDKM:
Nuclear data, information and knowledge are very expensive in terms of human, time and financial resources due to its intrinsic complexity and nature;
The pioneering nuclear generation has now retired, the generation trained during the nuclear expansion period are approaching retirement, and new generations are hard to emerge due to the national policy contrary to, or simply uncertain about, the use of the nuclear energy;
Nowadays, there is a high risk to fail (partially or totally) the transfer of the data, information and knowledge, gained with so many efforts, to the next generations (risk of loss).
We "forget" how to go to the Moon. We should do not forget how to build nuclear power reactors, how we generated or how we disposed waste…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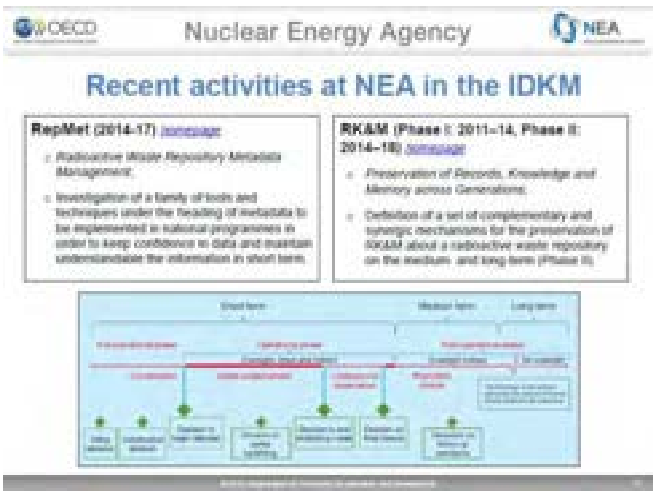
Why RWM is interested in IDKM
National programmes for RWM tend to run for decades. This timescale is an additional crucial factor for IDKM in this domain:
Data – They increase in number, type and quality as national programmes proceed through the successive stages of repository commissioning
Information – Users have to be confident with data and able to access and understand the associated information for the long term
Knowledge – The (explicit and implicit) knowledge that RWMOs acquire during the national programmes development has to be transmitted from generation to generation of workers to reduce the risk of loss
In addition to the long development of national programmes, the final repositories are to remain safe from hundreds of years to millennia, while future generations have to be able to take their own-informed decisions…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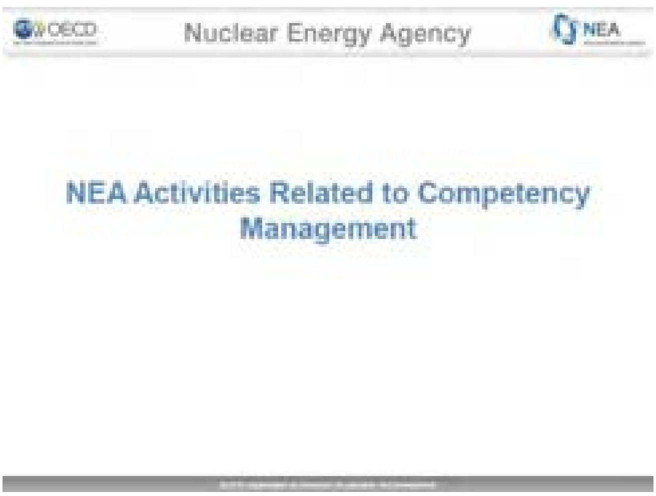
Recent activities at NEA in the IDKM
RepMet (2014-17) homepage
Radioactive Waste Repository Metadata Management
Investigation of a family of tools and techniques under the heading of metadata to be implemented in national programmes in order to keep confidence in data and maintain understandable the information in short term
RK&M (Phase I: 2011–14, Phase II: 2014–18) homepage
Preservation of Records, Knowledge and Memory across Generations
Definition of a set of complementary and synergic mechanisms for the preservation of RK&M about a radioactive waste repository on the medium and long term (Phase II)
Short term
Medium term
Long term


Nuclear Energy Agency
Recent activities at NEA in the IDKM (2)
EGIRM (Phase I: 2014-16, Phase II: 2017-18) homepage
Expert Group on Inventorying Reporting Methodology;
Development of an innovative methodology for presenting data and information about spent fuel and radioactive waste national inventories and management strategies in a common, unified and unified format
RK&M
Final Report
(coming soon)


Nuclear Energy Agency
New activities at NEA in the IDKM
IDKM Workshop (22-24 January 2019)
Development of the "IDKM Roadmap", a document collecting activities for which the country member representatives have expressed willingness and interest to carry out under the RWMC auspices
The NEA Radioactive Waste Management Committee (RWMC) has approved the creation of the "IDKM Working Party". It will act as:
A group managing and coordinating all of the activities included in the IDKM Roadmap that the same group will maintain and update based on rising needs of RWMOs and innovations in the IDKM area;
A neutral forum for the exchange of experiences, lessons learned, common needs and challenges in IDKM among RWMOs, nuclear regulators, TSOs and other stakeholders;
A platform following major innovations and trends, emerging technologies and consolidating best practices in all forms of the dynamic area of IDKM, in order to assist member countries in their understanding and applications to the RWM field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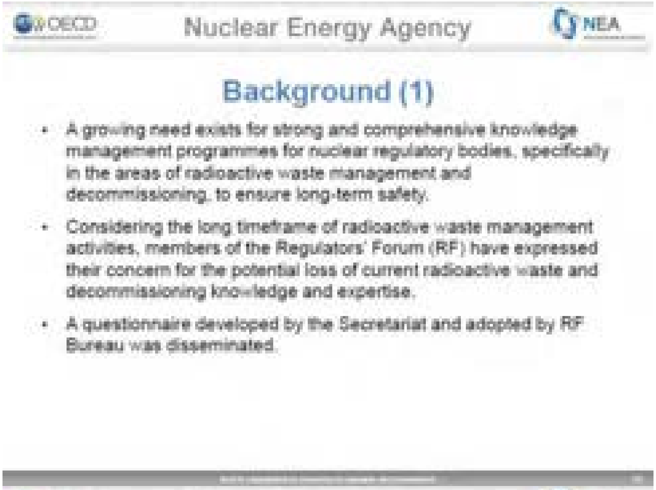
NEA Activities Related to Competency Management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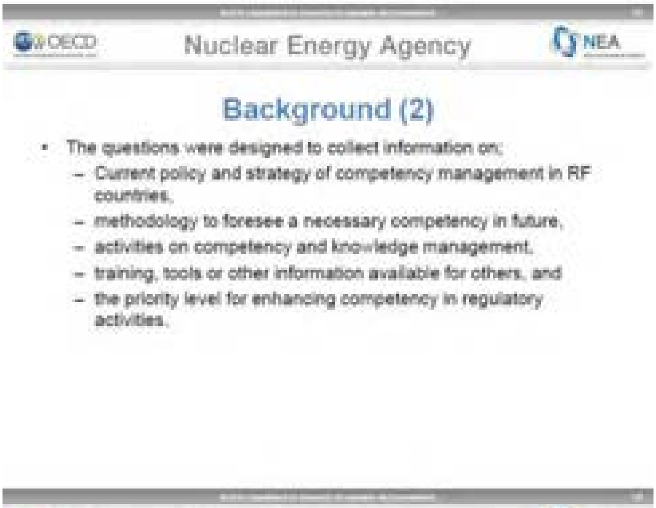
NEA
Background (1)
• A growing need exists for strong and comprehensive knowledge management programmes for nuclear regulatory bodies, specifically in the areas of radioactive waste management and decommissioning, to ensure long-term safety.
• Considering the long timeframe of radioactive waste management activities, members of the Regulators' Forum (RF) have expressed their concern for the potential loss of current radioactive waste and decommissioning knowledge and expertise.
• A questionnaire developed by the Secretariat and adopted by RF Bureau was disseminated.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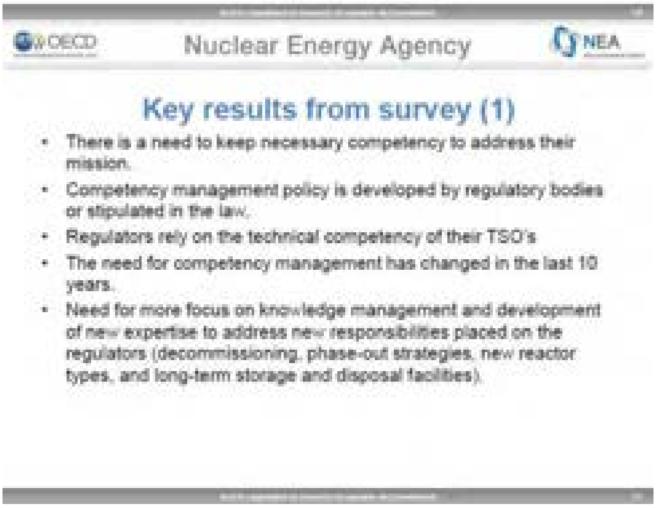
Background (2)
• The questions were designed to collect information on:
– Current policy and strategy of competency management in RF countries,
– methodology to foresee a necessary competency in future,
– activities on competency and knowledge management,
– training, tools or other information available for others, and
– the priority level for enhancing competency in regulatory activities.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Key results from survey (1)
• There is a need to keep necessary competency to address their mission.
• Competency management policy is developed by regulatory bodies or stipulated in the law.
• Regulators rely on the technical competency of their TSO's
• The need for competency management has changed in the last 10 years.
• Need for more focus on knowledge management and development of new expertise to address new responsibilities placed on the regulators (decommissioning, phase-out strategies, new reactor types, and long-term storage and disposal facilities).

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Key results from survey (2)

- Need to review necessary competency in line with their missions.
- Need for retiring staff to maintain their knowledge within the organisation and supply necessary competency.
- Participation in international meetings/workshops to gain competencies required in the field of waste management and decommissioning.
- Bilateral or multilateral agreement on staff training is valuable, although it can be difficult if the regulatory systems are different between countries.
- On the job training is important. Challenge is how to transfer "know-how" and "experience".
- RF is a valuable platform for effective communication/interaction with interested parties; best (most effective) practices in the transfer of knowledge/competencies for regulators.

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Competency Management if Regulators Workshop

- Workshop Date February 25-26, 2019 at NEA
- Workshop objective
  - Focus discussion on the core concepts of competency management,
  - Identify effective mechanism for building competency,
  - Identify members needs is support of the development of national framework of regulators' competency management.

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Other NEA Activates related to Radioactive Waste Management

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New initiative on the application of RRS in nuclear back-end

RWMC approved the establishment of a new initiative on RRS application in the nuclear back-end.

Objectives:

- Promote the exchange of information on RRS development and application amongst the participants; collection and analysis of inputs from all participants;
- Study the main and emerging challenges for the RRS application. Identify the main factors influencing RRS development and application. Arrange the identified factors and develop a road map (a plan of actions) to support the development in the area of provision of the nuclear back-end programmes with RRS;
- Develop recommendations (road map) to members on establishing a framework allowing the wider application of RRS in the nuclear back-end area. Strive to achieve shared approaches and standards, where appropriate;
- Support the development and implementation of common procedures, rules, standards, etc. that can facilitate the process of RRS application amongst the potential users of the systems.

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Potential participants

Members should be senior technical specialists who have considerable experience and knowledge in the development and application of RRS:

- representatives of decision-makers;
- research and development institutions/organisations in the field of RRS;
- test sites, laboratories and facilities;
- regulatory bodies (various) and technical supporting organisations to the regulatory bodies;
- developers of the main and auxiliary elements for maintenance and repairing of RRS;
- RRS producers, suppliers and service providers;
- soft and electronic elements developers;
- environmental organisations and public communication experts;
- other relevant specialists.

The CDLM will be invited to be part of the initiative as well as the CRPPH and other NEA STCs. Communication with NI-2050.

International organisations (IAEA, EC, WNA, others) and initiatives (e.g. SHARE) will be invited.

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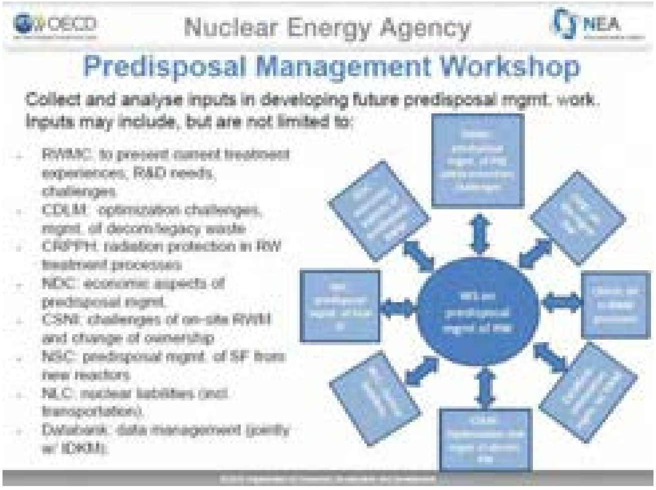
Predisposal Management Workshop

Objectives:

- To review the latest RW treatment/conditioning technologies within the RWM community, R&D needs, technical and social challenges in predisposal management.
- To better understand the impact of various factors, i.e. legal, technical, economics, societal, etc. on predisposal management and future WAC.
- To identify work topics for continuing the RWMC predisposal work, and potential collaborations with relevant STCs.

Next step:

- assemble a PC to plan for an NEA workshop, with all relevant STCs.
- WS to be held in Q1-Q2 2020.



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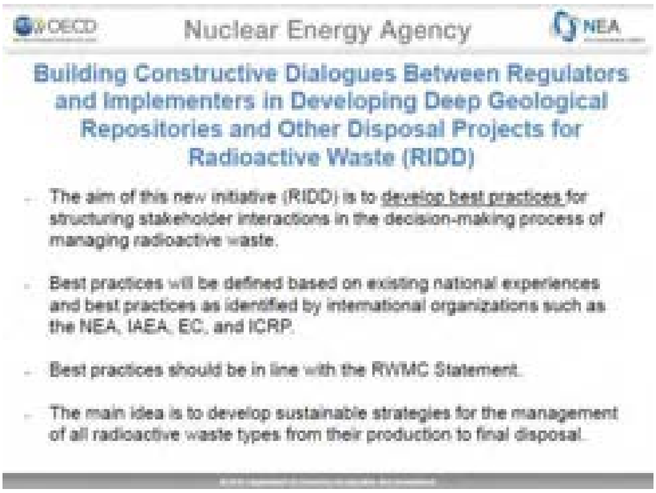
Predisposal Management Workshop
Collect and analyse inputs in developing future predisposal mgmt. work.
Inputs may include, but are not limited to:
- RWMC: to present current treatment experiences, R&D needs, challenges
- CDLM: optimization challenges, mgmt. of decom/legacy waste
- CRPPH: radiation protection in RW treatment processes
- NDC: economic aspects of predisposal mgmt.
- CSNI: challenges of on-site RWM and change of ownership
- NSC: predisposal mgmt. of SF from new reactors
- NLC: nuclear liabilities (incl. transportation).
- Databank: data management (jointly w/ IDKM).



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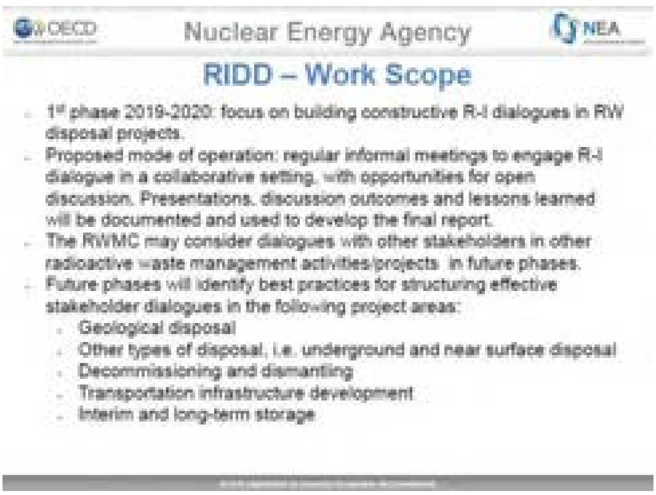
Building Constructive Dialogues Between Regulators and Implementers in Developing Deep Geological Repositories and Other Disposal Projects for Radioactive Waste (RIDD)
- The aim of this new initiative (RIDD) is to develop best practices for structuring stakeholder interactions in the decision-making process of managing radioactive waste.
- Best practices will be defined based on existing national experiences and best practices as identified by international organizations such as the NEA, IAEA, EC, and ICRP.
- Best practices should be in line with the RWMC Statement.
- The main idea is to develop sustainable strategies for the management of all radioactive waste types from their production to final disposal.



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RIDD – Work Scope
- 1st phase 2019-2020: focus on building constructive R-I dialogues in RW disposal projects.
- Proposed mode of operation: regular informal meetings to engage R-I dialogue in a collaborative setting, with opportunities for open discussion. Presentations, discussion outcomes and lessons learned will be documented and used to develop the final report.
- The RWMC may consider dialogues with other stakeholders in other radioactive waste management activities/projects in future phases.
- Future phases will identify best practices for structuring effective stakeholder dialogues in the following project areas:
  - Geological disposal
  - Other types of disposal, i.e. underground and near surface disposal
  - Decommissioning and dismantling
  - Transportation infrastructure development
  - Interim and long-term storage


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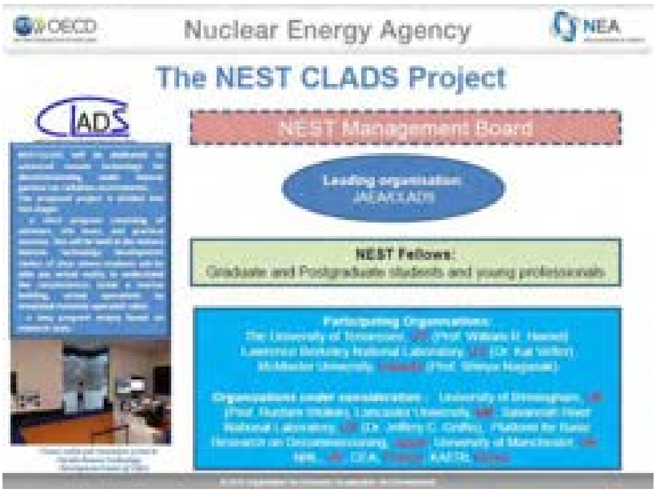
The Nuclear Education Skills and Technology (NEST) Framework:
– Building-up practical experience and expertise by exposing the next generation to real-wold problems, through hands-on activities in multi-disciplinary and multi-national contexts;
– International co-operation allows identifying and accessing a critical mass of capacities (infrastructures, construction or decommissioning projects, innovative activities…);
– Establishing links between Universities, Research Institutes, Industry and Regulatory bodies.
• 15 organisations from 10 countries are signatories to the NEST Framework Agreement (entry into force 15 February 2019).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The NEST CLADS Project
CLADS
NEST Management Board
NEST Fellows:
Graduate and Postgraduate students and young professionals
Participating Organisations:


OECD
Nuclear Energy Agency
NEA
The NEST PDC UGR Project
NEST Management Board
NEST Fellows:
Graduate, Postgraduate students and young professionals

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Available online at:
https://www.epj-n.org

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EDF, France

A NUCLEAR OWNER/ OPERATOR PERSPECTIVE ON WAYS AND MEANS FOR JOINT PROGRAMMING ON PREDISPOSAL ACTIVITIES

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Abstract. Nuclear decommissioning is a worldwide competitive market. It is also the main source of radioactive waste from the nuclear energy field. In order to reduce the waste volume, it is necessary to sort the actual radioactive waste to be disposed of and to separate them from other materials that could be recycled.

Since 2015, Electricité de France (EDF) has gathered the waste management and dismantling (WM&D) projects, the related competences and human resources in the WM&D field, in a dedicated directorate (DP2D) and a company group called Cyclife (including waste treatment facilities).

Taking into account the experience gained by carrying out its own WM&D projects as well as contributing to international cooperation, EDF considers that integrating collaborative research and development (R&D) on pre-disposal and waste management could be carried out following four main objectives.

- Alignment of the application of regulatory frameworks through appropriate definition of criteria and rules for radioactive waste to enable sensible worldwide comparison of technics,
- Improvement of technical and organisational aspects of nuclear reactors decommissioning using a demonstrator facility to be in operation, at first for graphite reactors, by 2022,
- Development of new techniques to decontaminate/homogenize metallic materials through a dedicated recycling route. These technics will be implemented in a new treatment facility foreseen to be available by 2030, and
- Increased training of decommissioning operators with the help of new technologies.
- All these improvements are aiming, beyond technical and experimental aspects, at reducing environmental impacts of nuclear activities as well as preserving the radioactive disposal volumes, as they are considered by EDF as rare resources.

1. Introduction

As owner/operator of a nuclear fleet with the responsibility of the dismantling of already shutdown NPPs, EDF has acquired a sound and robust experience in WM&D. Since 2015, EDF has created in the WM&D field a dedicated directorate (DP2D) and its holding called Cyclife. These new entities gather all corresponding projects, all necessary human skills and resources as well as technical means. Such new organisation enables DP2D to define and make applied the WM&D strategy for the entire EdF Group and its partners.

The main objective of this new organization is to reinforce EDF's capacity and leadership in this field. It will allow the integration of R&D aspects such as decommissioning operators' training, testing of innovative technologies (virtual reality, 3D simulation, remote operations) and development of technical demonstrators. Therefore, EDF intends to develop international collaboration directly through industrial cooperation and through participation in collaborative R&D projects. These projects can be carried out under the umbrella of international organisations such as the European Commission, OECD/NEA or IAEA, in which EDF already contributes actively.

To define R&D programmes for improving radioactive waste management during pre-disposal periods, it is necessary to agree on the definition of "radioactive waste" and the various current or potential sources. There is now a global international agreement within the nuclear industry to call "radioactive waste" the ultimate status of a considered material that will require disposal. Thus, to assess the status of waste, all materials to be generated by nuclear activities should be precisely characterized and sorted out in order to reduce significantly the amount of actual radioactive waste to be disposed of.

The importance of reducing the radioactive waste volume has increased over the last decade since repositories are considered as rare resources to be preserved in order to limit environmental impacts as much as possible. This care about reducing waste volume is taken during the four steps of the lifetime of a nuclear facility: design, construction, operation and decommissioning. Then, as users of radioactive disposals, nuclear operators take on their responsibility, by enhancing their expertise as well as increasing their credibility by mastering techniques and costs. In addition, they contribute to avoid spoiling resources by disposing materials that can be reused or recycled.

Defining relevant R&D programs in WM&D require that all aspects of predisposal activities are properly evaluated, considering the great diversity of type, nature and activity of waste generated by decommissioning as well as the involved quantities. Sufficient operational experience and feedback from existing practices help to identify remaining needs, commonly shared at the European or the international level.

2. Strategy on Waste Management and Decommissioning

Experience gained in performing decommissioning on an industrial scale

The last 10 years EDF has acquired experience in the decommissioning of four different types of nuclear reactors. This fruitful learning stage makes it possible to benefit from some lessons learned. They can be summarized as follow:

- For Pressurized Water Reactors (PWRs), which compose the current French operating fleet, the feasibility of the decommissioning process has already been demonstrated. The focus is now on optimizing the sequence of future operations and scenarios.

- For graphite reactors, the remote handling systems to dismantle these huge reactors are still under development. In parallel, the graphite waste management remains a major issue. Considering the size and complexity of this kind of reactors, dismantling design and operation will lead to long timeframes.
- A sound experience in waste management driven decommissioning is the cornerstone to successfully perform the dismantling of a nuclear reactor.
- France can rely on a complete and efficient radioactive waste management system for nuclear waste produced during decommissioning. However, this system could be improved by addressing the issue of clearance levels to allow the recycling of ingots produced after the melting of very low-level radioactive metallic waste.
- Specific care should be given to the use of terms for decommissioning For instance, the term ”immediate dismantling” recommended by the IAEA, should not mean that dismantling should be hurried, irrespective of associated risks and costs, but that the decommissioning of the nuclear plant should start soon after its shutdown. This kind of misinterpretation could lead to counterproductive attitudes of counterparts including local stakeholders.

Organisational issues

Taking into account the experience gained, EDF, in 2015, decided to create and structure an entity devoted to decommissioning and waste management with three main objectives:

- Support ongoing EDF dismantling worksites,
- Prepare the decommissioning of the nuclear fleet in operation,
- Become a major actor in the WM&D market, which is emerging but already highly competitive.

This restructuring has been progressively conducted in three parallel phases:

- The creation of a dedicated directorate called DP2D gathering all corresponding projects, resources and skills. It reports directly to EDF Group Board.
- The creation of specialized subsidiaries providing waste treatment services in order to optimise the sorting and the volume of waste to be disposed of. In addition, it has aimed at increasing EDF’s technical and financial mastery for its own needs (as a responsible owner/operator of a world nuclear fleet) or those of its partners/customers (who trusts and relies on EDF capacities and skills worldwide to preserve and develop their own competitiveness),
- The establishment of industrial partnerships regarding innovative and key technologies or targeted geographic areas.

In order to take advantage of the ongoing development of digital/numeric methods and techniques and to gain in efficiency, a specific study has been initiated. The aim is to analyse what would be the potential benefits of the implementation of numerical techniques in the organization model; would it be better to address the related topics thanks to a dedicated structure (as it is currently performed) or to consider this specific field as a crosscutting topic with its own strategy and associated business plan?

Regulatory Framework

Currently, technological developments are due to EDF engineering means and capacities, international cooperation (IAEA, OECD/NEA and World Nuclear Association (WNA)), feedback on various worksites as well as the R&D research programmes. One of the lessons learned in this particular field is that the efficiency of a technological development depends not only on the techniques used or the operator's ability and mastery but also on regulatory aspects.

Actually, the application of regulations, originally initiated by international directives (IAEA, EC), can vary from one country to another as they are adapted to local considerations and national policies. This point is critical for neighbouring countries as it may result in a risk of confusion in the perception of the public. For instance, some technique performed in one country could be restricted or forbidden in a neighbouring country only due to regulatory constraints, leading to confusion, weakening nuclear operators' credibility as well as lowering public acceptance.

For example, clearance levels, despite a global common European regulation, are not systematically implemented in national policies. This is an illustration of the national policies heterogeneity, preventing from a more efficient circular economy in waste management, at least at the European Union level.

It would, thus, be advantageous to align and harmonize the application of the internationally agreed regulatory basis. Such a framework shared and applied by all countries with nuclear activities could enable an efficient comparison of the efficiency, the suitability as well as the limits of available techniques being operated in similar situations.

As a consequence, it will become easier to identify the remaining needs of improvements as well as the necessary R&D developments. In addition, a common regulatory basis will help to qualify the decommissioning operators on the common basis of an international shared assessment, which is important as decommissioning is becoming an international business.

Financial issues

Strategic considerations in WM&D and R&D have to take into account the cost issues. This includes accurate cost assessment, funding availability, on time, and the associated mechanisms to provide funds.

Since 2006, France, like most other countries, has developed and structured a rigorous and demanding financial system, to guarantee future financing of WM&D operations. French nuclear operators are on a regular basis audited on their own financial capabilities. The audits include the demonstration of the relevance of the dismantling and waste treatment or conditioning scenarios, the efficiency of the chosen processes as well as the operators' carefulness to maintain them up to date along the years.

3. Ways and means for R&D on predisposal activities

Mainly deduced from EDF observations throughout its decades of experience as worldwide nuclear operator and its strategies developed in WM&D, 4 ideas for international cooperation are presented here after. They could be the starting point for future R&D activities at European or international levels in the frame of predisposal activities development.

These preliminary ideas are not exhaustive, as decommissioning and waste management business, being a competitive and emerging market, constitutes a continuous field of innovation and improvements.

3.1. Alignment of the implementation of the Regulatory Framework

Considering the long timeframe and the complexity of the decommissioning activities, the research and innovation effort makes sense if the application of the regulatory framework is similar or at least coherent amongst the countries. For instance, an appropriate definition of criteria and rules for waste management routes may foster the circular economy in material management at European and international level.

Such improvements in regulations should be developed with the support of IAEA and European Commission through their Research and Innovation (R&I) programmes. Creating exchange forums will help develop the sharing of experiences and competences. Furthermore, it will enable sensible and relevant comparison of techniques efficiency being performed worldwide.

Alignment of decommissioning objectives, regulatory framework and operating rules will help building confidence among the stakeholders mitigating the risk of confusion in population perception of facility dismantling operations and waste management practices.

3.2. Improvement of Technical and Organizational Aspects of Decommissioning Graphite Reactors

In line with its strategy, EDF has already launched the Decommissioning Demonstrator project scheduled to be in operation in 2022. Based on a modular design, the aim of this demonstrator facility is first to check the feasibility of decommissioning scenarios foreseen for graphite reactors. In particular, it will help to improve safety as well as tools and operators' efficiency thanks to an adequate training. This will help to face unexpected situations that will undoubtedly occur during real dismantling as none of the graphite reactors have been designed to be decommissioned. This demonstrator should therefore help to strengthen the technical mastery at appropriate cost. This new flexible facility will enable to test, improve and implement innovative technologies while performing decommissioning on site.

Beyond these objectives, the ambition of the Decommissioning Demonstrator project is to become an international training centre for decommissioning operators. Settled in Chinon (France), this location has the advantage to be at nearly equal distance from most European graphite reactors' locations. This demonstrator will allow operators from foreign countries to share experiences and train themselves on representative mock-ups in safe conditions.

The decommissioning of graphite reactors presents specific characteristics and constraints in terms of scales, dimensions and volumes of waste. Although these specific characteristics are common for all reactors of this type, no real set of decommissioning scenarios and tools are commonly agreed.

Thus, the Decommissioning Demonstrator is a full scale facility with a modular design, ensuring flexibility and adaptability. It will allow the implementation of R&D projects aimed at testing tools as well as training operators. This facility is composed of two main parts: a 3D simulation platform enabling digitalization and virtual reality and a huge experimental hall with scale one representative mock ups. The hall will serve to improve and qualify innovative techniques, such as remote handling and automated operations.

In addition, the experimental activities aim at improving decommissioning operators' confidence and experience in managing unexpected operational situation. They will also help to determine accurately the types and quantities of secondary induced waste produced in dismantling operation. Moreover, complementing the decommissioning scenarios assessment through this new angle will allow the reduction of waste volume and consequently the limitation of the number of waste packages thanks to relevant compromise and choice of tools.

Furthermore, the Decommissioning Demonstrator will allow the development of innovative and applied R&D in an international cooperation framework. The perspective of implementing R&D based on real cases has already drawn the attention and interests of the United Kingdom and Spain, currently involved in graphite reactors decommissioning.

Supporting countries have been invited by EDF to express their own needs regarding their own decommissioning projects, not limited to graphite reactors, such that they can be taken into account during the design of representative mock-ups, operators training programs, or other topics to be addressed with associated priorities.

The Decommissioning Demonstrator will apply for European support through the 2019 - 2021 Euratom work programme and in particular through the launch of a specific European Joint Programme (EJP) comprising R&D as well as training activities.

In addition, considering the expression of interest of some members, the OECD/NEA Nuclear Innovative Program (NI2050) has identified this future facility as one of the 12 selected projects of interest in the nuclear field. This OECD/NEA initiative is aiming at accelerating R&D and market deployment of innovative nuclear fission technologies to go with the necessary energy transition towards a very low carbon energy mix.

Finally, the IAEA has recently expressed its willingness to consider such project becoming a formation centre as soon as its industrial objectives will be achieved.

Beyond improving dismantling operation and ongoing waste management (in operation and in decommissioning), the Decommissioning Demonstrator will positively direct the future NPPs design and associated maintenance operations whatever are their nuclear technologies.

3.3. Development of New Techniques to Decontaminate/Homogenize Metallic Materials

Currently, EDF considers the creation, in France, of a new treatment facility to recycle metals. Based on the circular economy principle, this new plant, foreseen to be available by 2030, will comprise a melting oven and a foundry. The new facility will allow preserving repository capacities thanks to a significant reduction of volumes to be disposed of. It will also preserve source of raw materials such as steel, carbon and nickel.

At the early stage of the project, joint R&D programmes are designed to establish a sound common technical and regulatory basis to design processes that could accommodate metallic waste coming from various countries. In particular, emphasis will be given to study the use of arc melting furnace technology to decontaminate/homogenize metallic materials.

When operating, such unique facility could allow centralizing and regulating metallic flows coming from worldwide decommissioning worksites, particularly from Europe and Asia. Metals could therefore be recycled and further reused thanks to this new sustainable industrial process.

3.4. Increased Training of Decommissioning Operators and implementation of robotics

A specific emphasis will be put on the need to increase nuclear operators training using automated tools. The training and qualification processes should be established on the common basis of an international shared assessment of current and future practices.

The operators' increased ability and effectiveness will be obtained by strengthening their training on representative configurations and mock-ups specifically designed to take into account the various nuclear technologies constraints and requirements,

For example, the development of remote exoskeleton is foreseen, as human skills and expertise appear irreplaceable in some cases with high dose rate exposure. This R&D will pave the way for progressively replacing operators by machines without losing human know-how and mastery.

Such improvements and associated R&D could consequently bring up safety and public acceptance as well as increasing operators' efficiency.

In the future, an operator would be able, safely, from his or her office or a representative mock-up, to operate remotely a humanoid robot present on site. Thanks to 3D and virtual reality, wearing its exoskeleton, the operator will act as if he or she were really operating, adapting his behaviour to the context.

Such evolution in working conditions could lead to several advantages:

- Improvements of the labour efficiency (up to ~2 times), increasing the time of work in conditions of ionized radiation (reduction of the collective dose),
- Reductions of personnel's dose exposure,
- Dismantlement of larger fragments without necessary heavy handling/lifting means,
- Easier worksite preparation with no (or less) need of time-consuming (and waste-producing) preliminary decontamination,
- Reduction of the volumes of secondary induced waste (work clothing, air locks, …), less washings leading to fewer liquid effluents, and
- A drastic mitigation of the risk of injury, electric shock, falling objects or falling from heights and their consequences.

Last, but not least, it will keep operators' motivation at high level and increase public confidence towards back-end activities by use of cutting-edge technologies. This innovative approach of performing nuclear decommissioning is also foreseen as a means to secure the roadmap by accelerating cutting rates upgrading/modernizing scenarios and technologies. This last characteristic could foster the attractiveness of back-end activities, particularly towards young generations.

3.5. Intellectual Property Rights (IPR) issues

Although IPR is not the prime aim of this paper, it is clear that in a highly technologic area like decommissioning it is important to address IPR since the preliminary phases of discussions, defining R&D programmes.

Several ways exist to address these topics. They usually depend on the level of involvement of each contributor, their respective internal policies and their will to share their own techniques/know-how aiming to improve them. EDF currently implements various possible

IPR schemes. All of them lead to specific agreements, defining respective contributors' commitments. The contractual framework and in particular IPR rules in view of commercial applications should be set specifically for each R&D project.

4. Conclusion

The worldwide experience gained from the last decade at decommissioning worksites lead to a first conclusion: ways and means of R&D implementation on dismantling activities and waste management are strongly linked to a suitable application of the regulatory framework.

A sound and efficient application will foster a circular economy in materials, will help to establish a common basis of comparison of techniques efficiency and decommissioning operators' ability and will allow waste volume reduction.

This first point is important for identifying the actual remaining lacks and needs of knowledge and consequently the associated R&D developments requirements.

The second point is to put in coherence at the International level operators' training rules (up to their certification). This goal could be achieved on one hand by the sharing of experiences through international cooperation and, on the other hand, by the use of experimental demonstrators equipped with representative mock-ups.

These experimental demonstrators will help to adapt already existing tools or to identify and implement the required applicable pragmatic innovations. It will increase the efficiency of operators and techniques, mitigating risks (dose exposure, human intervention, secondary induced waste (clothing, wash liquid effluents)) and associated costs while securing the global decommissioning roadmap.

The development of sustainable techniques may have a positive impact on public acceptance as well as stakeholders' confidence.

Achieving these objectives will improve future NPPs’ design in order to ease future decommissioning operations and thus, strengthening the nuclear industry credibility.

International cooperation, e.g. through the support of the European R&D work programmes in WM&D will help to reach a global commitment in a sustainable, internationally shared waste management policy and practices.

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JOINT CONCLUSIONS FISA 2019 – EURADWASTE '19

FISA 2019
EURADWASTE '19

4-7 June, 2019
Pitesti, Romania

CLOSING REMARKS

Mircea Popa

Ministry for Research and Innovation, Romania

I appreciate the wide participation of European and Romanian research at this event, which has enabled the valuable results to be known, the prospects that open up to be understood, the opening of new collaborations, as well as the new European projects.

We also appreciate the structured approach of the two major aspects of nuclear energy: nuclear safety and radioactive waste management, as well as addressing cross-cutting themes of interest: challenges of climate change, trends in energy production, and challenges in shaping the future human resources.

Beyond the solutions presented by the projects and the cases of good practice, it is to be mentioned the opening to collaboration through "unity in diversity", by complementarity rather than by competition, by valorizing the synergic effects.

The format of the conference included an important number of workshops in which it was possible to discuss issues specific to the different themes of research and technology. These workshops identified research directions that can be supported jointly by European and national programs. In particular, we appreciated the large interest in the Workshop dedicated to ALFRED demonstrator, a project planned to be implemented in Romania.

In the nuclear domain, it is necessary to share all these efforts not only to avoid parallelism but also to form a critical mass of specialists.

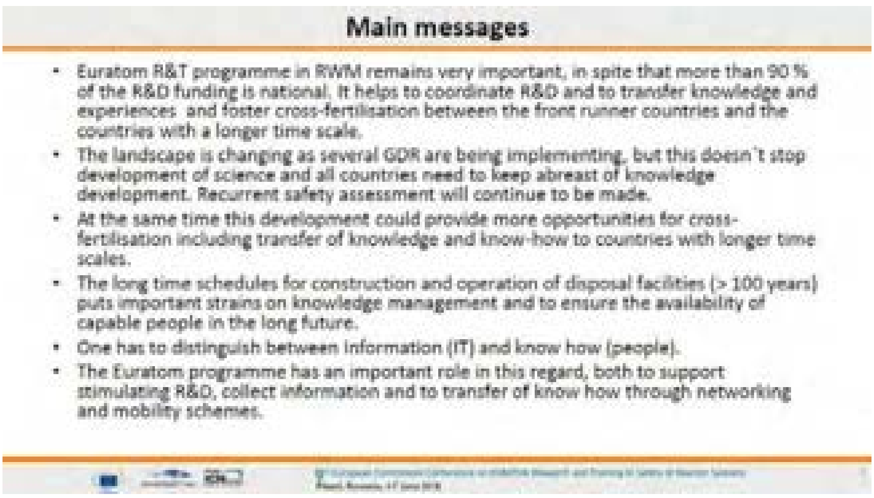
We enjoy the presence of an important number of young people and their enthusiastic participation in the competitions dedicated to them. Beyond these competitions, deepening the way we work in European projects is an important gain in shaping the future expertise in the field.

The Ministry of Research and Innovation thanks the European Commission for organizing this event in Romania, thanks the Institute for Nuclear Research (RATEN ICN) for its support, and to all participants for their active contribution to the conference's success.

Hans Forsström

Expert rapporteur, Sewden

EURADWASTE '19 - KEY MESSAGES AND FUTURE PERSPECTIVES



Main messages (2)

- A step change has been introduced in the management of the Euratom R&T programme in RWM.
- As of today a European Joint Programming project EURAD has become active. This project involves all actors concerned in RW R&D, i.e. WMOs, TSOs, Research Entities and representatives from the civil society. EURAD will propose, plan and manage all EU funded projects.
- The development of EURAD has a long history starting with the co-operation between WMO s through IGD-TP, followed by similar cooperation between TSOs in SITEX. Both projects, which were originally supported with Euratom funding, are now self-sustaining organisations.
- IGD-TP, SITEX and the Research Entities have developed their own Strategic Research Agendas, which have been introduced into EURAD. Input has also been given by civil society groups.
- In a first round EURAD will run 7 collaborative R&D projects, 2 strategic studies and 3 knowledge management projects.

Main messages (3)

- The latest Euratom R&T programmes have mostly dealt with issues connected to deep geological disposal. Taking into account interest expressed from several actors the programme is now being widened to also include pre-disposal RW management, decommissioning and legacy waste.
- In addition to discussions on EURAD, the results from several recently finished and on-going research projects were presented orally and in posters.
- Especially encouraging was the many good quality PhD-posters that were presented, not least in view to ensure human capacity for the future.

What is new since EURADWASTE 2013?

- The Euratom Directive on responsible and safe management of spent fuel and radioactive waste has become operational. First EC report in 2017.
- IAEA ARTEMIS Peer review services used by a number of MS.
- Construction licence for a DGR in Finland and good progress towards licensing in Sweden and France. Some progress on siting programmes in other countries.
- Several reactors finally shut down – Earlier decommissioning
- Good progress towards European Joint Programming involving WMOs, TSOs, REs and representatives from the civil society.
- Launch of the EURAD project for the implementation of a European Joint Programme on radioactive waste management based on a SRA and roadmap.

Status of Radioactive Waste Management – Key note speech

- LLW is adequately disposed in many existing facilities throughout the world.
- HLW, ILW and SNF can be disposed in DGRs. The knowledge exists and the development of these is progressing . 3 MS plan for operation around 2025/2030. Other MSs have a longer time scale and are still in the siting or pre-siting phase.
- Large volumes of VLLW and LLW will come from decommissioning and will require an efficient system for characterisation and treatment to optimize the waste routes.
- Long-lived waste with low activity, but large volumes (e.g. graphite, depleted uranium and NORM), will require new appropriate disposal routes.
- Radioactive sources in non-nuclear countries will require appropriate solutions.

EURADWASTE´19 Sessions

EURADWASTE included four oral sessions:

- Overview: International/EU/EURATOM Status
- Technology: Predisposal and disposal technology
- Science: Radioactive waste source term and science for disposal safety
- Organisation: Networking of research communities, Joint Programming of national programmes and Integration of Radioactive Waste Producers

In addition there was a continuous poster session with about 50 posters

Session on organisation of future work

The session called *Networking of research communites, Joint Programming of national programmes and Integration of radioactive waste producers* mainly dealt with how the different actors have prepared to join forces in the European Joint Programme on RWM (EURAD) and the remaining issue to also integrate the waste producers.

Presentations were made by IGD-TP, representing the WMOs, SITEX, representing the TSOs and EURADSCIENCE, representing the Research Establishments.

Presentations were also made on the possible interaction with IAEA and OECD/NEA and on the interests and needs from countries with longer time scales for implementation.

Finally a keynote speech was given from EdF on how to include the pre-disposal activities in the Joint Programme and in particular to ensure harmonization of standards in Europe to allow cross-country activities.

Session on organisation of future work (2)

Some highlights and messages:

- EURAD is a step change in the implementation of Euratom R&T programme in radioactive waste management. Instead of many smaller R&D projects the Commission is now funding a large project that will be based on an European Joint Programming (EJP).
- EURAD involves all actors concerned in RW R&D, i.e. WMOs, TSOs, Research Entities and representatives from the civil society. EURAD will propose, plan and manage all EU funded projects. In a second step also waste producers will be included.
- The development of EURAD has a long history starting with the co-operation between WMO s through IGD-TP, followed by similar cooperation between TSOs in SITEX. Both projects, which were originally supported with Euratom funding, are now self-sustaining organisations. The creation of EURAD is an achievement and has been successful thanks to the continuous support of the Euratom programme over a decade.
- IGD-TP, SITEX and the Research Entities have developed their own Strategic Research Agendas, which have been introduced into EURAD as a basis for EURADs SRA. Input has also been given by civil society groups.
- In a first round EURAD will run 7 collaborative R&D projects, 2 strategic studies and 3 knowledge management projects.

Session on organisation of future work (3)

Some highlights and messages (continued):

- For WMOs focus remains on geological disposal, but the missions are to be expanded to also accommodate more upstream interests and a wider inventory coverage (e.g. sealed sources and borehole disposal). However, it is important to recognise that WMO RD&D programmes have a much wider scope of activities than the commonly-agreed EURAD strategic research agenda will address.
- For TSO/SITEX community, the condition for participating to an EJP is to develop the high quality expertise function independent from WMOs as well as expanding interaction with Civil Society towards integration in R&D projects, meaning that CS may have a role on design of shared experiments.
- The European research organisations involved in RWM have organised themselves in a network, called EURADScience, with the vision of acting as an independent, cross-disciplinary, inclusive network providing scientific excellence and credibility to national radioactive waste management programmes.
- An important component of EURAD is knowledge management. These parts should lead to attract and train new competencies and new high level researchers to allow a cross fertilization of ideas and ensure that the competences will be present all along the duration of the disposal operation.

Session on organisation of future work (4) Involvement of civil society

- The involvement of representatives from the civil society is very important in programming projects for radioactive disposal.
- The Euratom programme has a long history of funding social research projects in the area.
- Civil society organizations are involved in the preparations and implementation of EURAD, primarily through SITEX and the TSOs, but also in an advisory role to the project.
- The role of these organizations need to be clearly defined.
- Primarily they have a role to influence the Strategic Research Agenda and to make their own evaluation of the results. They can also assist in making the R&D results understandable by the public at large
- In certain projects with a social impact direct participation can also be considered.

Technology session

The session on *Predisposal and disposal technology* included one keynote on the role of Research Entities in advancing knowledge, solutions and technologies for the management and disposal of RAW seen from the Czech perspective and five presentations, three on pre-disposal and two on disposal technology:

- Nuclear site characterization for radioactive waste minimization. INSIDER
- Characterization of conditioned nuclear waste. CHANCE
- Thermal treatment for radioactive waste minimization. THERAMIN

- Tunnel plugs and shaft seals demonstrations. DOPAS
- Monitoring strategies & technologies for geological disposal. Modern2020

The session was concluded with a panel discussion on remaining research needs in pre-disposal

Technology session (2)

Highlights and messages:

- Pre-disposal is becoming a new pillar in the Euratom programme. The results achieved in the pre-disposal project are promising and shows that further improvements in characterization, minimization and treatment of waste can be achieved. This might lead to even more safety and have commercial benefits.
- Waste Acceptance Criteria are important and should be developed in dialogue between all concerned parties (WMOs, waste producers, regulatory bodies and other stakeholders). Thus, a category of unacceptable waste can be avoided.
- Specific waste streams, like bituminized waste, graphite and powder waste from the back-end require further investigations with regard of their disposability and long-term behaviour.

- The activities performed during construction and operation of a DGR will have an important impact on the long term safety, e.g. plugs for tunnels and drifts as investigated in DOPAS.
- It is also important to be able to monitor the function of the disposal activities. As was shown in Modern 2020 this is not only a technical issue. Here the involvement of the representatives of the civil society has been very useful. Thus, it could be assessed if it does make sense to consider the implementation of R&D activity with regard to further and more intensive participation of stakeholders from civil society in set-ting up a monitoring programme.

Science session

The session on *Radioactive waste source term and science for disposal safety* included one keynote on the role of science for the safety case now and in the future and how to maintain knowledge and competence until final closure seen from the Swedish perspective and five presentations on R&D projects:

- Spent fuel dissolution. REDUPP and DISCO
- Carbon-14 source term generation and release from irradiated metals, ion-exchange resins and graphite. CAST
- R&I action on cement-based materials, properties, evolution and barrier functions. CEBAMA
- Bentonite erosion and Bentonite mechanical evolution. BELBAR and BEACON
- Microbiology in nuclear waste disposal. MIND

The session was concluded with a panel discussion on remaining challenges in science for the safety case of geological disposal.

Science session (2)

Highlights and main messages:

- The development of the safety case provides the platform to integrate the scientific and technical knowledge in a systematic and traceable manner to show the long term safety of a repository. For licensing a DGR a sound scientific and technological basis and the ability to compile a convincing post-closure safety case is needed.
- Also after receiving licenses and starting operation safety analyses will continue to be needed for periodic updates based on latest state of knowledge.
- The work done in the projects increases the knowledge (both scientific and technical)to be used for the licensing of the first HLW/SNF repositories in the advanced MS. This knowledge will also support the other MS in advancing their national programmes as rapidly as possible.
- All projects could to some extent build upon available experience and results from earlier projects. None of the projects did fundamentally change earlier understanding, but refinements have been made in all projects.

Science session (3)

Highlights and main messages (continued):

- Most projects include experimental work and modelling activities. This is important as adequate models help to transfer the evidence from experiments to the in-situ conditions of the repository analysed. The models also support the extrapolations for long-term evolution if needed and can provide information for sensitivity studies as part of the post-closure safety case.
- After completion of the reported projects some uncertainties will remain and should be specified. Whether these are acceptable or not, needs to be analysed within specific performance assessments and post-closure safety cases as the importance of remaining uncertainties depends upon the whole repository system and cannot be judged for one process alone in isolation.
- As science will to some extent continue also after the start of operation of a repository, there is a need to maintain oversight and knowledge in those areas of science that are important to post-closure safety until closure of the repository. This also includes the capability to compile a safety case. This are issues where future cooperative activities can play an important role.

Science session (4) – Knowledge management

- The time schedule from the start of a GDR project until the closing of the repository could be 100 years or more.
- Knowledge management was thus a key topic brought up during the science session. Knowledge management is also an important component in the new EURAD project.
- The difference between information and knowledge how to use the information should be recognised.
- For preservation of information different IT tools can be utilised.
- For preserving the knowledge how to use the information, active involvement in the work is needed. Here the recurrent safety assessments foreseen are key.
- The challenge to engage young people in R&D on RWM in the future remains. Challenging tasks are needed to attract young researchers and engineers.

Overview session

Covered several topics:

- Implementation of the different EU/EURATOM Directives
- EU R&T programme in nuclear area and in particular on radioactive waste
- The view of the STC, and
- A keynote speech on European and International status on RW management and disposal and challenges ahead.

Some highlights and messages were:

- Purpose of the Waste Directive is to ensure appropriate national arrangements for a high level of safety and to avoid imposing undue burdens on future generations. It should also ensure public information and participation.
- Each MS shall have a national programme for the management and disposal of all types of spent fuel and radioactive waste.
- The first report on the implementation of the Directive was presented to the Council and European Parliament in 2017 and a new report is due this year.
- Together with the EC, the IAEA has developed a peer review service, ARTEMIS, which has been used already by several States as required in the Directive.

Overview session (2)

Highlights and messages (continued):

- Since its start in 1975 the Euratom R&T programme on radioactive waste management progressed from a large number of uncoordinated projects to the call for one European Joint Programme in 2018, which brings together WMOs, TSOs, REs and representatives from the Civil Society.
- This closer cooperation has developed successively over a long period, starting in the early 2000s between WMOs and then through platforms and networks like the IGD-TP for the WMOs, SITEX for TSOs and recently EURADSCIENCE for the REs.
- Advanced programmes will be able to address specific cutting-edge science, while less advanced programmes will be able to plan, structure and implement the necessary R&D, with guidance, training and transfer of competence and knowledge from advanced programmes.

Overview session (3)

Highlights and messages (continued):

- In its opinion in 2018 the STC advocated for an increased budget for nuclear R&D given the need to maintain capability in the nuclear field to ensure that nuclear gets an important role in the road-map to a zero carbon society.
- In its proposal for the next FP the Commission is proposing a doubling of the funding.
- In addition to describing the status of radioactive waste management, the key note highlighted the usefulness of international cooperation through IAEA, NEA and EC.
- In particular as concerns RD&D the support by the EC is positive and the developments towards a European Joint Programming are very good and the efforts of the EC in this to promote the sharing of ideas and plans between all actors concerned is commendable.

Poster session and PhD presentations

In the poster session 38 posters were presented belonging to the EU-funded projects or responding to an open call.

In addition 10 PhD posters were presented, which were generally of very high quality. One observation from talking to the students was that there is often a need for the WMOs and the professors to better explain the context of the work being performed.

Summing up

- EURADWASTE 2019 has been very successful with very high quality and interesting presentations and quite vivid panel discussions.
- The organization has been excellent and the venue of the theatre very interesting.
- Good progress is being made towards an efficient continued implementation involving all important stakeholders through the EURAD European Joint Planning project.

Thanks for your attention

The future is bright

Stefano Monti

Section Head, Nuclear Power Technology Development section, Division of Nuclear Power, Department of Nuclear Energy (IAEA)

FISA 2019 - KEY MESSAGES AND FUTURE PERSPECTIVES

Despite different energy policies in EU Member States, Europe produces about 25% of its electricity through the operation of 126 reactors. It represents about 50% of European clean electricity production. Moreover, in a number of EU Member States nuclear energy plays a significant role as a component of low carbon electricity supply to address, in particular, the obligations under the Paris Agreement on climate change, also highlighted in the latest 2050 roadmap for carbon-neutral economy.

Nuclear energy also contributes to security of energy supply and competitiveness of European industry.

All the EU Member States, including those with no NPPs, have a primary interest to ensuring nuclear safety throughout the EU. Maintaining a high level of safety and competitiveness is a major challenge and requires the establishment of a coordinated and well-focused R&D programme at European level, grounded on the corresponding national efforts and interconnected at international level, in particular with the International Atomic Energy Agency and the Nuclear Energy Agency of the OECD

Most European countries operating NPPs are now considering prolonging the lifetime of their reactors from an originally foreseen 40 years' operation to 60 years. In order to safely extend the lifetime of these reactors, the nuclear sector – in particular both operators and regulators - needs to have, in addition to a skilled and well-trained workforce, reliable tools to assess the ageing and degradation processes of components and structures, as well as methods and guidelines for their validation and safe management. Reactor performance, system reliability, accident tolerant fuels, advanced numerical simulation and modeling for reactor safety, are also equally important to maintain the current European NPPs fleet safe and competitive with the other carbon-free energy sources. The contribution from the Euratom R&D programme to this top priority must continue and be focused on the expressed needs of the European Member States and their industry.

After a forthcoming period of stagnation, also characterized by the definitive shutdown of the most aged NPPs and by a limited number of new NPP realization, all the medium-, long-term energy scenario studies forecast a new and increasing deployment of nuclear energy after 2050. This is coherent with the maturity of Generation III+ reactors like EPR, as well as with the industrial scale deployment of so-called Generation IV nuclear energy systems expected in Europe around the middle of the current century. As a consequence, European contribution, above all to safety, sustainability, non-proliferation resistance, physical protection and competitiveness aspects of these innovative systems, is key and already clearly recognized at the international level, in particular within the Generation-IV international Forum (GIF). JRC remains the implement agent of Euratom in GIF, whilst specific indirect actions should be aimed at coordinating the contribution from interested Member States, also with the goal to proceed in the next two decades to the realization of GEN-IV experimental and demo plants.

In view of these first realizations, after a first broad-spectrum investigation of all the possible technology options which has characterized the last 20 years of R&D, there is an increasing consensus in the European nuclear community on the need to focus on the most promising innovative nuclear energy systems and associated fuels and fuel cycles for Europe. Concentration of effort, critical mass and synergies between national and European programmes seem to be seem to be necessary conditions for success.

However, Europe should also broaden the available offer to meet national specificities. To this purpose, there is the need to maintain flexibility within current and future Euratom programmes to consider, at appropriate time, other emerging nuclear technologies, including those given high priority in other regions of the world, like for instance Small Modular Reactors, micro-reactors, hybrid energy systems integrating NPPs, renewables, energy storage and non-electric applications. The establishment of a shared R&D programme at European level could lead to a detailed European SMR design – to be integrated with increasing new renewables and based on harmonized European safety standards - by 2025.

Hydrogen production, district heating, several industrial applications, desalination, etc. are of increasing interest in many regions of the world including some EU Member States. The imperative to conjugate extended industrial deployment with decarbonization of the energy sector, offers to nuclear power a unique opportunity to finally penetrate the non-electric energy market. Synergies and integration with chemical industry should be developed and pursued as soon as possible, and related R&D in Europe should be focused on near-term deployment while maintaining a correct balance with the very high temperature applications expected in the second half of the century.

Despite the planned life extension of aging NPPs, a number of NPPs in Europe are expected to be shut-down in coming years. Decommissioning and dismantling industrial-oriented R&D activities have to be appropriately supported by forthcoming Euratom programmes.

Many efforts have been devoted during last decades to develop advanced physical models and computer simulation codes of high fidelity, including in the very challenging area of severe accident Monitoring and Simulation. However new technologies such as artificial intelligence, on-line monitoring, deep-learning, etc. are rapidly being introduced in many advanced technology sectors. Forthcoming Euratom programmes should take into account these new trends and foster the early involvement of European industry and TSOs which represent the final users.

Nuclear applications and technologies, and related competence and expertise, in the fields of medicine, radiation protection and in general non-power applications are recognized of great value for a modern society in all the EU Member States. As a consequence, Euratom programme should be seen as an integral part of the broader Horizon Europe proposal able to capitalise on synergies over a much wider range of research areas. Joint projects between Euratom and Horizon Europe programmes should be pursued whenever possible.

Research and technology development must be accompanied by appropriate actions to further develop and strengthen education and training, infrastructures, cooperation throughout EU and at international level. To this end:

- Ensuring a top-level education & training, involving basic academic education as well as continuous professional development and capacity building, is of paramount importance to create a new generation of nuclear researchers and experts able to maintain high levels of safety in all the fields, as well as address the challenges posed by advanced nuclear power and non-power technologies of European interest;

- It is more and more urgent to assure adequate maintenance and strengthen a robust, enduring and efficient infrastructure base across the EU to underpin all aspects of research and innovation throughout the sector;

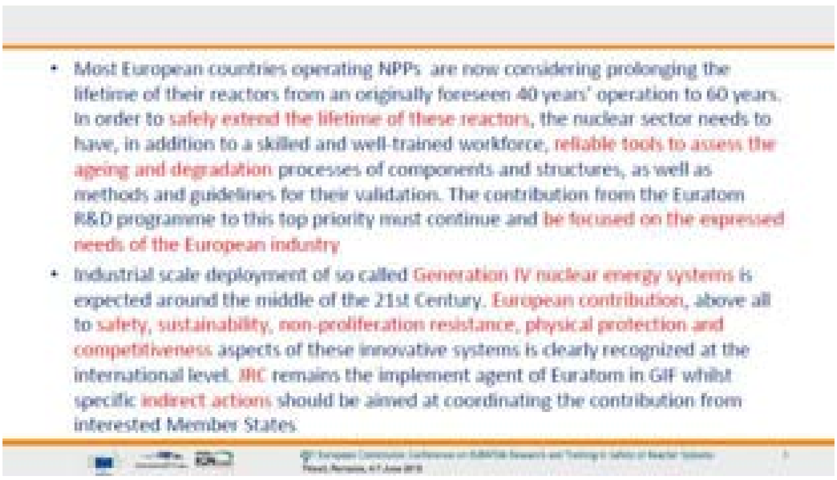
- It is highly advisable to capitalize on the European Technology Platforms SNETP-NUGENIA, -ESNII, -NC2I as well as ENEN as for E&T. ETPs have proved to be very effective in fostering and strengthening collaboration between research/academic institutes and industry. This successful mechanism of collaboration should be enhanced and further implemented

- International cooperation and synergies with initiatives launched by other international agencies like NI2050 (Nuclear Innovation 2050) & NEST (Nuclear Education, Skills and Technology Framework) by OECD-NEA, ICERR (International Centre based on Research Reactors), Collaborating Centres and E&T networks by IAEA, GIF task forces on infrastructure and E&T have to be encouraged and intensified.

Finally, there are significant cross-cutting benefits and synergies that can be realised between fission and fusion energy research programmes, as the latter evolves from activities focused on basic plasma physics to ones focused more on technology and safety-related aspects.

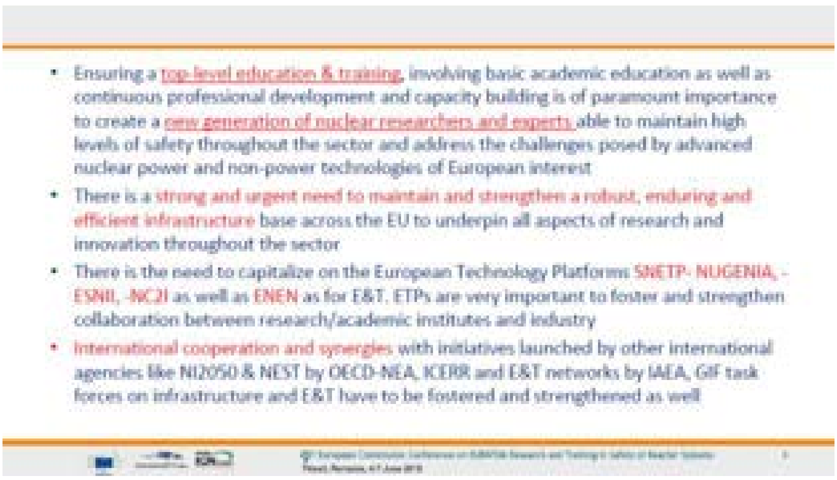

FISA 2019
FISA 2019 - Key messages and future perspectives
Stefano Monti

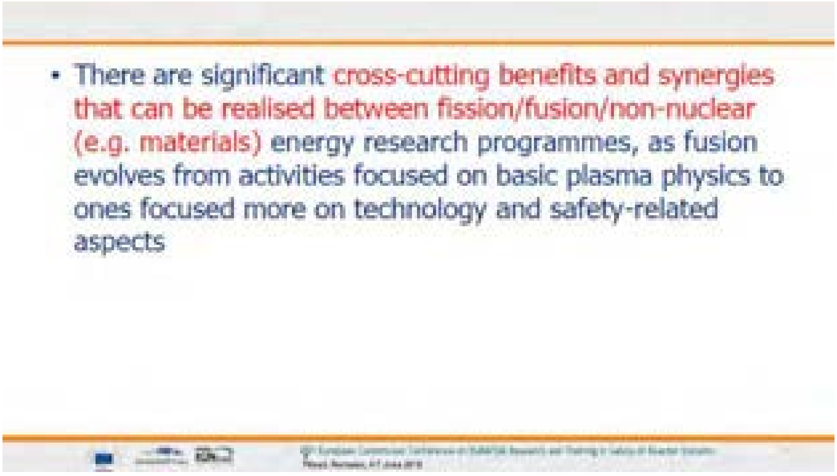

• In a number of EU Member States nuclear energy plays a significant role as a component of low carbon electricity supply to address, in particular, the obligations under the Paris Agreement on climate change, also highlighted in the latest 2050 roadmap for a carbon-neutral economy.
• Nuclear energy also contributes to security of energy supply and competitiveness of European Industry
• All the EU Member States, including those with no NPPs, have a primary interest to ensuring nuclear safety throughout the EU
• Despite different energy policies in EU MSs, Europe produces about 25% of its electricity through the operation of 126 reactors. Maintaining a high level of safety and competitiveness is a major challenge and requires the establishment of a coordinated and focused R&D programme at European level, well interconnected with IAEA and OECD-NEA activities


• Most European countries operating NPPs are now considering prolonging the lifetime of their reactors from an originally foreseen 40 years' operation to 60 years. In order to safely extend the lifetime of these reactors, the nuclear sector needs to have, in addition to a skilled and well-trained workforce, reliable tools to assess the ageing and degradation processes of components and structures, as well as methods and guidelines for their validation. The contribution from the Euratom R&D programme to this top priority must continue and be focused on the expressed needs of the European industry
• Industrial scale deployment of so called Generation IV nuclear energy systems is expected around the middle of the 21st Century. European contribution, above all to safety, sustainability, non-proliferation resistance, physical protection and competitiveness aspects of these innovative systems is clearly recognized at the international level. JRC remains the implement agent of Euratom in GIF whilst specific indirect actions should be aimed at coordinating the contribution from interested Member States


• Limited resources at European level on advanced reactors and related fuels and fuel cycles suggest prioritization on the most promising nuclear systems for Europe
• In the meantime there is the need to maintain flexibility within current and future Euratom programmes to consider, at appropriate time, other emerging nuclear technologies, including those given high priority in other regions of the world, like for instance SMRs, nuclear-renewable hybrid energy systems, etc.
• Non-electric applications of NP, like H2 production, district heating, several industrial applications, desalination, etc. are of increasing interest in many regions of the world including some EU Member States. They have the potential to decarbonize the whole energy sector. Synergies with chemical industry should be developed as soon as possible and related R&D in Europe should be focused on near-term deployment


• Despite the planned life extension of aging NPPS, a number of NPPs in Europe are expected to be shut-down in coming years. Decommissioning and dismantling industrial-oriented R&D activities have to be appropriately supported by forthcoming Euratom programmes
• Many efforts have been devoted during last decades to develop advanced physical models and computer simulation codes of high fidelity, including in the very challenging area of severe accident M&S. However new technologies such as artificial intelligence, on-line monitoring, deep-learning, etc. are rapidly being introduced in many advanced technology sectors. Forthcoming Euratom programmes should take into account these new trends and foster the early involvement of European industry and TSOs which represent the final users
• Nuclear applications and technologies, and related competence and expertise, in the fields of medicine, radiation protection and in general non-power applications are recognized of great value for a modern society in all the EU Member States. As a consequence Euratom programme should be seen as an integral part of the broader Horizon Europe proposal able to capitalise on synergies over a much wider range of research areas. Joint projects between Euratom and Horizon Europe programmes should be pursued whenever possible (mission oriented projects)


• Ensuring a top-level education & training, involving basic academic education as well as continuous professional development and capacity building is of paramount importance to create a new generation of nuclear researchers and experts able to maintain high levels of safety throughout the sector and address the challenges posed by advanced nuclear power and non-power technologies of European interest
• There is a strong and urgent need to maintain and strengthen a robust, enduring and efficient infrastructure base across the EU to underpin all aspects of research and innovation throughout the sector
• There is the need to capitalize on the European Technology Platforms SNETP- NUGENIA, -ESNII, -NC2I as well as ENEN as for E&T. ETPs are very important to foster and strengthen collaboration between research/academic institutes and industry
• International cooperation and synergies with initiatives launched by other international agencies like NI2050 & NEST by OECD-NEA, ICERR and E&T networks by IAEA, GIF task forces on infrastructure and E&T have to be fostered and strengthened as well


• There are significant cross-cutting benefits and synergies that can be realised between fission/fusion/non-nuclear (e.g. materials) energy research programmes, as fusion evolves from activities focused on basic plasma physics to ones focused more on technology and safety-related aspects

Summing up EURADWASTE ’19

EURADWASTE ‘19 has been very successful with very high quality and interesting presentations and quite vivid panel discussions. The R&D activities presented have shown a high scientific content and are very valuable for the continued implementation of radioactive waste management and disposal. Most projects have been connected to the safety of disposal of intermediate and high level waste and spent nuclear fuel. Some projects also cover the management of low-level waste (especially waste from decommissioning). Further such projects are foreseen to be included in the future programme.

As concerns the organisation of the R&D activities good progress is being made towards an efficient continued implementation involving all important stakeholders through the EURAD European Joint Programming project. The European Joint Programming is an efficient way of utilising capacities of different types in Europe, including EURATOM funding. It will also provide a tool for transfer of knowledge and experiences from the countries with an advanced programme to countries with a longer time schedule as well as to new generations of scientists. The EURAD project has many important challenges, especially concerning the decision-making process, but the structure is built to get the best results out of the work and the funding provided.

FISA 2019
EURADWASTE '19

4-7 June, 2019
Pitesti, Romania

EURADWASTE '19 AWARDS

The following contributions have been awarded in the 1st FISA-EURADWASTE Project competition.

Full papers are published in the free open access journal EJP Nuclear Sci. Technol. 5, 7 (2019)

FISA 2019
EURADWASTE '19

4-7 June, 2019
Pitesti, Romania

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R&D TOPIC AWARD

Volodymyr Gulik
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NEW COMPOSITE MATERIAL BASED ON HEAVY CONCRETE REINFORCED BY BASALT-BORON FIBER FOR RADIOACTIVE WASTE MANAGEMENT

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Shortened version of the title: **Composite material based on concrete reinforced by basalt-boron fiber**

Abstract: new composite material with neutron radiation shielding properties is presented. This fiber reinforced concrete material incorporates basalt-boron fiber, with different concentrations of boron oxide in fiber, and is applicable to nuclear energy and nuclear waste management. The methodology for production of boron oxide (B_2O_3) infused basalt fiber has been developed. First experimental samples of basalt boron fiber containing 6 % of B_2O_3 and 12 % B_2O_3 have been produced in laboratory conditions. The concrete samples reinforced by two types of basalt-boron fiber with different dosages have been prepared for neutron experiment. The neutron experimental investigations on radiation shielding properties of concrete reinforced by basalt-boron fiber have been performed by means of Pu-Be neutron source. The prepared samples have been tested in the course of several series of tests. It is shown that basalt-boron fibers in concrete improve neutron radiation shielding properties for neutrons with different energies, but it appears to be most effective when it comes to thermal neutrons.

1. Introduction

For safe operation of various sources of radioactivity, it is necessary to have reliable radiation protection. To date, there are many different types of radiation sources in the world, such as conventional fission reactors, fusion neutron sources, D-D and D-T neutron generators, plasma focus devices used as neutron sources and many gamma sources [1, 2]. These radiation sources are used for industrial, scientific and medical purposes.

At the moment, there are different types of radiation shielding. The most widespread is heavy concrete with various additives [3-12]. Such heavy concrete should have radiation shielding properties, both against neutron and gamma irradiation. For example, in order to protect against gamma radiation, we need to use materials with large values of the atomic number Z [13]. As a result, for protection against gamma radiation, fillers are used most widely, among them such natural minerals as barite containing a lot of barium, magnetite, which consists of titanium and iron, and serpentinite. For VVER reactors, heavy concrete with serpentinite is used as biological shielding [14]. Serpentinite contains such heavy elements as iron and magnesium.

In addition to heavy minerals, concrete should contain elements that are well scattering and absorb neutrons. By default, the concrete contains a large amount of hydrogen, on the nuclei of which effective neutron scattering is observed.

In this paper, the authors suggest a new type of composite material based on heavy concrete reinforced by improved basalt-boron fiber (BBF), in which the boron oxide is added during the production process.

2. Basalt-boron fiber

The proposal to add a basalt fiber (BF) containing boron is based on the fact that there is enough hydrogen in the concrete to slow down fast neutrons, and if we add a material with a large neutron absorption cross section (for example, B-10), then it can become very effective material with neutron radiation shielding properties [14].

Basalt fiber is produced similarly to glass fiber. The BF production contains several stages: the preparation of the basalt rock, the melting, the formation of fiber, the drying of the fiber, cutting the fiber and obtaining final products [15].

However, the process of BBF production is easier than the production of glass fiber: it does not require a complicated and expensive process of preparation of the charge, but requires only one supply line of crushed basalt rocks in the furnace for melting. The basalt breed is first crushed, then washed, dried and loaded into containers attached to the heater, which mixes the basalt to the melting bath in gas ovens (see Fig. 1).

A number studies have shown that concrete reinforced with BF has high chemical and corrosion resistance, durability, resistance to abrasion, and frost resistance [1, 13-17]. Since the specific density of the BF is approximately the same as that of the main components of the concrete, it is evenly distributed over the entire volume of concrete in the form of steel and other types of polymer fiber.

The first experimental samples of BBF were prepared in Institute for Problems in Materials Science in Ukraine for two different types of basalt fibers infused with boron as reinforcing material. The first type of BBF, hereinafter referred to as BasBor6, contains 6 % of B_2O_3, of which 19.8 % B-10 and 80.2 % B-11. The second type of BBF, represented in the text as BasBor12, contains 12 % of B_2O_3, of which 19.8 % B-10 and 80.2 % B-11. The chemical composition of the BBF with the infusion of boron BasBor6 is displayed on Table 1. The chemical composition of the BBF with the infusion of boron BasBor12 is displayed on Table 2.

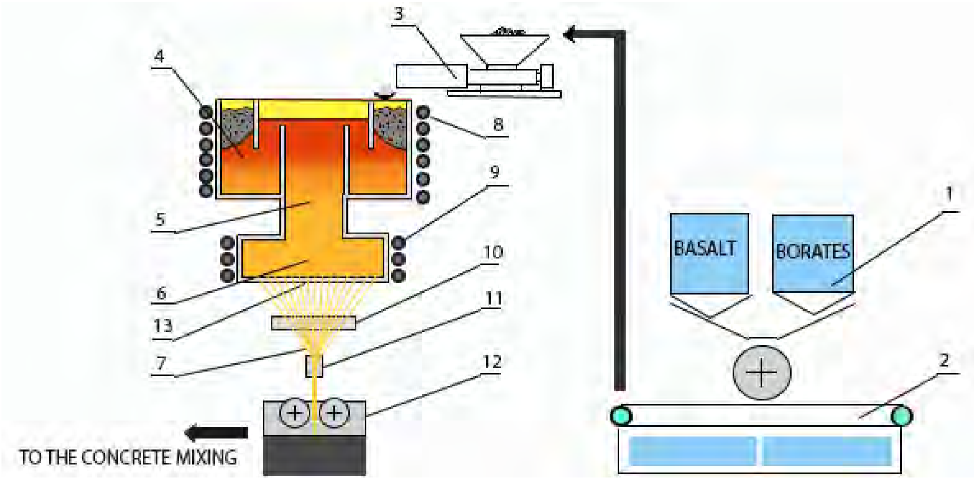

Fig. 1. Scheme of the process for BBF production. 1. Metering & mixing equipment (batch preparation). 2. Conveying equipment. 3. Batch charger. 4. Melting chamber. 5. Conditioning chamber. 6. Fiber forming chamber. 7. Fiber's strand. 8. Induction coil of melting chamber. 9. Induction coil of fiber forming chamber. 10. Sizing applicator. 11. Gathering shoe. 12. Direct chopper. 13. Fiber drawing plate [13]

Tab. 1. The chemical composition of BBF type BasBor6

Main constituents	B_2O_3	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl
%	6.2	1.809	5.93	13.888	50.40	0.125	0.015	0.010
Main constituents	K_2O	CaO	TiO_2	V_2O_5	MnO	Fe_2O_3	Co_2O_3	NiO
%	1.439	8.040	1.134	0.08	0.164	10.590	0.0033	0.002
Main constituents	CuO	ZnO	Ga_2O_3	Rb_2O	SrO	Y_2O_3	ZrO_2	BaO
%	0.003	0.014	0.002	0.0067	0.0349	0.006	0.0032	0.03

Tab. 2. The chemical composition of BBF type BasBor12

Main constituents	B_2O_3	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl
%	11.7	1.715	5.66	13.120	47.64	0.117	0.010	0.008
Main constituents	K_2O	CaO	TiO_2	V_2O_5	MnO	Fe_2O_3	Co_2O_3	NiO
%	1.313	7.421	1.044	0.051	0.149	9.688	0.0028	0.003
Main constituents	CuO	ZnO	Ga_2O_3	Rb_2O	SrO	Y_2O_3	ZrO_2	BaO
%	0.0028	0.012	0.003	0.0061	0.0313	0.005	0.0029	0.03

3. Radiation shielding properties experiment for Pu-Be neutron source

3.1 Description of experiment

For measurements a plutonium-beryllium neutron source, (ИБН-12) was used, creating a flux of fast neutrons with isotropic distribution and intensity $5 \cdot 10^7$neutrons. s^{-1}. Table 3 shows its main technical characteristics.

Tab. 3. The main technical characteristics of neutron source

Source type	Source dimensions (active part), mm		Neutron intensity, neutrons·s^{-1}	Maximum activity Pu-239 at source	
	Diameter, D (d)	Height (Length) H (h), (L)		Bq	Ci
ИБН-12	54 (46)	64 (46)	$(5.0 \pm 1.0) \cdot 10^7$	$1.3 \cdot 10^{12}$	35

Measurements of the neutron flux were carried out with a radiometer-dosimeter МКС-01Р with a detection unit БДКН-03Р. The apparatus measurement error of the МКС-01Р when measuring the neutron flux does not exceed 20 %. Measurements of neutron flux were carried out in two types of the neutron energy spectrum:

- for "thermal" neutrons;
- for intermediate and fast neutrons (with cadmium attachment to the detecting unit).

The measurements were carried out for two conditions of irradiation of the samples, in different geometries:

- Concrete samples are placed in an isotropic neutron field from a Pu-Be neutron source ("simple" neutron experiment);
- measurements with geometry, allowing to take into account the reflected and scattered neutrons ("complex" neutron experiment).

During the measurements, the neutron source ИБН-12 was in the transport container. The transport container is a metal container with a central tube into which the source is installed. The inner space of the container is filled with paraffin. For personnel protection, a container with a source from three sides was surrounded by panels of "neutron stops" of type TP12-41-MMS 065/73 and metal tanks with water. "Neutron stops" are blocks of polyethylene with boron content and are effective neutron absorbers. The thickness of the neutron-stop panels is 70 mm. Water tank thickness 150 mm.

The floor plan and layout of equipment is shown in Fig. 2, and Fig. 3 shows a front view of the source and the overall dimensions of the equipment.

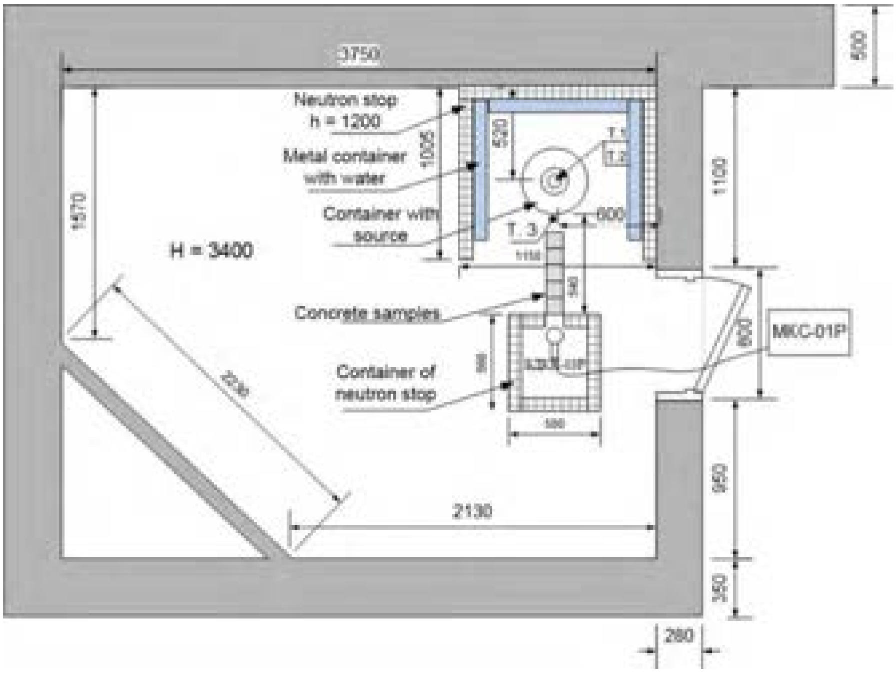

Fig 2. Layout of the room and equipment placement during measurements

As mentioned above, this study investigates two different types of basalt fibers infused with boron as reinforcing material (**BasBor6** and **BasBor12**). There are 5 types of concrete mixtures in the neutron experiment conducted, all of them with same type of cement, CEM I 42.5R, same water-to-cement ratio and same river sand as fine aggregate.

The density of concrete was 2.33 g/cm^3. All in all, there are five main types of concrete mixtures in this study and they are noted throughout the paper as follows: **R** – plain concrete without BBF; **A** – concrete with **BasBor6** dosage: 5 kg/m^3; **B** – concrete with **BasBor6** dosage: 20 kg/m^3; **C** – concrete with **BasBor12** dosage: 5 kg/m^3; **D** – concrete with **BasBor12** dosage: 30 kg/m^3. Concrete samples have dimensions: 10 cm x 10 cm x 10 cm.

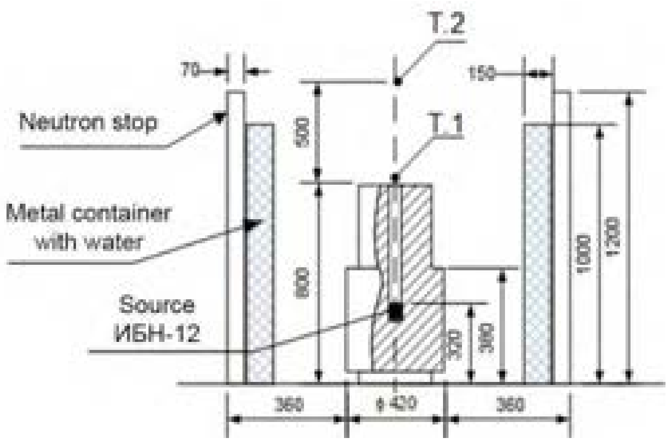

Fig 3. Frontal view and overall dimensions of the container with a neutron source

3.2 “Simple” experiment

The scheme of measurement of geometry in a “simple” experiment is shown on Fig. 4. The detecting unit was located along the axis and at the height of the source in the containers. The distance between the detecting unit and the front wall of the container is L = 500 mm.

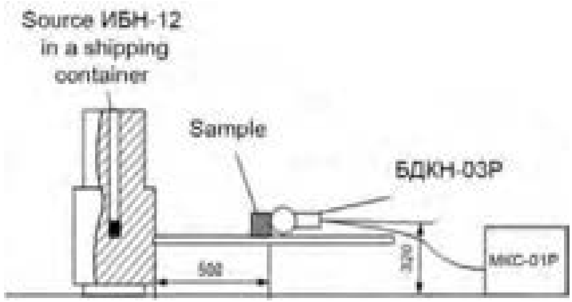

Fig 4. Schematic representation of measurement geometry in a “simple” experiment

Ten measurements were conducted without samples of concrete. The measurements were carried out for thermal (see Fig. 5) as well as intermediate and fast neutrons (using a detection unit with an installed cadmium packing (see Fig. 6).

Fig 5. The measurements for thermal neutrons

Fig 6. The measurements for intermediate and fast neutrons

Between the detecting unit and the source, one to five concrete samples from each set were sequentially installed. Ten measurements were conducted for each configuration and set of samples. The measurements were carried out for thermal as well as intermediate and fast neutrons (a detection unit with an installed cadmium packing). All experimental and simulations results will be presented in next journal paper which is currently being prepared.

3.3 "Complex" experiment

A diagram of the measurement geometry in a "complex" experiment is shown in Figure 7.

For measurements, a container was assembled from "neutron stops". The container is a box with dimensions of 580 × 500 × 300 mm closed on all sides, with wall thickness 70 mm. In one of the walls of the container, a rectangular opening with a section equal to the section of the samples is made. A detection unit was installed inside the container opposite the opening. This measurement geometry allows shielding from neutrons reflected from the walls of the room and equipment, and taking into account their contribution to the measurement results of neutron flux.

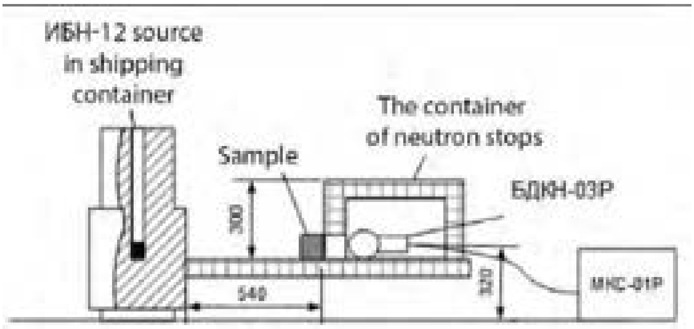

Fig. 7. Schematic representation of the measurement geometry in a "complex" experiment

The hole in the container was closed with a stopper made of neutron stops and 10 measurements of $\varphi_ф$ - background neutron flux were performed. The measurements were carried out for thermal as well as intermediate and fast neutrons (a detection unit with an installed cadmium packing).

10 measurements of neutron flux φ_0 were conducted without samples of concrete. The measurements were carried out for thermal as well as intermediate and fast neutrons (a detection unit with an installed cadmium packing).

Opposite the opening between the detection unit and the source, one to five concrete samples from each set were sequentially installed. 10 measurements of neutron flux were then conducted for each configuration and set of samples. The measurements were carried out for thermal as well as intermediate and fast neutrons (a detection unit with an installed cadmium packing).

Based on the results obtained of neutron flux density measurements, the mean values, the standard deviation and the relative statistical error of each measurement by formulas (1) - (3) were calculated.

$$\overline{\varphi} = \frac{\sum_{i=1}^{i=n} \varphi_i}{n} \quad (1)$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{i=n} (\varphi_i - \overline{\varphi})^2}{n-1}} \quad (2)$$

$$\delta = 2 \cdot \frac{\sigma}{\overline{\varphi} \cdot \sqrt{n}} \cdot 100\% \quad (3)$$

where, φ_i - measured values of neutron flux, neutron / ($cm^2 \cdot sec$); $\overline{\varphi}_i$ - the average value of neutron flux, neutron / ($cm^2 \cdot sec$); n = 10 is the number of measurements; σ - standard deviation, neutron / ($cm^2 \cdot sec$); δ is the limit of the relative statistical error, %.

The results of measurements and calculations in the "complex" experiment for all series of measurements are given in Tables 4, 5. The numbers 1-5 mean that: 1 – one concrete sample between source and detector; 2 – two concrete samples between source and detector; 3 – three concrete samples between source and detector; 4 – four concrete samples between source and detector; 5 – five concrete samples between source and detector.

It can be seen from Table 4 that there is a slight increase of neutron radiation shielding properties (up to 5 %) in the case of low concentrations of BBF in concrete (A and C types of concrete samples), but considerable increase of neutron radiation shielding properties (up to 13 %) with the addition of higher concentration of BBF in concrete (B and D types of concrete samples) for intermediate and fast neutrons. It can also be noted from Table 5 that a similar trend can be observed for thermal neutrons, which is a direct result of the increased fraction of neutrons with high absorption cross-section for Boron-10 in the thermal neutron spectrum. Therefore, it could be argued that the use BBF could decrease the thickness of radiation shielding protection at nuclear energy applications.

4. Conclusions

In present work, the radiation shielding properties of basalt-boron fiber reinforced concrete are investigated. The samples of basalt fibers infused with boron oxide are prepared for neutron experiment. Two types of basalt-boron fiber referred to as BasBor6 (contains 6 % of B2O3) and BasBor12 (contains 12 % of B2O3) are used for preparation of four types of fiber concrete samples. The neutron radiation shielding experiment for concrete samples with different dosages of basalt-boron fiber are conducted with help of Pu-Be neutron source. The experiment includes Pu-Be neutron source (ИБН-12), a radiometer-dosimeter МКС-01Р with a detection unit БДКН-03Р and panels of "neutron stops" of type TP12-41-MMS 065/73.

It is found that the addition of basalt-boron fiber in concrete has effects for fiber dosages 20 kg/m3 and 30 kg/m3 in case of thermal and fast neutrons. Obviously, a low dosage of basalt-boron fiber (5 kg/m3) does not produce a noticeable effect in neutron radiation shielding properties.

The presented experimental results indicate that basalt-boron fiber reinforced concrete has a good potential for use in nuclear energy application and in nuclear waste management. Also, the basalt-boron fiber reinforced concrete is expected to have good mechanical properties including enhanced tensile strength and strong durability, based on its fiber content.

Tab. 4. The neutron-physical characteristics on radiation shielding experiment for intermediate and fast neutrons

Measurement	Neutron flux for intermediate and fast neutrons, neutron / (cm^2·sec)										Average flux, neutron/ (cm^{2}sec)	Standard deviation	δ, %
	1	2	3	4	5	6	7	8	9	10			
φ_0	633.7	659.3	644.8	651.5	646.6	638.2	645.9	620.8	653.5	650.5	644.5	11.1	1.1
φ_ϕ	289.4	294.1	300.4	282	306.1	297.6	302.2	289.4	297.3	298.3	295.7	7.1	1.5
R1	411.5	413.8	397.6	392.5	400.8	396.3	409.2	385.2	405.7	391.7	400.4	9.4	1.5
R2	337	355	352	314	333	331	390	302	321	371	340.6	26.8	5.0
R3	294	310	311	305	310	315	289	311	306	337	308.8	12.8	2.6
R4	263	300	309	318	324	316	313	309	311	334	309.7	18.8	3.8
R5	325	326	301	327	300	288	296	305	303	283	305.4	15.7	3.3
A1	421	393	370	425	407	398	401	434	394	404	404.7	18.4	2.9
A2	314	351	329	382	327	360	334	332	315	326	337.0	21.3	4.0
A3	318	322	329	314	325	299	259	351	317	296	313.0	24.4	4.9
A4	292	324	351	316	301	326	319	362	313	304	320.8	21.7	4.3
A5	313	308	315	305	332	301	277	303	308	306	306.8	13.7	2.8
B1	412	364	423	400	384	431	360	399	415	395	398.3	23.6	3.7
B2	322	325	333	317	318	297	342	331	315	342	324.2	13.7	2.7
B3	280	304	306	275	307	295	302	286	319	303	297.7	13.6	2.9
B4	270	298	282	286	282	295	279	296	272	297	285.7	10.4	2.3
B5	290	271	259	279	281	265	257	259	287	264	271.2	12.2	2.9
C1	426	394	357	395	396	388	456	382	449	409	405.2	30.6	4.8
C2	344	350	336	349	332	326	337	302	347	346	336.9	14.6	2.7
C3	295	328	348	312	300	331	317	312	305	321	316.9	15.8	3.2
C4	304	309	294	297	302	334	294	293	304	331	306.2	14.8	3.1
C5	321	258	302	278	309	295	280	332	333	297	300.5	24.3	5.1
D1	373	389.5	388.7	384.5	376.9	368.8	369.7	401.6	400.8	388.2	384.2	11.9	2.0
D2	327	324	336	306	309	330	321	304	308	335	320.0	12.3	2.4
D3	277	285	316	302	295	282	331	292	329	297	300.6	19.0	4.0
D4	248	289	280	293	289	298	297	287	274	293	284.8	14.9	3.3
D5	296	282	280	274	269	254	273	288	261	279	275.6	12.4	2.8

Tab. 5. The neutron-physical characteristics on radiation shielding experiment for thermal neutrons

Measurement	Neutron flux for thermal neutrons, neutron / ($cm^2 \cdot sec$)										Average flux, neutron / ($cm^2 \cdot sec$)	Standard deviation	δ, %
	1	2	3	4	5	6	7	8	9	10			
φ_0	129.7	133	132.6	134.6	126.3	133.4	132.8	129.9	129.8	128.9	131.1	2.6	1.2
φ_Φ	21.6	20.8	18.5	18.6	22.7	18.1	19.1	19.3	22.6	20.2	20.2	1.7	5.4
R1	52	49	46	48	50	56	49	45	46	50	49.1	3.2	4.2
R2	45	52	48	41	58	51	50	47	52	47	49.1	4.6	6.0
R3	47	45	53	47	48	49	44	53	50	51	48.7	3.1	4.0
R4	55	41	43	46	40	46	52	44	54	52	47.3	5.5	7.4
R5	49	54	47	43	48	42	47	48	52	50	48.0	3.7	4.8
A1	48.8	49.3	51.3	51.8	56.8	51.5	51.6	49.9	51.3	54.1	51.6	2.3	2.9
A2	45.6	49.7	47	49.1	46.1	46.2	44.8	48.5	50	45.7	47.3	1.9	2.5
A3	46.5	45.8	45.7	47.1	41.5	45.6	46.3	46.9	49.3	50.2	46.5	2.3	3.2
A4	49.5	46.5	48.5	48.8	45.3	47.7	46.6	45.3	45.5	44.9	46.9	1.7	2.2
A5	44.6	44.7	45.7	46.9	50.7	42.7	46.9	44.8	45.5	42.6	45.5	2.3	3.2
B1	47.6	50.3	47.9	49.8	46.8	47.1	45.7	50.6	48.2	42.4	47.6	2.4	3.2
B2	42.9	41.7	44.1	42.8	46	44.9	46.5	44.2	46.9	45.4	44.5	1.7	2.4
B3	42	39.7	42.7	42.6	44	40.1	41.8	40.7	44.2	43.4	42.1	1.6	2.4
B4	42.7	41.9	42.2	41.1	41.4	40.7	40.3	43.9	39.5	41.3	41.5	1.3	1.9
B5	40.9	40.2	42.5	44.3	41	43.5	43.8	40.9	42.9	44.8	42.5	1.6	2.4
C1	45	52	48	50	44	45	41	49	45	41	46.0	3.7	5.1
C2	44	47	48	39	48	43	35	40	35	38	41.7	5.0	7.6
C3	34	37	40	37	40	33	45	42	46	32	38.6	4.9	8.0
C4	43	35	39	44	32	44	42	32	44	45	40.0	5.2	8.2
C5	39	41	37	36	31	34	36	39	37	45	37.5	3.8	6.5
D1	44.2	50.9	48.3	45.8	46.1	43.1	46.9	44.4	46	47.8	46.4	2.3	3.1
D2	43.7	39.8	41.3	42.4	41	41.1	44.1	41.5	41.2	41.7	41.8	1.3	2.0
D3	42.3	41.3	39.1	42.3	42.2	41.9	41.7	39.2	42.6	42.2	41.5	1.3	2.0
D4	42	39.5	40.1	40.7	39	37.5	41.5	40.5	40.1	37.5	39.8	1.5	2.4
D5	40	38.1	40.7	38.4	40.4	36.2	39.2	40.1	39.3	39.5	39.2	1.3	2.2

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References

1. Accelerator Driven Systems: Energy Generation and Transmutation of Nuclear Waste. Status Report. IAEA, Vienna. 1997.
2. Use of Accelerator Based Neutron Sources. IAEA-TECDOC-1153. IAEA, Vienna. 2000.
3. Ipbuker C., Nulk H., Gulik V., Biland A., Tkaczyk A.H. Radiation shielding properties of a novel cement-basalt mixture for nuclear energy applications. Nuclear Engineering and Design. 2015. Vol. 284. P. 27–37.
4. Singh V.P., Badiger N.M. Investigation on radiation shielding parameters of ordinary, heavy and super heavy concretes. Nuclear Technology & Radiation Protection. 2014. Vol. 29, P. 149–156.
5. Singh V.P., Badiger N.M. Gamma ray and neutron shielding properties of some alloy materials. Annals of. Nuclear Energy. 2014. Vol. 64, P. 301–310.
6. Icelli O., Yalcin Z., Okutan M., Boncukcuoglu R. Determination of photon energy absorption parameters for pellet waste, trommel sieve waste and original tincalconite. Annals of Nuclear Energy. 2012. Vol. 47. P. 38–45.
7. Sidhu B.S., Dhaliwal A.S., Mann K.S., Kahlon K.S. Study of mass attenuation coefficients, effective atomic numbers and electron densities for some low Z compounds of dosimetry interest at 59.54 keV incident photon energy. Annals of Nuclear Energy. 2012. Vol. 42, P. 153–157.
8. Singh N., Singh K.J., Singh K., Singh H. Comparative study of lead borate and bismuth lead borate glass systems as gamma-radiation shielding materials. Nuclear Instruments and Methods in Physics Research Section B. 2004. Vol. 225. P. 305–309.
9. Sharma R., Sharma V., Singh P.S., Singh, T. Effective atomic numbers for some calcium-strontium-borate glasses. Annals of Nuclear Energy. 2012. Vol. 45, P. 144–149.
10. El-Khayatt A.M., Akkurt I. Photon interaction, energy absorption and neutron removal cross section of concrete including marble. Annals of Nuclear Energy. 2013. Vol. 60. P. 8–14.
11. Singh V.P., Badiger N.M. Gamma photon exposure buildup factors for somespin ice compounds using g-P fitting method. Journal of Nuclear Physics, Material Sciences, Radiation and Applications. 2015. Vol. 2 (2), P. 169–179.
12. Maslehuddin M., Naqvi A.A., Ibrahim M., Kalakada Z. Radiation shielding properties of concrete with electric arc furnace slag aggregates and steel shots. Annals of Nuclear Energy. 2013. Vol. 53. P. 192–196.
13. Zorla E., Ipbuker C., Biland A., Kiisk M., Kovaljov S., Tkaczyk A.H., Gulik V. Radiation shielding properties of high performance concrete reinforced with basalt fibers infused with natural and enriched boron. Nuclear Engineering and Design. 2017. Vol. 313, P. 306—318.
14. Romanenko I.M., Holiuk M.I., Nosovsky A.V., Vlasenko T.S., Gulik V.I. New Composite Material Based on Heavy Concrete and Basalt-Boron Fiber for Neutron Radiation Shielding Properties. Nuclear & Radiation Safety. 2019. Vol. 2(82), P. 19–25.

15. Ipbüker C., Zorla E., Gulik V., Kovaljov S., Kiisa M., Biland A., Tkaczyk A.H. Optimization of basalt fiber in concrete composite for industrial application in Estonia. Fresenius Environmental Bulletin. 2016. Vol. 25 (1), P. 355 – 364.
16. Romanenko I.M., Holiuk M.I., Nosovsky A.V., Vlasenko T.S., Gulik V.I. Investigations of Neutron Radiation Shielding Properties for a New Composite Material Based on Heavy Concrete and Basalt Fiber. Nuclear & Radiation Safety, Vol. 3(79), P. 42 – 47, 2018.
17. Romanenko I.M., Holiuk M.I., Nosovsky A.V., Gulik V.I. Investigation of Novel Composite Material Based on Extra-Heavy Concrete and Basalt Fiber for Gamma Radiation Protection Properties. Nuclear & Radiation Safety, Vol. 1(77), P. 52 – 58, 2018

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R&D Project Award

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CHROMIUM DOPED UO2-BASED MODEL SYSTEMS: THE MODEL MATERIALS FOR THE STUDY OF THE MATRIX CORROSION OF MODERN SPENT NUCLEAR FUELS

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Abstract

The current efforts to improve fuel performance in nuclear power generation resulted in an increased utilization of a variety of new types of light-water reactor (LWR) fuels such as Cr-, Al-, and Si-doped fuels. The corrosion behavior of these types of fuels in the systems relevant to deep geological waste repository has hardly been studied so far. Experiments with spent nuclear fuel (SNF) cannot entirely unravel all of the various concurring dissolution mechanisms due to the chemical and structural complexity of spent nuclear fuel and its high beta- and gamma radiation field and technical restrictions allowing only for a very limited number of experiments. Therefore, within the EU-DISCO project (www.disco-h2020.eu) experiments on irradiated Cr-doped fuels are complemented with systematic dissolution studies carried out with carefully prepared and characterized, simplified UO2-based model materials. A bottom-up approach is followed to understand how the addition of Cr-oxide into the fuel matrix affects SNF dissolution behavior under repository relevant conditions.

Here, we present recent results on the development and optimization of the process steps for a wet-chemical route to produce pure reference UO_2, Cr-doped UO_2 as well as Cr- and alpha doped (^{238}Pu) pellets. A wet chemical route was favored due to the very low doping levels of ^{238}Pu required to mimic fuel ages between 1,000 and 10,000 a later in DISCO. Process optimisation was achieved by a systematic investigation of various process parameters such as calcination temperature and pelletisation pressure. Syntheses were performed by co-precipitation and wet-coating methods and had to be free of any grinding steps to be applicable in a dedicated glove box. In order to provide insights into the effects of the material's micro-structure on the dissolution behaviour (e.g. regarding the larger grain size in doped fuels and contributions of grain boundaries) the model materials are produced in form of sintered pellets. The microstructure (grain size, grain orientation) of and dopant distribution (i.e. either in solid solution within the UO_2 matrix or segregated on grain boundaries) in the model materials were characterised using various methods (e.g. SEM, EBSD, EMPA, ToF-SIMS, XRD).

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PhD Awards

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EFFECTS OF THE INITIAL GRANULAR STRUCTURE OF CLAY SEALING MATERIALS ON THEIR SWELLING PROPERTIES: EXPERIMENTS AND DEM SIMULATIONS

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Abstract: Pellet-based expansive clay materials are considered as a sealing material for closing the galleries in radioactive waste disposal concepts. In repository conditions, the granular mixture progressively homogenises upon hydration by the host rock pore water. The present study focuses on the material behaviour before homogenisation. A grain-scale experimental characterisation is first performed in the laboratory. A model describing the hydromechanical behaviour of a pellet is proposed based on the experimental results. Then, suction-controlled swelling pressure tests are performed in the laboratory. Using Discrete Element Method (DEM) and the model proposed for a single pellet, the tests are successfully simulated. It is highlighted that i) the swelling pressure evolves in two phases in the investigated suction range, controlled by the granular structure of the mixture; ii) wall effects at the laboratory scale affects the material response; iii) measurement variability associated to the sensor diameter is non-negligible; iv) DEM is a valuable tool able to provide insight into the material behaviour.

1. Introduction

Concepts of radioactive waste disposal vary between the different countries. A general feature of the repository concepts is the reliance on the multi-barrier principle [1], which for a HLW repository consists of: i) a canister containing waste, ii) a host rock, and iii) an engineered barrier system that also limits fluid flow in the repository.

Compacted expansive clay-based materials are candidate materials for engineered barriers in radioactive waste disposal concepts. These materials are characterised by a low permeability, good radionuclide retention capacity, and ability to swell upon hydration and thus filling technological voids and exerting a confining pressure on the excavation damaged zone.

Owing to operational convenience, pellet-based materials have been considered as an alternative to compacted blocks [2, 3, 4, 5]. Pellets are emplaced in the galleries as a granular material. The granular material undergoes hydration by the pore water of the host rock and progressively becomes homogeneous. Before homogenisation, the mechanical behaviour of the material is controlled by its granular nature. The influence of the initial granular structure on the macroscopic response of the material upon hydration needs to be characterised to better understand the engineered barrier evolution under repository conditions.

The present work focuses on the study of the influence of the granular structure on the macroscopic response upon hydration under constant-volume conditions. Suction-controlled swelling pressure tests are performed in the laboratory. These tests are simulated using the Discrete Element Method (DEM) to obtain insight into grain-scale phenomena. Finally, interesting results regarding the performance of swelling pressure tests in the laboratory and the DEM model results contributing to the characterisation of the influence of the granular structure are presented and discussed.

2. Material

2.1. Bentonite pellet

In the French concept of radioactive waste disposal [6], 32-mm subspherical MX80 bentonite pellets are envisaged as one element of the engineered barriers. In the present study, a smaller version of this pellet is used to perform laboratory tests. Pellets are composed of a central cylinder with two spherical ends (Figure 1). The initial properties of the pellet are presented in Table 1.

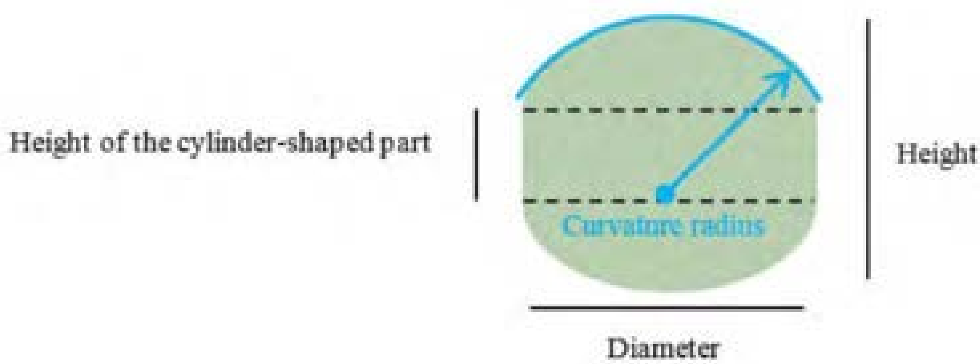

Figure 2: Geometry of the pellet.

Table 2: Initial properties of the pellet.

Properties at initial state	
Geometrical properties	
Diameter: mm	7
Height of the cylinder part: mm	5
Height: mm	7
Curvature radius: mm	6.5
Physical properties	
Suction: MPa	89
Water content: dimensionless	0.12
Dry density: Mg/m^3	1.91
Void ratio: dimensionless	0.45

2.2. Pellet assembly

Swelling pressure tests are performed for a pellet assembly. The average dry density of the granular material is 1.05 Mg/m^3. The pellet volume fraction (ratio of volume of pellet to total volume) is 0.553.

3. Work performed

3.1. Description of the hydromechanical behaviour of a pellet

A model describing the hydromechanical behaviour of a pellet is required to perform DEM simulations of pellet assemblies. The experimental characterisation of the pellet behaviour in the laboratory has been performed and is described in [7]. In the experimental study, the vapour equilibrium technique [8] is used to impose a suction to pellets. At equilibrium, the volumetric strain of the pellet is measured using a camera. Pellet Young modulus and strength are obtained through compression tests. Evolution of the pellet volumetric strain, Young modulus, and strength is measured upon suction decrease.

Assuming that i) the pellet macroporosity is negligible, ii) pellet behaviour remains elastic, iii) pellets are fully saturated and expand upon water uptake, and iv) pellet strength is proportional to pellet stiffness, the following equations are used to describe the pellet behaviour upon suction decrease:

$$E = \mathbf{3}(1 - \mathbf{2}\nu)\frac{\mathbf{1}}{\beta_m}\mathbf{exp}(\alpha_m\ s) \qquad \text{eq. 1}$$

$$\varepsilon_V = \frac{\beta_m}{\alpha_m} [\exp(\alpha_m \, s) - \exp(\alpha_m \, s_0)] \qquad \text{eq. 2}$$

$$R = C \, E \qquad \text{eq. 3}$$

where: E is the pellet Young modulus, ε_V is the pellet volumetric strain, R is the pellet strength, ν is the pellet Poisson ratio, s is the suction, s_0 is the initial suction, α_m, β_m and C are parameters.

Parameters used in the model for the 7-mm pellet are presented in Table 2. Figure 2 presents a comparison between model predictions and experimental results.

Table 3: Parameters of the model for the 7-mm pellet [7].

Parameters of the model	
α_m: MPa^{-1}	2.4 $\times 10^{-2}$
β_m: MPa^{-1}	1.6 $\times 10^{-2}$
C: m^2	1.206 $\times 10^{-7}$

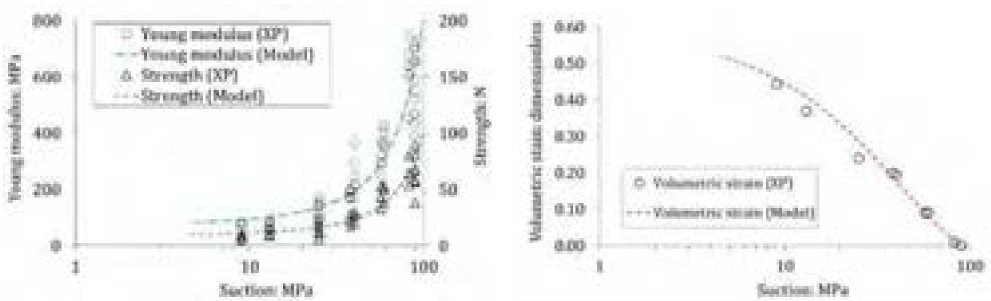

Figure 3: Experimental results and model predictions: left, pellet Young modulus and strength and right, pellet volumetric strain [7].

The model aims at describing the pellet behaviour upon partial hydration, before losing the granular structure. Experimental results in the literature suggest that, for MX80 bentonite, the model would no longer be valid for suction below ~3 to ~7 MPa [9]. The model assumptions are discussed in [7].

3.2. Vapour hydration of pellet assemblies under constant-volume conditions

Two swelling pressure tests are carried out and referred to as SP1 and SP2. Isochoric cylindrical cells are used to perform swelling pressure tests. Two porous disks are placed at the bottom and at the top of the cell. Humid air is allowed to directly flow from the bottom to the top of the cell through a side tube. The side tube prevents increase of air pressure and allows humid air to diffuse in the inter-pellet porosity. 209 pellets are placed in the cell to reach the target pellet volume fraction. Diagrams of the isochoric cell are presented in Figure 3. Dimensions of the cell are presented in Table 3.

Hydration is performed using the vapour equilibrium technique. Upon pellet hydration, owing to the constant-volume conditions, swelling pressure develops against the cell walls. This latter is measured by an axial pressure sensor. Suction considered in the study are: 82 MPa, 59 MPa, 40 MPa, 38 MPa, 25 MPa, 13 MPa, 9 MPa, and 4 MPa. A new suction step starts when equilibrium is reached at the current suction. Equilibrium is considered when swelling pressure remains constant for three days.

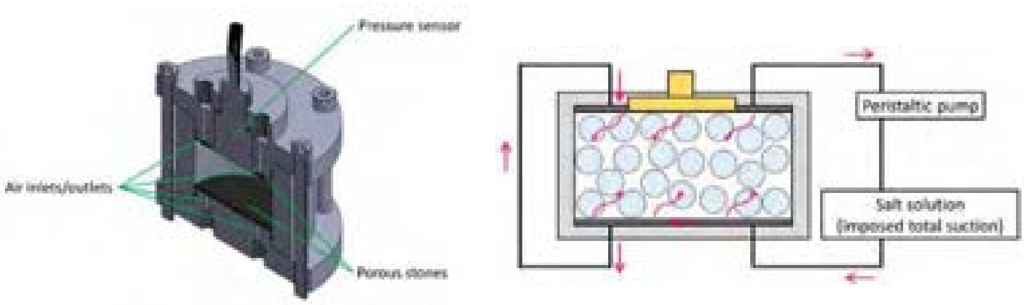

Figure 4: Diagram of the experimental apparatus used for swelling pressure tests: left, 3D view of the isochoric cell and right, sketch of the suction control system.

Table 4: Dimensions of the isochoric cell used for swelling pressure tests

Dimensions of the cell	
Height: mm	30
Diameter: mm	60
Sensor diameter: mm	30

3.3. DEM simulations of laboratory tests

In the DEM simulations, the pellet assembly is modelled as a sphere assembly. Each sphere behaves as a pellet, according to the model presented in 3.1. The sphere diameter is denoted by a. Its initial value, a_0, is chosen such that its volume and density are the same as for the real pellets. The cell is modelled as a cylinder of infinite Young modulus. The cylinder dimensions are the same as the cell used in the laboratory. Simulations consist of two steps: i) sample preparation and ii) pellet hydration.

During the simulations, the granular assembly is always under gravity. Interactions at contacts are described by normal and tangential reactions. Normal forces are elastic-perfectly plastic. Elastic limit is set to the pellet strength (eq. 3). Tangential reaction is described using a simplified form of the Cattaneo-Mindlin-Deresiewicz laws [10] and the Coulomb friction as in [11], denoting by μ the friction coefficient for all contacts. Damping in contacts is considered as in [11]. Elastic normal forces are calculated using Hertz's law as follows:

$$N = \frac{1}{3}\frac{E}{1-\nu^2}a^{\frac{1}{2}}\delta_N^{\frac{3}{2}}$$ eq. 4

or

$$N = \frac{2^{\frac{3}{2}}}{3}\frac{E}{1-\nu^2}a^{\frac{1}{2}}\delta_N^{\frac{3}{2}}$$ eq. 5

Eq. 4 is used for contacts between two pellets. Eq. 5 is used for contacts between a pellet and an infinitely stiff flat wall. In both expressions, N is the normal force and δ_N is the normal deflection (Figure 4).

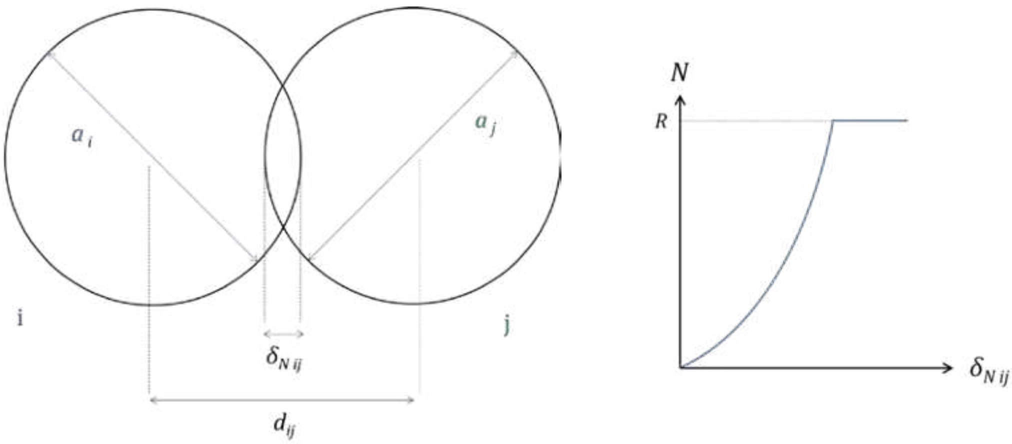

Figure 5: Left: contact between two pellets i and j of diameter a_i and a_j, distance between centres d_{ij}, and normal deflection $\delta_{N\,ij}$. Right: Evolution of normal force as a function of normal deflection.

Sample preparation is performed by placing 209 pellets in the cell. The first 20 pellets are placed at random positions at the bottom of the cell. Then, pellets are placed one by one at the lowest available elevation in the rigid cylinder each 1 second. When all pellets are placed, the elevation of the top of the cylinder is set at the elevation of the highest pellet, then progressively decreased to its target elevation. During preparation step, μ is set to 0 in the model to avoid high initial pressure to arise during the closure step. Following preparation, μ is set to 0.3. Hydration is modelled as an increase of the diameter of all pellets. Swelling pressure is calculated as the sum of normal forces on the area corresponding to the pressure sensor. The area corresponding to the pressure sensor can be set to the same area as in experiments, or a larger/smaller area to study the influence of this parameter.

At each calculation step (i.e. decrease of the elevation of the top wall or diameter increase) the granular assembly is considered at equilibrium in the model when both the ratio of the net force to the maximum normal force and the ratio of the net moment to the maximum moment are smaller than 10-4 for each pellet. The next step starts when this condition is fulfilled.

100 simulations are performed to assess the reproducibility of the results. Parameters used for the simulations are summarised in Table 4.

Table 5: Parameters used in the DEM simulations of swelling pressure tests

Parameters used in DEM simulations	
a_0: mm	7.53
Cell diameter: mm	60
Cell height: mm	30
Tolerance for equilibrium: dimensionless	10^{-4}
μ, preparation step: dimensionless	0
μ, hydration step: dimensionless	0.3

4. Results

4.1. Evolution of the swelling pressure upon suction decrease in the experiments

Both SP1 and SP2 tests displays comparable swelling pressure-suction relationships upon hydration. First, hydration is characterised by an increase of the measured swelling pressure. Then, a plateau/decrease of swelling pressure is measured.

Following the cell closure, the initial pressure in SP1 is 0.055 MPa. Upon hydration from initial state ($s = s_0 = 89$ MPa) to s = 40 MPa, swelling pressure increases from 0.055 MPa to 0.173 MPa. Then, the swelling pressure remains nearly constant until s = 25 MPa and decreases and reaches 0.128 MPa at s = 9 MPa.

Following the cell closure, the initial pressure in SP2 is 0.010 MPa. Upon hydration from initial state to s = 9 MPa, swelling pressure increases from 0.010 MPa to 0.153 MPa. Then, swelling pressure decreases and reaches 0.135 MPa at s = 4 MPa.

A picture of the samples is taken at s = 9 MPa (SP1) and s = 4 MPa (SP2). Both materials are still granular at these values of suction. Pellets and inter-pellet voids can be identified. The pellets still have the same shape as initially. Some pellets in contact with the top wall are irreversibly deformed at the contact area. It is not known if the deformation occurred during cell closure or as a result of the hydration and subsequent swelling of the pellets (Figure 5).

The evolution of swelling pressure upon suction decrease in SP1 and SP2 is presented in Figure 6.

Figure 6: Pictures of samples following hydration: left, SP1 and right, SP2.

4.2. Evolution of the swelling pressure upon suction decrease in the simulations

The DEM results are presented for an identical sensor diameter in the simulations as in the experiments. The mean value of swelling pressure (for 100 calculated samples) evolves in two phases upon hydration.

Following the cell closure, the initial pressure in the DEM simulations is negligible. Upon hydration from initial state to s = 60 MPa, the swelling pressure increases to 0.330 MPa. Then, the swelling pressure decreases and reaches 0.110 MPa at s = 4 MPa.

The simulation results are presented in Figure 6 along with SP1 and SP2 measurements. Variability of the apparent swelling pressure is determined by calculating the standard deviation for the 100 simulations. In Figure 6, a two-standard-deviation interval is plotted to highlight the result variability. Variability of simulation results is discussed in the following section.

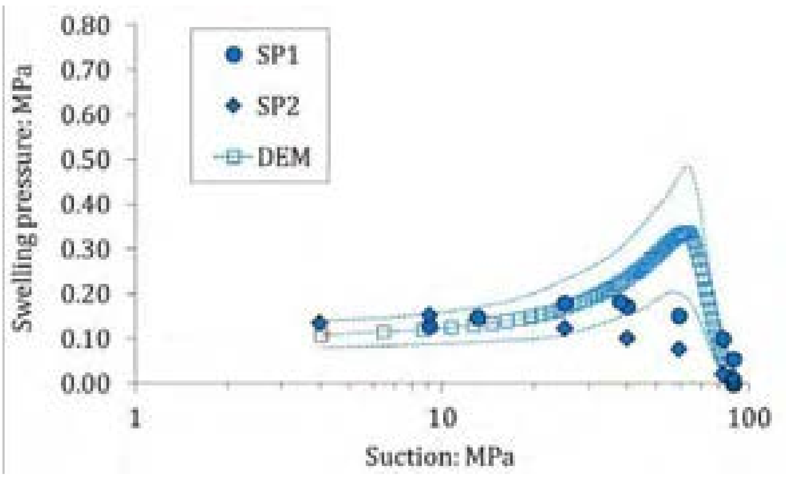

Figure 7: Comparison of experimental and numerical evolution of swelling pressure upon suction decrease. Dashed lines represent a two-standard-deviation interval of numerical simulation results.

4.3. Evolution of the pellet-scale features in the simulations

The evolution of the proportion of plastic contacts in the simulated samples, x_{plas}, is calculated upon suction decrease (mean value for the 100 samples). Following the cell closure, x_{plas} is zero. Upon hydration from s = 89 MPa to s = 70 MPa, the swelling pressure increases still with a constant $x_{plas} = 0$. Between s = 70 MPa and s = 60 MPa, x_{plas} sharply increases. This suction range corresponds to the peak swelling pressure. Then, swelling pressure keeps decreasing while x_{plas} keeps increasing (Figure 7).

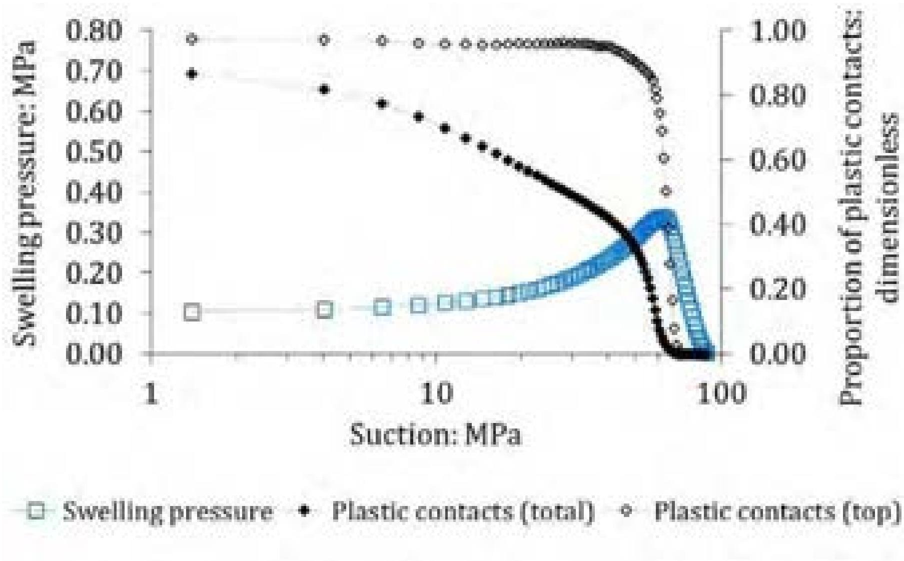

Figure 8: Evolution of the proportion of plastic contacts and swelling pressure upon suction decrease in in the simulated samples.

Notable differences are obtained between x_{plas} and $x_{plas\ sup}$, the proportion of plastic contacts among contact between pellets and with the top wall of the cell. Between s = 70 MPa and s = 60 MPa, $x_{plas\ sup}$ increases from $x_{plas\ sup} = 0$ to $x_{plas\ sup} = \sim 0.80$ (Figure 7).

The mean value (for the 100 samples) of the increment of elastic normal deflection in the contacts between the pellets and the top wall, where swelling pressure is measured, as a function of the imposed increment of pellet radius (i.e. a/2) is presented in Figure 8. The two values are almost identical until the peak value is reached, as highlighted in Figure 8 by plotting a "y = x" line.

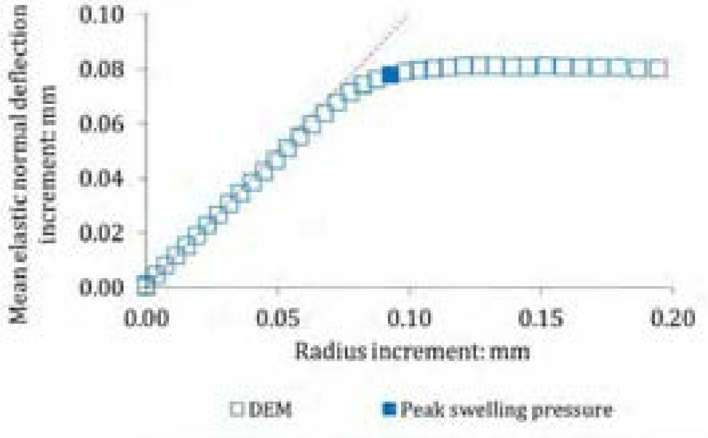

Figure 9: Calculated increment of the mean elastic deflection in the contacts between the pellets and the top wall, as a function of the imposed increment of pellet radius. The dashed line represents the "y = x" line.

4.4. Influence of the sensor size on the apparent macroscopic response

Depending on the position of pellet-top wall contacts, the simulation results can be characterised by different calculated swelling pressure depending on the chosen sensor diameter. The influence of the sensor size on the variability of the measured swelling pressure is determined by considering different values of the sensor diameter. The mean value for the 100 simulations is found to be close for all sensor diameters. The coefficient of variation is defined as the ratio of the standard deviation to the mean value. Figure 9 presents the value of the coefficient of variation for the swelling pressure at peak value and at s = 9 MPa, for different values of the sensor diameter, for the 100 simulated samples.

Figure 9 highlights that i) variability significantly increases for diameter ratios smaller than 4, ii) variability is lower at low suction than at peak and iii) even at diameter ratio of 6 the coefficient of variation is non-negligible (~0.10).

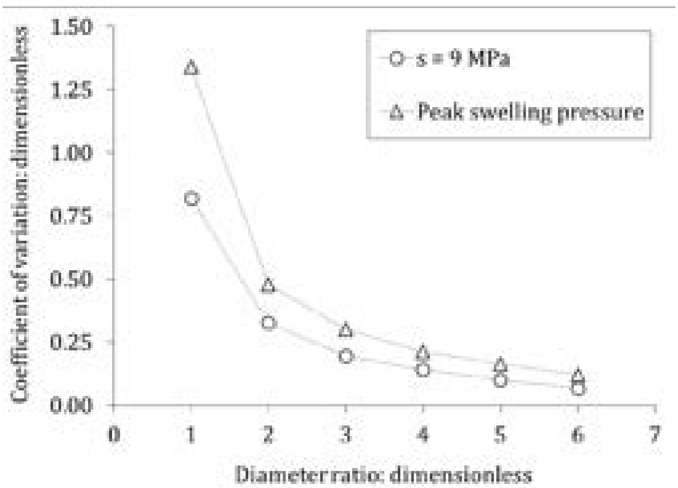

Figure 10: Calculated coefficient of variation of the swelling pressure as a function of the ratio of pressure sensor diameter to initial pellet diameter.

5. Discussion

5.1. Validity of the DEM modelling approach

The validity of the DEM approach depends mainly upon the following assumptions: i) the material remains granular, and ii) contact laws used are adequate to describe interactions between pellets.

Sample dismantling allowed the material to be observed. It is highlighted in Figure 5 that the pellet assembly remained granular at suctions as low as 4 MPa. Pellets are still subspherical. Modelling the pellet assembly as a sphere assembly is considered appropriate within the investigated suction range.

The contact laws used in the present study assume that the pellets are characterised by an elastic-perfectly plastic behaviour. Experimental results [7] suggest that pellet behaviour is not fully reversible before reaching pellet strength. However, the same contact law is used in [7] to satisfactorily reproduce the force-displacement relationship in compression tests. Irreversible deformations observed in Figure 5 suggest that using plasticity is an adequate approach compared to grain crushing to account for pellet strength.

The model is able to reproduce the two phases of evolution of the swelling pressure. The peak swelling pressure is overestimated by the model. It is considered to be a consequence of modelling the pellets by equivalent beads of exactly the same stiffness and strength. As highlighted in Figure 2, the pellet properties are characterised by a non-negligible variability at high suction. Accounting for these variations in the model would decrease the peak swelling pressure and apparent stiffness before the peak since i) the pellet Young modulus could be characterised by significantly lower values at high suction, and ii) x_{plas} would start to increase at higher suction.

Upon hydration at lower suction, it is expected that the material will undergo microstructural rearrangement [9]. Owing to the material dry density, a final swelling pressure of ~0.25 MPa can be estimated [12]. The model can neither handle the microstructural rearrangement nor the second increase of swelling pressure. It is considered that it is no longer valid at suction lower than ~3 MPa, as for the model for a single pellet.

5.2.Influence of the initial granular structure

In pellet materials, interaction at contacts have been suggested to control the material response upon suction decrease [5], [13]. Experimental results highlight that the material remains granular at low suction, with dry inter-pellet porosity. DEM simulations provide insight into grain-scale phenomena. Comparison of experimental and numerical simulation results suggests that the swelling pressure of bentonite pellet materials evolves in two phases upon suction decrease, which are controlled by the interaction at the contacts. At high suction, swelling pressure increases as a result of pellet swelling. This phase is mainly controlled by the pellet stiffness. As contact forces between pellets start to reach the pellet strength, swelling pressure reaches a plateau/decreases upon suction decrease. This phase is characterised by irreversible deformation at contacts and is mainly controlled by the decrease of pellet strength and stiffness upon suction decrease.

5.3. Influence of the cell walls

In a true representative elementary volume, the variability of the results would be negligible. In the present work, simulation results highlight that, even with a ratio of pressure sensor diameter to pellet diameter of 6 (i.e. sensor diameter of 45 mm, for a cell diameter of 60 mm), the coefficient of variation of swelling pressure is non-negligible.

It is also evidenced that each increment of pellet radius is associated to an equivalent increment of deflection in contacts between pellets and the top wall. This is possible if no rearrangement of the granular assembly occurs. Owing to the low volume fraction of the granular assembly, this is considered as a consequence of wall effect due to the small size of the cell.

Influence of the wall is also highlighted by comparing the evolution of x_{plas} and $x_{plas\ sup}$. The absence of particle rearrangement induces a faster increase of $x_{plas\ sup}$, because contact stiffness is higher in pellet-wall contacts (eq. 4 and eq. 5). In this respect, the measured post-peak swelling pressure in small size cells can be overestimated [14].

It is thus recommended to either use larger cells to perform swelling pressure tests, or carefully interpret and compare experiments performed at laboratory scale using comparable cell size to pellet size ratios.

5.4. Measurement of swelling pressure

In addition to the variability associated to the small size of the cell, simulation results highlight that significant measurement variation can be obtained for small pressure sensors. DEM allowed this variability to be quantified. It is suggested that the results of laboratory-scale swelling pressure tests performed on pellet materials should be interpreted even more carefully if the ratio of sensor diameter to pellet diameter is low.

6. Conclusion

The present work addressed the hydromechanical behaviour of bentonite pellet materials upon partial hydration, in a suction range which allows the behaviour of the material to be controlled by its granular structure.

From grain-scale experimental characterisation in the laboratory, a DEM modelling approach was presented. Using DEM, suction-controlled swelling pressure tests performed in the laboratory on pellet materials were successfully simulated.

It was highlighted that, upon suction decrease from 89 MPa to ~3 MPa, the swelling pressure evolves in two phases: i) an increase of swelling pressure, controlled by pellet stiffness, and ii) a decrease of swelling pressure, characterised by irreversible deformation at contacts, controlled by the decrease of pellet strength and stiffness.

Numerical simulation results evidenced that the behaviour of pellet material in swelling pressure tests performed at laboratory scale are influenced by the small size of the cell. In addition, variability of the apparent swelling pressure associated to the sensor size was quantified and shown to be non-negligible.

References

[1] Sellin, P., & Leupin, O. X. 2014. Clays Clay Miner., 61(6), 477–498.

[2] Volckaert, G., Bernier, F., Alonso, E.E., Gens, A., Samper, J., Villar, M.V., Martín, P.L., Cuevas, J., Campos, R., Thomas, H.R., Imbert, C., & Zingarelli, V. 1996. EUR 16744. Commission of the European Communities, Luxembourg.

[3] van Geet, M., Volckaert, G., & Roels, S. 2005. Appl. Clay Sci., 29(2), 73–87.

[4] Imbert, C., & Villar, M.V. 2006. Appl. Clay Sci., 32(3–4), 197–209.

[5] Hoffmann, C., Alonso, E.E., & Romero, E. 2007. Phys. Chem. Earth., 32(8–14), 832–849.

[6] Andra (2005). Evaluation of the feasibility of a geological repository in an argillaceous formation. Andra, Chatenay-Malabry, France.

[7] Darde, B., Tang, A.M., Pereira, J.M., Roux, J.N., Dangla, P., Talandier, J., and Vu, M. N. 2018. Géotech. Lett., 8(4): 330–335.

[8] Tang, A.M., & Cui, Y.J. 2005. Can. Geotech. J., 42(1), 287-296.

[9] Saiyouri, N., Tessier, D., & Hicher, P.Y. 2004. Clay Miner., 39(4), 469–479

[10] Johnson, K.L. 1985. Contact Mechanics. Cambridge, UK: Cambridge University Press.

[11] Agnolin, I., & Roux, J.N. 2007. Phys. Rev. E: Stat. Nonlinear Soft Matter Phys., 76(6), 1–27.

[12] Wang, Q., Tang, A.M., Cui, Y. J., Delage, P., & Gatmiri, B. 2012. Eng. Geol., 124(1), 59–66.

[13] Alonso, E.E., Hoffmann, C., & Romero, E. 2010. J. Rock Mech. Geotech. Eng., 2(1), 12–31.

[14] Darde, B., Roux, J.N., Dangla, P., Pereira, J.M., Tang, A.M., Talandier, J., & Vu, M.N. 2020. In CIGOS 2019, Innovation for Sustainable Infrastructure (pp. 871-876). Springer, Singapore.

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ANALYSIS OF REDUCTION OF THE DETECTION LIMIT FOR THE BETA DETECTOR USED IN DIRECT METHOD OF SPECIFIC ^{14}C ACTIVITY DETERMINATION

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Abstract: In this research improvement of the detection system used in a direct analysis method for the ^{14}C massic activity determination in small graphite samples of the 1-100 µg range is analysed. The method is based on the graphite combustion and subsequent CO_2 and ^{14}C measurements by using the commercial elemental analyzer and the semiconductor detector, without sample weighing. The detection procedure for small (1-100 µg) samples containing >14 Bq ^{14}C activity takes approximately 10 minutes. The reduction of the background by coincidence event detection in the system of semiconductor detectors would allow reduction of the detection limit and enables measurement of the samples below 14 Bq of activity. The MCNP modelling of the main background components: muons, electrons and Compton gammas was performed and a scheme of detection upgrade was analysed. The estimated efficiency of the semiconductor detector system is about 15%, and is in an acceptable range (10-20%) for radioactive waste characterization purposes. Graphite activity measurements using LSC method and the semiconductor detectors were performed for comparison. Linear approximation function between the two methods was determined and serves as the ^{14}C activity calibration curve. The proposed direct analysis method could be implemented for direct radioactive waste characterization using the scaling factor method.

Introduction

Nuclear graphite waste management strategy during decommissioning of Ignalina NPP is the pending decision in Lithuania. In the RBMK type reactor, graphite is a neutron moderator and reflector. The total mass of radioactive graphite from the both Ignalina NPP units is up to 3,800 t. Worldwide there is about 250,000 t of reactor graphite (~50,000 t in France, 80,000 t in UK) from AGR, MAGNOX, RBMK, UNGP, plutonium production reactors, etc. This nuclear material is foreseen also in GEN-IV nuclear reactors: PBMR and VHTR as well as in Molten Salt reactors for transmutation and others.^{14}C is the limiting radionuclide for long-term disposal of irradiated graphite due to its half-life of 5730 years and relatively high activity, as well as mobility in geological media in the RBMK reactor. ^{14}C is generated in the graphite moderator-reactor due to the neutron capture by $^{13}C(n, \gamma)^{14}C$ in the graphite matrix or by the neutron activation of ^{14}N and ^{17}O impurities. The main contributor to ^{14}C generation is $^{14}N(n, p)^{14}C$ reaction due to high neutron reaction cross section and because of ^{14}N abundance in the helium-nitrogen mixture used to flush the graphite stack in the core [1, 2, 3]. Characterization of irradiated graphite in terms of ^{14}C activity is crucial for the optimization of treatment technology (e.g. geological disposal, landfill storage, recycling, etc.) [4]. The most sensitive technology to measure low energy β particles radiation is liquid scintillation counting [5]. The 1σ uncertainty of radiocarbon activity determination was around 6%. However, it takes a lot of time to prepare and measure β active samples using this method. Recently we proposed the novel express analysis method for specific ^{14}C activity determination in small graphite samples which can be used for radiological characterization of radioactive waste. The method applies an oxidation procedure to remove the ^{14}C (as CO_2) from the different carbonaceous matrices in a controlled manner [6], with on-line detection of the ^{14}C present in the off-gas. The method could be used to measure higher than 14 Bq ^{14}C activity samples (as it is common in nuclear industry), but also it is important to be able to measure lower ^{14}C activity in small samples.

The aim of this work was to analyse the possible improvements of detection system used in direct analysis method by using semiconductor detectors for the massic ^{14}C activity determination in small samples. The reduction of the background by eliminating coincidence events in the system of semiconductor detectors could allow the reduction of the detection limit and enable measurement of lower activity samples. It has to be noted that the proposed method is specifically useful for rapid rapid mass activity determination of ^{14}C of small samples (less than 100 μg) making it potentially applicable also in other fields such as biomedicine.

The limit of detection (LOD) by semiconductor silicon planar PIPS is of the order of 14 Bq for ^{14}C active samples. Theoretical estimation of LOD is determined with competition between the net counts coming from ^{14}C (in CO_2) and the background composed mainly from muons, electrons and Compton gammas (from construction materials). The MCNP modelling of the main background components was performed in order to understand which part of background could be suppressed.

The detector efficiency could not be improved as it is determined by the detector geometry (less than the ideal 2π geometry), but the net counts of ^{14}C could be measured during the longer period. In such case, if effective background discrimination is applied the LOD can be lowered.

This method can be applied for the rapid online radiological characterization of irradiated graphite during dismantling of reactor graphite constructions and sorting of graphite waste, as well as for measuring ^{14}C concentration in other (e.g. bioorganic) materials and background suppression could even extend the limits of its applicability.

2. Methodology

2.1. Experimental equipment and analysis methods

The analysed graphite samples are from the Ignalina NPP RBMK-1500 reactor central and peripheral zones. We have investigated small, cylindrical graphite samples from Ignalina NPP to determine the distribution and concentration of ^{14}C. Prior to combustion, the mass of each graphite sample was determined using the XP105 (Mettler-Toledo, Switzerland) dual range balance. The amount of carbon in the CO_2 form evolved during combustion process was estimated using TCD from an elemental analyser.

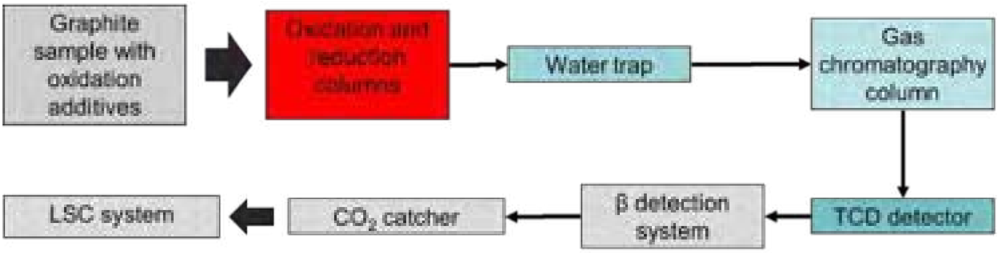

Fig 1. Direct system for the ^{14}C specific activity determination in the sample

Experimental setup used in this research is shown in Fig 1. It consists of a commercial elemental analyser, in which a graphite sample is combusted and the mass of carbon in the sample is determined, and the semiconductor β detection system for the online ^{14}C determination. The semiconductor β particle detection system consists of a chamber and 2 semiconductor detectors. Additionally, gas catchers and the liquid scintillation counting system were used for the semiconductor system accuracy evaluation.

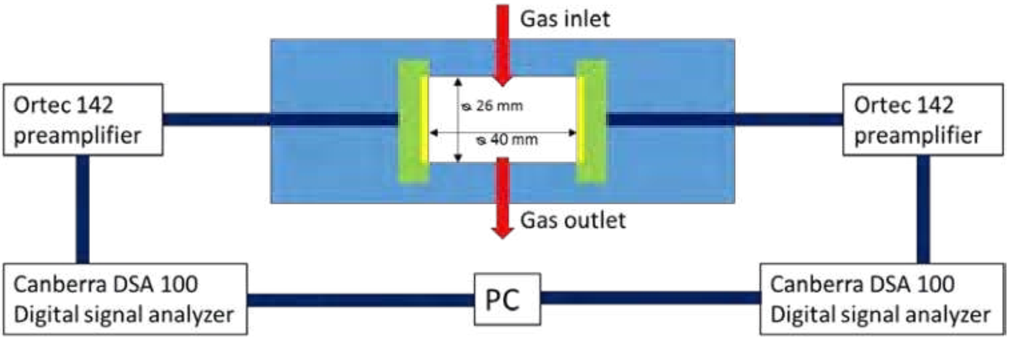

Fig 2. β particle registration system in CO_2 gas flow with semiconductor detectors

For the β particle registration in CO_2 gas flow the silicon planar PIPS (Passivated Implanted Planar Silicon, Canberra, USA) detectors were used. The detecting system was located between the sample combustion system (elemental analyser) and the CO_2 alkali condenser, as shown in Fig 1. The detector of this type was chosen because of a wide operating temperature range, it can also work in harsh and ambient light environments and it has a higher efficiency compared with other types of semiconductor detectors [7].

During the measurement process, gas from the sample combustion system passes through the detection chamber, where the gas activity is registered. Pulses from each of the detectors were amplified and registered (see Fig 2).The bias voltage for each detector was set to 70 V, the amplifier gain was set to 100 and the pulse shape time – 2 µs. In order to avoid counter saturation with electronic noise pulses DSA low level discriminator (LLD) was set up to 13 channel (20mV equivalent). Spectra were measured using 100 second steps and each spectrum was integrated to find out the sum of pulses per step. ^{14}C activity was measured using 5 steps per combustion cycle. During the first 3 steps only the background spectra were collected, while during step four CO2 gas flow was observed and decay particles were registered. The gas flow delay in the detection chamber appears due to the volume being much larger than that of gas tubes. Each combustion cycle does not influence the next one because all CO2 gas is flushed away from the chamber during the combustion cycle of 500 seconds. Condensation of the material is minimised as the temperature differences between gas in the chamber and the chamber walls are controlled.

After the graphite combustion and ^{14}C measurement in β detectors chamber, CO_2 gas was passed through the NaOH 3M solution placed in two catchers connected serially to check the on-line measurement versus classical ^{14}C measurement by LSC. It was known from previous experiments that the combination of two catchers ensured the 94% trapping (recovery) efficiency for radiocarbon in the $^{14}CO_2$ form [8]. The exposed solutions were mixed with a liquid scintillation cocktail OptiPhase HiSafe 3 (PerkinElmer, USA) applying the mixing ratio of 4 ml and 16 ml, respectively and were measured with a liquid scintillation counter Quantulus-1220 (PerkinElmer, USA). LSC measurements were traceable to the national standard of activity [9]. The obtained LSC spectra confirmed the presence of pure ^{14}C β activity in the samples showing no other radionuclides in the exposed NaOH 3M solution. The radiocarbon activity in a graphite sample was calculated taking into account activities determined in catchers, the counting efficiency, the recovery efficiency and the aliquot volume. The 1σ uncertainty of the radiocarbon activity determination by LSC was 6%. The estimated efficiency of the semiconductor detectors system is ~15. In order to lower the limit of detection (LOD) for semiconductor silicon planar PIPS detector additional scheme have to be introduced.

2.2. MCNP modelling of the background in beta detection system

MCNP6 was used for efficiency determination as well as for the background in beta detection system analysis. The active thickness of the detector is 300 μm at the depletion voltage of 70 V, and the active area is 450 mm^2. The detection chamber diameter is d = 26 mm, the height h = 40 mm, volume V = 21.2 cm^3. The evaluation of the ^{14}C β particle detection efficiency was performed by using Monte Carlo (MCNP6) simulation [10]. The estimated efficiency of system with both detectors is 15 %. This low efficiency is due to the less than the ideal 2π geometry; the prolonged chamber allows a larger measurement volume.

The detection limit of the system can be computed using:

$$p = K * \sqrt{\rho_0 * \left(\frac{1}{t_0} + \frac{1}{t_m}\right) + \frac{1}{4} * K^2 * \left(\frac{1}{t_0} + \frac{1}{t_m}\right)} \qquad (1)$$

K – Statistical certainty (Σ), ρ_0 – background (cps), t_0 – background measurement time (s), t_0 – measurement time (s).

The MCNP modelling of the main background components: muons, electrons and Compton gammas were performed utilizing spontaneous fission of Radium-226 in the water tank. Coincidence events of two semiconductor detectors were modelled using MCNP pulse-height tally PHL function. Response functions for separate detectors were also calculated.

2.3. MCNP6 modelling results

In this work theoretical analysis of possible improvements of the detection system used in direct analysis for the ^{14}C activity determination was performed by using MCNP6. This was done in order to understand which part of background could be suppressed and how much LOD could be reduced by eliminating coincidence events registered in the system. The procedure of background and count registration in ^{14}C activity measurements by using semiconductor detectors is explaned. Also the results of ^{14}C activity measurements in INPP graphite by using semiconductor detectors and LSC are presented in order to understand the ^{14}C activity typical in nuclear graphite samples and also to determine the correlation between LSC and semiconductor detector measurements.

Simulation showed that using anti-coincidence background reduction will decrease background noise by 30% for common gamma backgrounds. Fig3. shows the probability of detecting electrons from natural background gamma rays using the described detection system. From Fig 3. it could be seen that using anti-coincidence a part of counts which are registered by both detectors (related to background gamma rays Compton scattering or cosmic ray muons) could be omitted, because of coincident counts could not be produced after 14C beta decay.

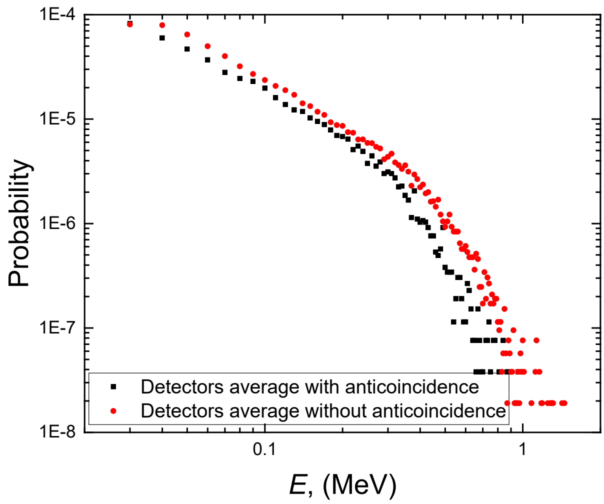

Fig 3. MCNP modelling results of the of the background registration in the beta detection system

2.4. ^{14}C activity measurements in graphite by using semiconductor detectors

19 small (<100 µg), cylindrical graphite samples from the Ignalina NPP RBMK-1500 reactor have been investigated. The samples were collected from different locations within the core – from the central and peripheral zone. The same samples were divided into several parts for ^{14}C distribution analysis. ^{14}C activity in released CO_2 gas was measured online with the convenient semiconductor detector and later by the LSC method.

The carbon mass in the sample was measured simultaneously with an elemental analyser after the graphite combustion process. Using the proposed configuration we are able to determine the ^{14}C specific activity of the graphite samples which contained less than 1 μg of carbon – it is of particular importance taking into account high activities of the radioactive waste generated by the nuclear reactor.

2.5. Background registration procedure

The background was measured using CO_2 from combusted natural flour. 130 measuring steps (100 seconds each) were used as a background evaluation dataset. The background is stable, as shown in Fig. 4. The first 300 s (first 3 steps) of radioactive sample measurements were also determined as background because of no CO_2 in nitrogen flow from the combustion chamber. From Fig. 4 it could be seen that median and mean are similar, the median is equal to 0.18 and mean – 0.182. The mean of counts per second values was used as the background and it was subtracted from radioactive gas measurements.

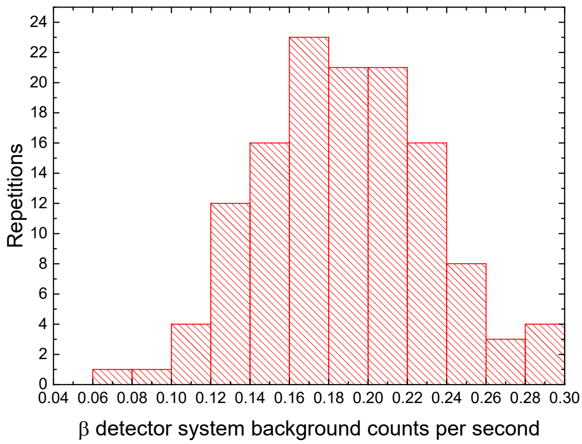

Fig 4. Histogram of background counts per second spectra measured in 100 s periods. Mean – 0.182, standard deviation - 0.04, median – 0.18.

2.6. Counts registration procedure

For online ^{14}C activity measurements, the detector chamber with two Si detectors were located between the sample combustion system and CO_2 alkali catchers (for cross-check measurements). Additionally, LSC measurements were carried out after the completed sample combustion and CO_2 collection by trapping in NaOH solution. Additional subsequent combustion cycles with the same timing were used to completely combust the graphite so that the TCD would not show the CO_2 flow and the β-detection system detected no significant changes between measured and background spectra. Combined first combustion cycle spectra of TCD and the β-detection system are shown in Fig 5. This type of distribution is seen in all the samples and it is due to the strong decrease in the fraction of CO_2 gas in the later cycles. For better visualisation of activity 50 seconds steps were chosen for this graph.

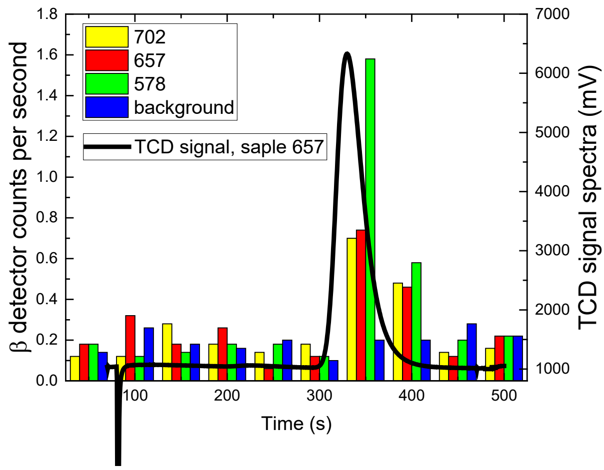

Fig 5. TCD signal from CO_2 flow and β detector measured counts per second spectra obtained per one combustion. Columns represent measured CPS per 50 seconds period.

3. Results

3.1. Comparison of activity measurements using both LSC and semiconductor beta detection system

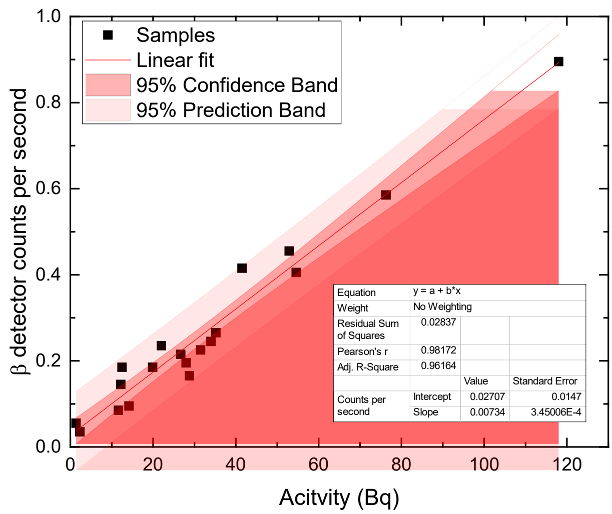

Fig 6. LSC and semiconductor detectors data. x axis represents LSC measurement data of ^{14}C activity and y axis represents semiconductor β detector pulse count per second obtained per first combustion cycle in the period between 300 and 400 s (β-counts collection time – 100 s). Obtained coefficient of correlation is 0.96.

Fig. 6 represents the correlation between LSC and semiconductor detector measurements. The linear dependence is observed for measurements of both methods. Data of the semiconductor detector counts were taken only from the first combustion cycle within 300 and 400 seconds (4^{th} step). Considering data from Fig. 5, it could be assumed that most of the radioactive nuclides flowed through the system in the period between 300 and 400 seconds. However, the confidence band of the linear approximation function shows that uncertainty of the correlation of the 14C activity determination between two methods is in the range of 10-20%. This is a reasonable range for radioactive waste characterization purposes.

The linear approximation function between the activity measured by LSC and with semiconductor detectors presented in Fig. 6 could serve as the ^{14}C activity calibration curve and could be used for the direct ^{14}C activity determination in routine measurements. By using the β-detector setup with two silica detectors, the ^{14}C activity in samples containing more than 14 Bq of ^{14}C can be determined in less than ten minutes. By comparison, the more complicated and time consuming LSC method requiring sample preparation takes much longer (up to 5 hours). The limitation of 14 Bq derives from the measured background data. As mentioned before, from statistical background data analysis we get background mean equal to 0.19 and standard deviation SD – 0.04. The statistically reliable activity of the detection could be described by value of 3 SD, which is 0.12 counts second. 0.12 counts per second correspond to the gas activity equal to 13.3 Bq as could be seen from Fig 6.

4. Discussion

According to the existing radiological classification the irradiated graphite waste is attributed to the long-lived low and intermediate activity radioactive waste [11]. ^{14}C is generated by neutron activation predominantly by $^{13}C(n, \gamma)^{14}C$, $^{14}N(n, p)^{14}C$ reactions. As ^{14}C is dominating in activity of the radioactive graphite waste (about 40% for the first 30 years and almost all the activity for the rest of the time), it is important to measure the specific activity of this β nuclide in the irradiated graphite from the nuclear power plant during the dismantling of the reactor using less costly and time consuming experimental means.

Our proposed rapid analysis method for the ^{14}C specific activity determination could be successfully used for graphite waste characterization. In this work 19 small (< 100 μg), cylindrical graphite samples from the Ignalina NPP have been investigated. ^{14}C activity in released CO_2 gas was measured online with the convenient semiconductor detector and later by the LSC method.

The experiments showed that the proposed method could be applied as the online measurement system of the ^{14}C activity determination. By using the elemental analyser and the detector chamber with two semiconductor detectors the ^{14}C specific activity in the samples containing more than 14 Bq of ^{14}C was determined in less than 10 min. This may be compared to the more complicated and time consuming LSC method which is, though, sufficiently accurate for the same activity level (the statistical uncertainty of 1% is achievable within 12 min. of counting the samples), however sample preparation takes much longer (up to 5 hours) [12].

Good correlation between results of the semiconductor detector and LSC was obtained in the range of 1.5 - 118 Bq. Semiconductor detectors can be used for the direct ^{14}C activity determination with standard uncertainty of 15 %, while if higher accuracy of ^{14}C

measurement is needed, the LSC method should be used additionally, as the latter is a well-established and widely used method for the ^{14}C activity determination.

However, due to the detection limit of semiconductor detection systems the samples with lower activity could not be measured without additional background suppression. Theoretical analysis of the main background components: muons, electrons and Compton gammas was performed by using Monte Carlo simulation. The modelling has shown that applied effective background discrimination can decrease LOD by 30% without changing the detectors geometry.

The improved ^{14}C activity determination method with reduction of the detection limit could be successfully used in biomedical applications, where the ^{14}C specific activity needs to be analysed in small bioorganic samples. Additional calibration and measurement time adjustments needed for best bioorganic samples combustion. While a ^{14}C measurement itself can be performed with any detection system, determination of the carbon content for the ^{14}C specific activity evaluation in the sample can be problematic due to the presence of additional substances. In our proposed concept, the mass is determined without the sample preparation, while the ^{14}C specific activity in the sample is measured online calibrated by the LSC method. Using the online configuration the specific activity of the bioorganic sample can be assessed in less than 10 min, which makes it favourable for biomedical applications.

References

1. Ancius D, Ridikas D, Remeikis V, Plukis A, Plukiene R, Cometto M. Evaluation of the activity of irradiated graphite in the Ignalina Nuclear Power Plant RBMK-1500 reactor. Nukleonika. 2005;50(3):113-20.
2. Narkunas E, Smaizys A, Poskas P, Kilda R. Assessment of different mechanisms of C-14 production in irradiated graphite of RBMK-1500 reactors. Kerntechnik. 2010;75(4):185-94.
3. Plukienė R, Plukis A, Barkauskas V, Gudelis A, Gvozdaitė R, Duškesas G, et al. Actinides in irradiated graphite of RBMK-1500 reactor. Nucl Eng Des. 2014;277:95-105.
4. Remeikis V, Plukis A, Juodis L, Gudelis A, Lukauskas D, Druteikienė R, et al. Study of the nuclide inventory of operational radioactive waste for the RBMK-1500 reactor. Nucl Eng Des. 2009;239(4):813-8.
5. Hou X. Direct analysis of 14C and 3H in graphite and concrete for decommissioning of nuclear reactor. Applied Radiation and Isotopes. 2005;62(6):871-82.
6. Remeikis V., Lagzdina E., Garbaras A., Gudelis A., Garankin J., Plukienė R., Juodis L., Duškesas G., Lingis D., Abdulajev V. and Plukis A. (2018) Rapid Analysis Method for the Determination of 14C Specific Activity in Irradiated Graphite, PLOSONE, p. 1-16.
7. Batten JR. Evaluation of passivated ion implanted planar silicon detectors for the spectroscopy and assay of low energy electrons. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. 1989;277(2-3):478-84.
8. Gudelis A, Gvozdaitė R, Lukoševičius Š. On determination of radiocarbon leakage from a shallow-land radioactive waste repository. LSC. 2008:415-20.
9. Cassette P, Butkus P, Gudelis A, Shilnikova T. 3 H activity comparison between FTMC, VNIIM and LNE-LNHB. Applied Radiation and Isotopes. 2016;109:41-3.
10. Goorley T, James M, Booth T, Brown F, Bull J, Cox L, et al. Initial MCNP6 release overview. Nuclear Technology. 2012;180(3):298-315.

11. Lukauskas D, Plukiene R, Plukis A. Method to determine the nuclide inventory of low-activity waste of the RBMK-1500 reactor. Lithuanian Journal of Physics (2000). 2006;46(4):497-503.
12. Broda R, Pochwalski K, Radoszewski T. Calculation of liquid-scintillation detector efficiency. International Journal of Radiation Applications and Instrumentation Part A Applied Radiation and Isotopes. 1988;39(2):159-64.

ENEN PhD Event and Prize

FISA 2019
EURADWASTE '19

4-7 June, 2019
Pitesti, Romania

Pedro DIEGUEZ PORRAS
European Nuclear Education Network, Brussels, Belgium

Main outcomes of 13th ENEN PhD Event & Prize 2019

The 13th ENEN PhD Prize & Event took place in the framework of the FISA EURADWASTE Conference in Pitesti, Romania, on 5 June 2019. After one full day of presentations, questions and answers, the jury decided that the 3 Winners of the ENEN PhD Event & Prize 2019 were:

- *Claire Le Gall*, "Contribution to the study of fission products release from irradiated nuclear fuels under severe accident conditions: effect of oxygen partial pressure on the speciation of Cs, Mo and Ba"
- *Wael Hilali,* "Debris Bed Formation in Degraded Cores of Light Water Reactors"
- *Florian Muller,* "Hydraulic and statistical study of metastable phenomena in PWR rod bundles"

Main outcomes

The three winners were selected from the finalists according to the evaluation of the Jury based on their presentations and the work delivered within the application and at the conference. They were awarded grants to attend an international conference with a support from ENEN up to 1000 Euro (conference fee, travel, accommodation and expenses - upon receipt of justification documents) and hereby encouraged to present the result of his/her research work.

The following finalists were selected, among all applications received, and invited to present their research work at the event:

- *Erik Branger*, "Enhanced verification of irradiated nuclear fuel using Cherenkov light"
- *Wael Hilali,* "Debris Bed Formation in Degraded Cores of Light Water Reactors"
- *Elke Jacops,* "Development and application of an innovative method for studying the diffusion of dissolved gases in porous saturated media"
- *Claire Le Gall*, "Contribution to the study of fission products release from irradiated nuclear fuels under Severe accident conditions: effect of oxygen partial pressure on the speciation of Cs, Mo and Ba"
- *Florian Muller,* "Hydraulic and statistical study of metastable phenomena in PWR rod bundles"
- *Pablo Romojaro Otero*, "Nuclear Data Analyses for Improving the Safety of Advanced Lead-cooled Reactors"
- *Alberto Tosolin,* "Experimental investigation and modelling of thermo-chemical and thermo-physical properties of fluorides for the Molten Salt Fast Reactor"
- *Evgenii Varseev,* "Simulation Model of Mass transfer and crystallization process in liquid metal coolants"

This year's event was highly remarkable because of the friendly and competitive spirit of the participants, and questions between the participants raised the interest and appreciation for each other's work. A group picture was taken with all the attendants.

The members of the ENEN Jury were:

- Prof. Francisco Javier Elorza (Universidad Politécnica de Madrid, Spain)
- Prof. Petre Ghitescu (University Politechnica Bucharest, Romania)
- Prof. Iztok Tiselj (Jožef Stefan Institute, Slovenia)
- Prof. Piero Ravetto (CIRTEN, Italy)
- Prof. Danny Lathouwers (TU Delft, The Netherlands)

With this activity, ENEN aims to promote the research of PhD students, and in particular experimental work, in order to set up a bridge between PhD students and professionals in the nuclear field. The ENEN PhD Events are co-sponsored by the European Nuclear Education Network Association (ENEN), the European Commission Joint Research Centre (JRC), and the organizer of the international conference.

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CONTRIBUTION TO THE STUDY OF FISSION PRODUCTS RELEASE FROM NUCLEAR FUELS IN SEVERE ACCIDENT CONDITIONS: EFFECT OF THE PO_2 ON CS, MO AND BA SPECIATION

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Abstract: The objective of this work is to experimentally investigate the effect of the oxygen potential on the fuel and FP chemical behaviour in conditions representative of a severe accident. More specifically, the speciation of Cs, Mo and Ba is investigated. These three highly reactive FP are among the most abundant elements produced through ^{235}U and ^{239}Pu thermal fission and may have a significant impact on human health and environmental contamination in case of a light water reactor severe accident.
This work has set out to contribute to the following three fields:

- Providing experimental data on Pressurized Water Reactor (PWR) MOX fuel behaviour submitted to severe accident conditions and related FP speciation
- Going further in the understanding of FP speciation mechanisms at different stages of a severe accident
- Developing a method to study volatile FP behaviour, involving the investigation of SIMFuel samples manufactured at low temperature through SPS.

In this paper, a focus is made on the impact of the oxygen potential towards the interaction between irradiated MOX fuels and the cladding, the interaction between Mo and Ba under oxidizing conditions and the assessment of the oxygen potential during sintering.

1. INTRODUCTION

At the time of rising concerns about greenhouse gases emission and confronted to an increase of the world needs in energy, nuclear power appears as a sustainable solution that intends to develop across the world. Guaranteeing the safety and security of the existing and future nuclear facilities is thus a top priority. Nowadays, 65% of the nuclear reactors in the world are PWR. These very complex facilities are composed of fuel pellets (UO_2 or MOX $(U,Pu)O_2$) piled up in a Zirconium (Zr) alloy cladding tubes placed in a vessel containing water at around 350°C under 150 bars. These pellets are thus submitted to important strains (temperature, pressure, radiation…) linked to both the fission reaction of heavy nuclei they contained and to the reactor's design.

Despite the constant improvements made on the safety systems implemented in the reactors, failures might happen and lead, in very rare cases, to nuclear severe accidents. These events, implying melting of all or part of the nuclear core, might also lead to radioactive materials release in the environment, as demonstrated in the cases of Chernobyl (1986) and Fukushima-Daiichi (2011). In addition, the damaged core remains hardly accessible even years after the accident because of the radiations it is still emitting. Among the numerous elements that are potentially released during such an accident, some fission products have a strong radiological impact. Moreover, their volatility can vary due to their high chemical reactivity and the physical-chemical evolution of the fuel. It is notably the case of Cesium (Cs), Molybdenum (Mo) and Barium (Ba).

Quantify the source term, corresponding to the nature and quantity of radioactive materials released during a severe accident, is thus a critical issue to:

- precisely estimate the consequences on populations and the environment,
- take decisions in term of crisis management,
- understand the chronology of the accident and predict the final state of the reactor's core,
- securely dismantle the facility in the long term.

To do so, models are developed and validated thanks to the results of experimental programs aiming at reproducing and understanding some phenomena occurring during a severe accident. However, the remaining uncertainties concerning the behaviour of the different systems involving the fuel, the cladding, Cs, Mo and Ba in severe accident conditions limit the current source term prediction capacities of these models.

In this framework, the objective of this work was to experimentally investigate the effect of the oxygen partial pressure (pO_2) and temperature on the fuel and fission products chemical behaviour in conditions representative of a severe accident. Two types of samples have been studies in detail: irradiated MOX fuels and simulated high burn-up UO2 fuels produced through sintering at high temperature (1650°C, 2h, H2 atmosphere). The samples were submitted to thermal treatments in conditions representative of a PWR severe accident. This approach made it possible to cover a large temperature range from 400°C up to 2530°C and oxygen potentials from -470 $kJ.mol(O2)^{-1}$ to -100 $kJ.mol(O2)^{-1}$.

Experimental data were interpreted thanks to thermodynamic calculations performed using ThermoCalc [1] coupled with the TAF-ID database [2], currently developed by OECD. They were then confronted to existing data on Cs, Mo and Ba speciation used in source term prediction models.

The high temperature sintering process used to produce SIMFuels prevents Cs confinement within the UO_2 matrix. Thus, a Spark Plasma Sintering (SPS) route was developed in collaboration with the Joint Research Centre of Karlsruhe. This process enabled obtaining dense samples containing Cs, Mo and Ba at 1200°C under Ar in 5 minutes. Thermodynamic calculations were performed using Factsage coupled with the SGPS database [3], [4] in order to better explain the different phenomena occurring during SPS.

2. EXPERIMENTAL METHODS

As explained in the introduction and detailed in the following section, three different types of samples were studied in this work to investigate the impact of the oxygen partial pressure on the fuel and FP behaviour during a severe accident:

Three irradiated MOX fuels enabled to study the impact of the cladding on the fuel's microstructure evolution under both oxidizing and reducing atmosphere at very high temperatures. The effect of the fuel-cladding interaction on FP behaviour has also been assessed.

SIMFuel samples sintered at high temperature made it possible to probe Mo and Ba speciation in conditions representative of intermediate stages of a severe accident, notably thanks to XAS experiments unavailable, up to now, on irradiated fuels.

SIMFuel samples sintered through SPS were developed to study Cs speciation under severe accident conditions as Cs cannot be confined in SIMFuels sintered at high temperature. The contribution of thermodynamics to this work axis was particularly important to assess the pO_2 conditions in the sintering furnace.

2.1. Irradiated fuels

2.1.1. Samples description

The three samples studied in this part were extracted from the FXP2CC-B05 father rod which consisted in MOX-E fuel irradiated 4 cycles in a PWR operated by EDF. The local burn-up of the segment where the three samples were taken from was around 60 $GWd.t_{HM}^{-1}$.

One of the three irradiated samples was characterized as irradiated and is termed $T_{0(IF)}$ in the following sections whereas the two other samples underwent the VERDON-3 and VERDON-4 tests described hereafter. Before the VERDON experiments, the samples were re-irradiated at low linear power (≈ 20 $W.cm^{-1}$) in the OSIRIS Material Testing Reactor for nine days to recreate the short half-life FP without any in-pile release.

2.1.2. VERDON tests

The samples were placed vertically in a hafnia crucible in the VERDON furnace, described in detail in [5], [6]. The main objective of the VERDON-3 and 4 complementary tests was the study of MOX fuel behaviour and FP release under oxidizing (VERDON-3) and reducing (VERDON-4) conditions at very high temperature (> 2300°C). The different stages of the VERDON-3 and 4 tests are summarized in Figure 11.

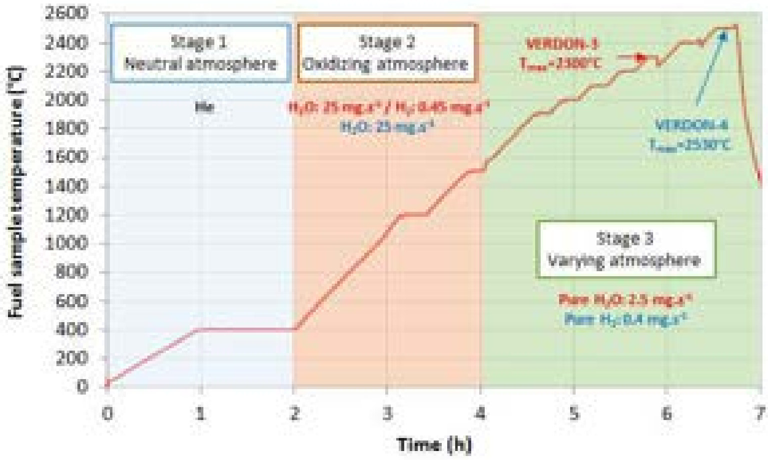


Figure 11: Thermal sequence of the VERDON-3 and 4 tests

The atmosphere during the test was imposed by the equilibrium of H_2O/H_2. Thermodynamic calculations were performed using the Thermo-Calc [1] software coupled with the TAF-ID database [2] in the conditions of stages 2 and 3 of the VERDON-3 and 4 tests. The evolution of the oxygen potential during stages 2 and 3 has been calculated from the H_2O/H_2 system by integration of the whole quantity of gas injected during the step considered (Figure 12).

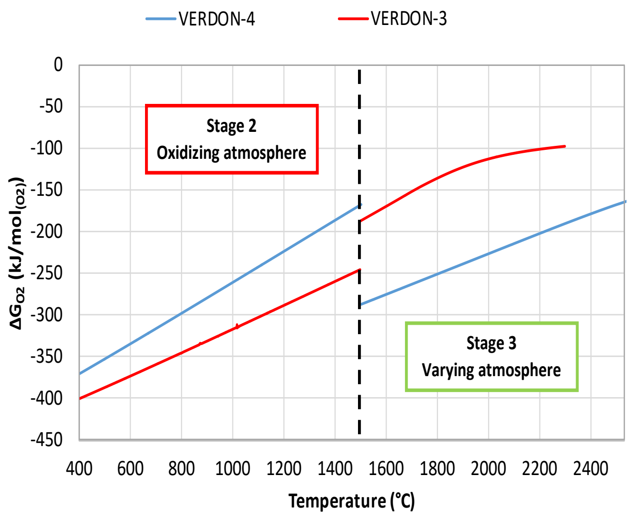


Figure 12: Evolution of the oxygen potential during the stage 2 and 3 of the VERDON-3 and 4 tests, calculated from the H_2O/H_2 system using Thermo-Calc [1] coupled with the TAF-ID [2]

2.1.3. Characterizations

Detailed characterizations were performed on the $T_{0(IF)}$ sample and the samples retrieved after the VERDON-3 and 4 tests. The objective was to study the evolution of the different phases observed in the fuel. OM and SEM observations enabled to study the microstructure of the samples. SIMS isotope mapping and X-ray maps enabled to determine FP location and associations in the fuel samples. Mass spectra were also recorded on different regions of the samples mainly to discriminate Zr coming from the cladding and Zr produced by fission within the fuel. EPMA quantitative profiles helped quantifying the amount of the different elements present in the fuel samples. These characterizations were performed in different locations along the radius of the pellets, 0R being the centre and 1R the periphery.

Thermodynamic calculations were performed using the Thermo-Calc [1] software coupled with the TAF-ID database [2] in the conditions of stages 2 and 3 of the VERDON-3 and 4 tests. The objective was to help interpreting the experimental data and to assess the TAF-ID performances in the case of calculations on irradiated fuels. No calculations were performed on the first stage of the VERDON tests because the sample is not at thermodynamic equilibrium.

2.2. SIMFuel samples sintered at high temperature

2.2.1. Samples description

The samples were synthesized with depleted UO_2 from batch TU2-792 (Areva NC) produced through wet route. The initial average stoichiometry of the powder was 2.20 (mixture of mainly $UO_{2.01}$ and U_4O_9). Eleven additives were used to simulate the major FP created in irradiated fuels except volatile FP. They were mainly added under oxide form or a carbonate form in the case of Ba (Table 6). The initial quantities of FP surrogates were weighted to correspond to the composition of a PWR UO_2 fuel with a burn-up of 76 $GWd.t_{HM}^{-1}$, calculated using the CESAR code [7].

Table 6: Final composition of the SIMFuel samples (the difference to 100% is due to the O content) and description of the additives used to synthesize the SIMFuel samples.

Elements	**U**	**Ba**	**Ce**	**La**	**Mo**	**Sr**	**Y**	**Zr**	**Rh**	**Pd**	**Ru**	**Nd**
Content (at%)	29.60	0.19	0.32	0.18	0.59	0.13	0.06	0.58	0.06	0.32	0.59	0.64
Additives	UO_2	$BaCO_3$	CeO_2	La_2O_3	MoO_3	SrO	Y_2O_3	ZrO_2	Rh_2O_3	PdO	RuO_2	Nd_2O_3

Sample preparation was carried out in a glovebox according to the procedure described in [8], [9]. The eleven FP surrogates were mixed together and added to UO_2. Planetary milling with Al_2O_3 balls was performed during 30 min in ethanol to achieve a well homogeneous dispersion of the additives in the matrix. The resulting slurry was dried in an oven and sieved first at 1000 µm and then at 160 µm. Pre-compaction (50 MPa), pressing (450 MPa) and sintering at 1650°C for 2h under flowing H_2 were then performed.

2.2.2. Thermal treatment conditions

Thermal treatments were performed in the DURANCE experimental loop located in the UO_2 laboratory described in [6], [10]. A polished disk of SIMFuel is placed in a metallic W crucible within an induction furnace. The pO_2 in the inlet gas (Ar + 4% H_2) is controlled in input of the loop thanks to a zirconia oxygen pump. The pO_2 is also measured in input and output of the loop thanks to two MicroPoas probes (provided by Setnag) maintained at

650°C (Gen'air and Jok'air respectively). The temperature below the crucible is monitored by a thermocouple during the tests.

Two campaigns of tests were carried. They consisted in a temperature ramp of 20°C.s^{-1} followed by a dwell time of 2h at 400°C, 700°C, 900°C, 1000°C and 1700°C under controlled pO_2. The pO_2 was maintained at 1.97×10^{-20} atm (H_2O/H_2 = 50) at 650°C in the case of the "oxidizing" campaign and at 5.08×10^{-27} atm (H_2O/H_2 = 0.02) in the case of the "reducing" campaign. The gas flow was set at 40 mL.min^{-1}.

Only the results of the "oxidizing" campaign will be treated in this paper. As shown in Table 7, the evolution of the oxygen potential during these tests is in the same range compared to the ones of the stage 2 of the VERDON-3 and 4 tests.

Table 7: Experimental conditions used to perform the "oxidizing" thermal treatments

Sample's name	O400	O700	O900	O1000
Temperature during the test (°C)	400	700	900	1000
Oxygen potential (kJ.mol^{-1})	-387.73	-340.30	-308.22	-292.05

2.2.3. Characterizations

Detailed characterizations were performed on the SIMFuels as-sintered ($T_{0(SIMF)}$) and after the different thermal treatments to study the chemical evolution of the different phases observed in these samples. These characterizations included density measurements, OM and SEM observations that enabled describing the evolution of the microstructure after the different treatments. X-ray maps and local EDX analyses were performed on the whole range of elements present in the SIMFuel samples but only the ones expected to compose the different phases of interest are shown (Mo, Ru, Rh, Pd, O and U in the case of metallic precipitates and Ba, Zr, Sr, Y, Ce, O and U in the case of the oxide precipitates). These analyses coupled to XANES measurements were performed in order to study the chemical evolution of the phases observed in the samples. More specifically, XANES measurements allowed to study Mo and Ba speciation in the different samples. XANES calculations using the FDMNES software [11] were performed when some reference samples were missing, in order to interpret the experimental spectra.

Only the results obtained on the $T_{0(SIMF)}$ and O1000 samples will be presented in the rest of this paper.

2.3. SIMFuel sintered through SPS

2.3.1. Fabrication process

Eight batches of SIMFuels were sintered (one was made out of pure UO_2) with different combinations of additives (Cs uranates, Cs or Ba molybdates, $BaCO_3$ or MoO_3). In this paper, only two batches of samples will be detailed: batch 3 (UO_2 + 1.2 wt%$Cs_2U_xO_y$) and 8 (UO_2 + 4 wt%$Cs_2U_xO_y$ + 4wt% $BaMoO_4$). The compositions of batch 3 is representative of a PWR UO_2 fuel with a burn-up of 76 GWd.t_{HM}^{-1}, calculated using the CESAR code [7]. Batch

8 was synthesized with higher concentrations in FP surrogates to enable easier the characterizations.

Commercial depleted UO_2 (Cogema) was first pre-reduced at 800°C during 4h under Ar + 6.5% H_2 in order to avoid a stoichiometry gradient in the pellets after sintering and to limit the deviation from stoichiometry of the as-sintered pellets [12]. Commercial MoO_3, $BaMoO_4$, Cs_2MoO_4 and $BaCO_3$ were used as received. Cesium uranate was synthesized according to the protocol described in [13]. The composition of the final orange powder was characterized through XRD to be a mixture between Cs_2UO_4 (22 %), $Cs_2U_2O_7$ (75 %) and Cs_2O (3 %). For the sake of clarity, in the following chapter, the Cs uranates will be termed as $Cs_2U_xO_y$.

Sample preparation was carried out in a glovebox under Ar atmosphere. The additives powders were first ground separately in an agate mortar. The pre-reduced UO_2 was then added to the mixture which was ground again manually. The powder was finally poured into a 6 mm diameter SPS matrix made out of graphite and containing a graphite foil to ease the extraction of the pellet after sintering. Graphite disks were also placed between the pistons and the powder to prevent the pellet from being stuck to the pistons. A pre-compaction step was performed at 500 N (~17.7 MPa) and the following cycle was run: the gas was evacuated from the sintering chamber and a pressure of ~88 MPa was applied to the powder. The chamber was then filled with Ar and heated up to the final temperature (1200°C, 200°C/min) maintained during 5 min. Finally, the furnace was cooled down and the pressure was released.

2.3.2.Characterizations

The characterizations performed on the SIMFuels sintered through SPS included density measurements and SEM observations that enabled studying the microstructure of the samples, notably the grain size and FP distribution in the pellets. EDX analyses and XANES experiments were also carried out on these samples in order to determine FP chemical state and more especially Cs speciation. Finally, quantitative chemical analyses using ICP-AES and ICP-MS [14] were used to quantify FP release after sintering.

Predominance diagrams were established using the Phase Diagram module of the FactSage 7.0 software coupled to the SGPS database [3], [4]. Only temperature and oxygen potential were set as variables. The elemental concentrations were determined using the results of chemical analyses performed on the samples, when available. Some redox indicators have been added to the diagrams:

- The equilibrium $C_{(s)}/CO_{(g)}$ at 0.1 and 1 bar.
- The equilibrium $CO_{(g)}/CO_{2(g)}$ at 1 bar.
- The oxygen potential corresponding to stoichiometric UO_2 in the calculation range of temperature.
- The oxygen potential corresponding to $UO_{2.01}$ in the calculation range of temperature.

3. MAIN RESULTS AND DISCUSSION

3.1. Irradiated fuel's microstructure evolution

The post-test examination of the VERDON-3 and 4 samples highlighted a change of microstructure after both tests linked notably to an interaction between the fuel and the cladding. This can clearly be observed in the micrographs of the three samples in Figure

13. The fuel-cladding interaction zone progressed from 5 µm in the $T_{0(IF)}$ sample's periphery up to 200 µm in the VERDON-3 sample without melting. This is not surprising as liquid would have stated to be formed in the VERDON-3 conditions above the maximal temperature of the texts (2300°C), at 2420°C, according to thermodynamic calculations. However, this interaction led to the melting and progression of a $U_yZr_{1-y}O_{2\pm x}$ phase through the cracks of the fuel sample during the VERDON-4 test.

The final compositions of the liquid phase were measured experimentally in the periphery of the VERDON-4 sample, and crossing the crack found at 0.75 R from the UO_2 matrix until the centre of the crack. They have been reported on the isotherm diagram presented in Figure 14 and calculated using the ThermoCalc coupled with the TAF-ID [1], [2]. As indicated in this diagram, the compositions measured in these points are consistent with the tie lines orientation. Moreover, a Zr enrichment is observed in the periphery of the pellet (1R) compared to the centre of the crack at 0.75R. This confirms the hypothesis made in [15], assuming progressive dissolution of UO_2 coming from the fuel matrix by the liquid $U_yZr_{1-y}O_{2\pm x}$ phase originally formed at the periphery when temperature increased:

First, Zr-U interdiffusion occurs until a certain $U_yZr_{1-y}O_{2\pm x}$ composition is reached.

Melting of this $U_yZr_{1-y}O_{2\pm x}$ phase occurs as soon as the composition meeting the minimum melting temperature is reached (probably around 2480°C in the test conditions according to thermodynamics calculations).

The molten phase then penetrates through the cracks of the pellet leading to progressive dissolution of the fuel by $U_yZr_{1-y}O_{2\pm x}$.

The melt is then reduced as the temperature increases.

$T_{0(IF)}$	VERDON-3	VERDON-4
As-irradiated	**2300°C, oxidizing**	**2530°C reducing**

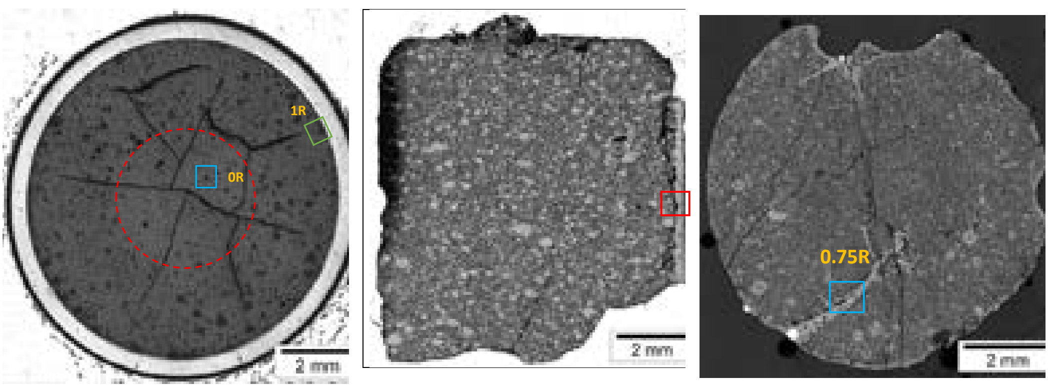


Figure 13: Micrographs of the three irradiated samples under study

Metallic precipitates also known as white inclusions have been observed across the three samples under study. They are common in irradiated fuels [16]. In the VERDON-3 and 4 samples, these precipitates differed by their size and location. Indeed, their size varied from around 1 µm up to 200 µm. The larger precipitates were only found in the molten zones at the periphery of the VERDON-4 sample whereas in the rest of the sample, smaller precipitates were mainly located in the Pu agglomerates, as it was the case in $T_{0(IF)}$.

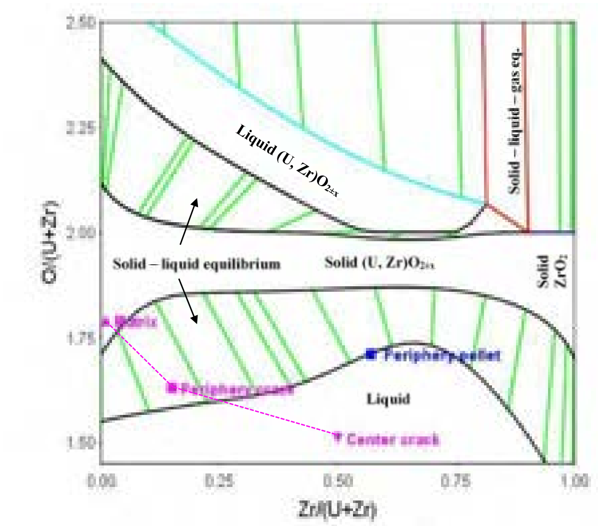


Figure 14: Calculated isotherm diagram of the Zr/(U+Zr) content as a function of O/(U+Zr) at 2530°C where the experimental data obtained in the molten regions at the periphery of the sample and in the the crack found at 0.75R of the VERDON-4 samples are reported, calculated with Thermo-Calc [1] and the TAF-ID [2]

Given the rounded flatten shape of these precipitates and their location in the sample, it is inferred that melting of the metallic precipitates occurred before melting of the (U, Zr)O_2 mixed oxide during the VERDON-4 test. Once these precipitates were in contact with the molten $U_yZr_{1-y}O_{2\pm x}$ phase, they migrated more easily towards the periphery of the sample and coalesced as they were blocked by the cladding. It is highly consistent with the melting temperature of metallic precipitates and the $U_yZr_{1-y}O_{2\pm x}$ phase calculated by thermodynamics.

In the case of VERDON-3, despite the calculated melting temperature of the metallic precipitates (2120°C), no clear experimental evidence of their melting could be brought besides their rounded shape and mobility during the test. Indeed, they were found to be mainly located in the Pu agglomerates in the father rod ($T_{0(IF)}$), whereas they were homogeneously distributed in the VERDON-3 fuel sample.

Globally, a homogenization of the fuel composition has thus been observed after the VERDON-3 test compared to the as-irradiated father rod whereas the fuel heterogeneity has been conserved after the VERDON-4 test. This phenomenon can thus be attributed to the enhanced metallic precipitates mobility in oxidizing conditions at high temperature. The evolution of the fuel played also an important role on the metallic precipitates' behaviour as the presence of a $U_yZr_{1-y}O_{2\pm x}$ phase in reducing conditions involved their coalescence after melting.

3.2. Interactions between Mo and Ba under oxidizing atmosphere

Ba and Mo were initially found in two types of phases in the $T_{0(SIMF)}$ sample consistently with the literature [16]. Complementary with the SEM-EDX results, XANES enabled to quantify the amount of element involved in each phase as well as identifying its crystallographic structure.

Mo was found in metallic precipitates alone in a bcc structure or with Ru, Rh and Pd in a hcp structure according to the XANES results shown in **Figure 15**. These precipitates are also observed in PWR irradiated fuels in normal operating conditions. No MoO_2 has been detected at the initial state in the SIMFuel samples, which is consistent with the strongly reducing atmosphere of the sintering.

Ba was found in oxide precipitates mainly whether as a simple oxide BaO (17% according to the XANES results shown in **Figure 15**) or as a more complex one known as grey phase (Ba, Sr)(Zr, U, RE)O_3 (where RE stands for Rare Earth).

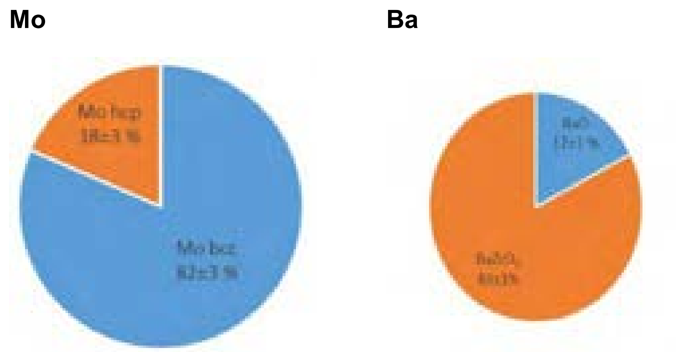


Figure 15: Linear combination fitting results performed between -20 and +60 eV around Mo K-absorption edge and Ba L_3-absorption edge of the $T_{0(SIMF)}$ sample

At 1000°C under oxidizing conditions, Mo has partially oxidized to form MoO_2 according to the XANES analyses (Figure 16).

In the same range of temperature, a reaction between Mo and Ba led to partial decomposition of $BaZrO_3$ into ZrO_2 and $BaMoO_4$ (Figure 16). This reaction has been inferred to an enhanced diffusion of Mo in oxidizing conditions: Mo would first dissolved as MoO_2 in the UO_{2+x} matrix, and might have migrated from the metallic to the oxide precipitates driven by a gradient of O concentration. It would then react with the Ba contained in $BaZrO_3$.

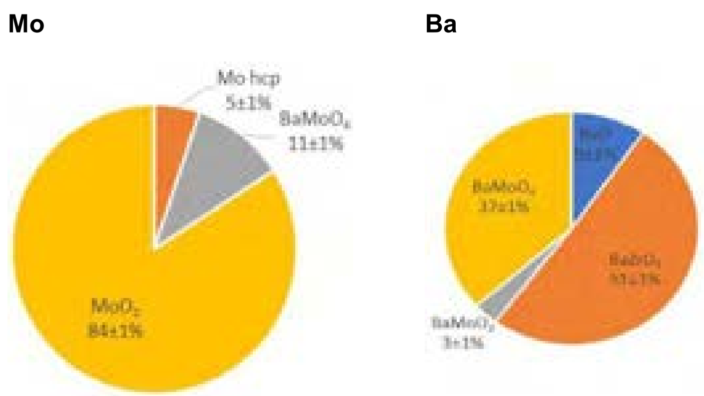
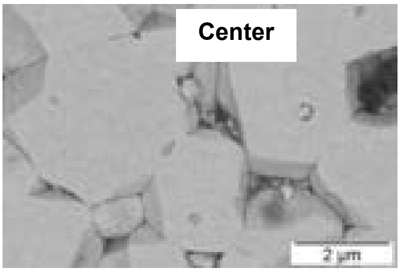


Figure 16: Linear combination fitting results performed between -20 and +60 eV around Mo K-absorption edge and Ba L_3-absorption edge of the O1000 sample

3.3. Estimation of the oxygen potential during SPS of SIMFuel samples

After sintering, pellets of batch 3 were polished and observed by means of SEM (**Figure 17**). The grain size is higher in the centre of the pellets (2.45 ± 0.17 µm) compared to the periphery (0.62 ± 0.13 µm). This phenomenon has already been observed in the study by [12]. This microstructure gradient was attributed to a higher oxidation state in the bulk of the samples compared to the surfaces due to a probable interaction between UO_{2+x} (where x = 0.01 in the study by [12]) and the graphite matrix according to reaction (2):

$$UO_{2+x} + xC \rightarrow UO_2 + xCO \quad (2)$$



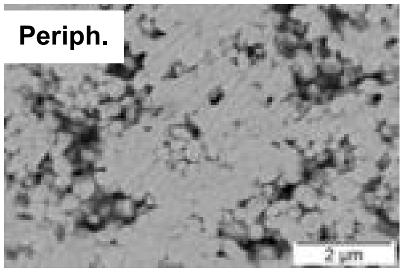


Figure 17: SEM-BSE images showing the morphology of the grains in the centre (left) and the periphery (right) of the pellets of batch 3 (UO_2 + 1.2 % $Cs_2U_xO_y$).

The XANES spectral signature of Cs in a sample of batch 3 is very close to the one of $Cs_2U_xO_y$ (Figure 18). Thus, Cs would still be present in the sample as uranates.

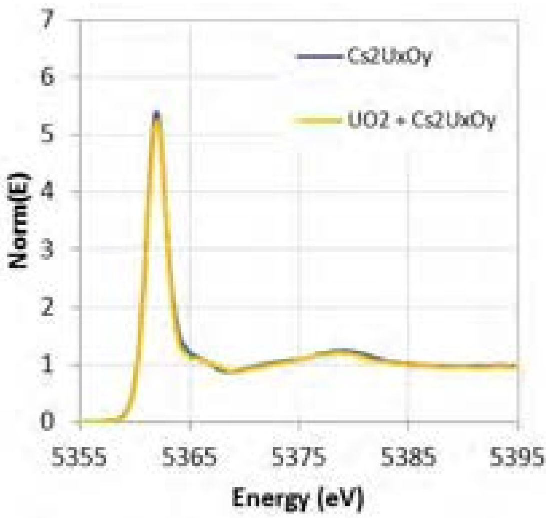


Figure 18: Experimental HERFD-XANES spectra of $Cs_2U_xO_y$ standard and a sample of batch 3 as-sintered acquired on the FAME-UHD beamline (ESRF)

However, ICP-AES results showed that around half of the initial Cs amount had been volatilized during sintering (Table 8).

Table 8: Concentration in U, Mo and Cs remaining in the samples of batch 3 after sintering at 1200°C during 5 min, obtained through ICP-MS and ICP-AES

Batch	U concentration (mg/g$_{sample}$)	Cs concentration (mg/g$_{sample}$)	% Cs remaining in the sample
UO_2 + 1.2 % $Cs_2U_xO_y$	870.9 ± 17.4	2.706 ± 0.271	55 ± 6

According to Figure 19, at 1200°C Cs can be present as free Cs (gaseous in these conditions) or under uranate condensed forms. These phases are both consistent with the experimental observations. The release of Cs at 1200°C results from the decomposition of uranates to form free Cs according to $Cs_2UO_4 \rightarrow UO_2 + 2\ Cs + O_2$.

Considering the experimental data, Cs and Cs_2UO_4 coexist in the samples of batch 3. As shown in Figure 19, the oxygen potential range during sintering is thus probably located around the limit between the UO_2 + Cs_2UO_4 and UO_2 + $Cs_{(l)}$ domains, which also corresponds to the area between the $C_{(s)}/CO_{(g)}$ equilibrium at 1 bar and the oxygen potential corresponding to $UO_{2.00}$. This domain is pointed out thanks to the grey circle on **Figure 19**, and extends from -550 kJ.mol$_{(O2)}^{-1}$ to -475 kJ.mol$_{(O2)}^{-1}$.

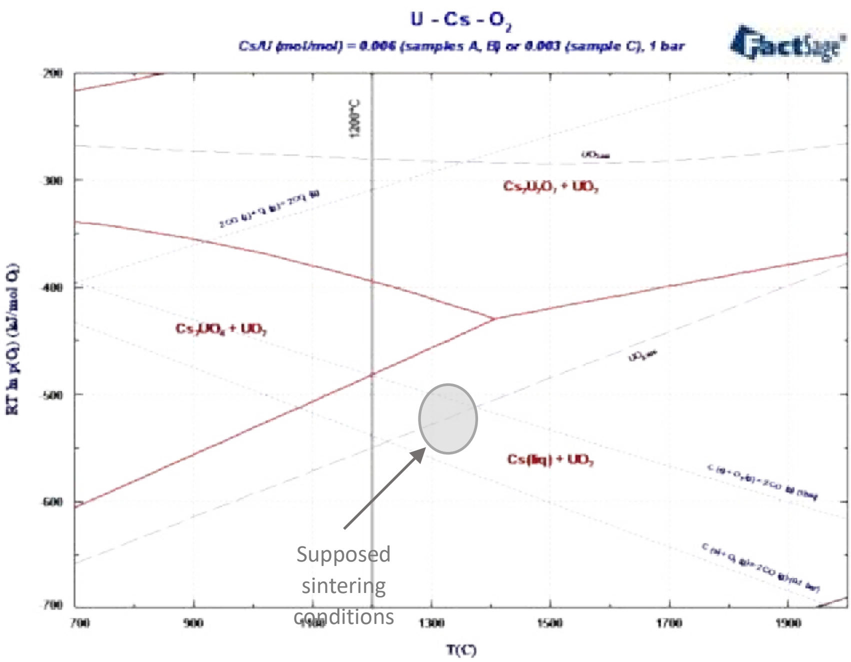


Figure 19: Predominance diagram for the Cs-U-O_2 system (Batch 3), considering the quantities of elements remaining in the system after sintering. obtained using the SGPS database of FactSage [3], [4].

In order to check the validity of this hypothesis, the samples of batch 8 were characterized by SEM-EDX. Ba and Cs were often found together but no chemical contrast could be observed in BSE mode (**Error! Not a valid bookmark self-reference.**). This is probably because Ba and Cs are associated to U and O, the mass of Ba or Cs uranates being quite close from the one of UO2.

Some Mo was observed alone as well as some Cs and Ba. These observations suggest that no BaMoO4 remained in the sample and apparently no Cs2MoO4 was formed.

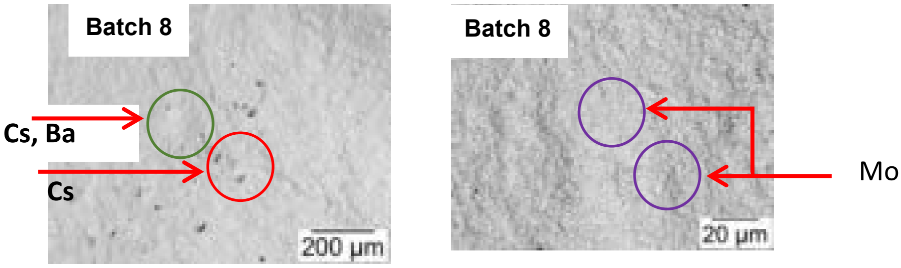


Figure 20: SEM-BSE images of fractured surfaces of a sample of batch 8 (UO_2 + 4.0 % $Cs_2U_xO_y$ + 4.0 % $BaMoO_4$) of the SPS-2 series.

According to the predominance diagram established for batch 8 (Figure 21), the decomposition of $BaMoO_4$ suggested by the SEM-EDX analyses would occur at 1200°C below -325 $kJ.mol_{(O2)}^{-1}$. Concerning Cs, it is calculated to be present either as free Cs or Cs_2MoO_4 at thermodynamic equilibrium at 1200°C. Mo is calculated to be present either as Cs_2MoO_4 or metallic Mo below -370 $kJ.mol_{(O2)}^{-1}$. The only oxygen potential range allowing to explain the absence of $BaMoO_4$ and Cs_2MoO_4 in the samples, is the one proposed in Figure 19 (-550 $kJ.mol_{(O2)}^{-1}$ to -475 $kJ.mol_{(O2)}^{-1}$).

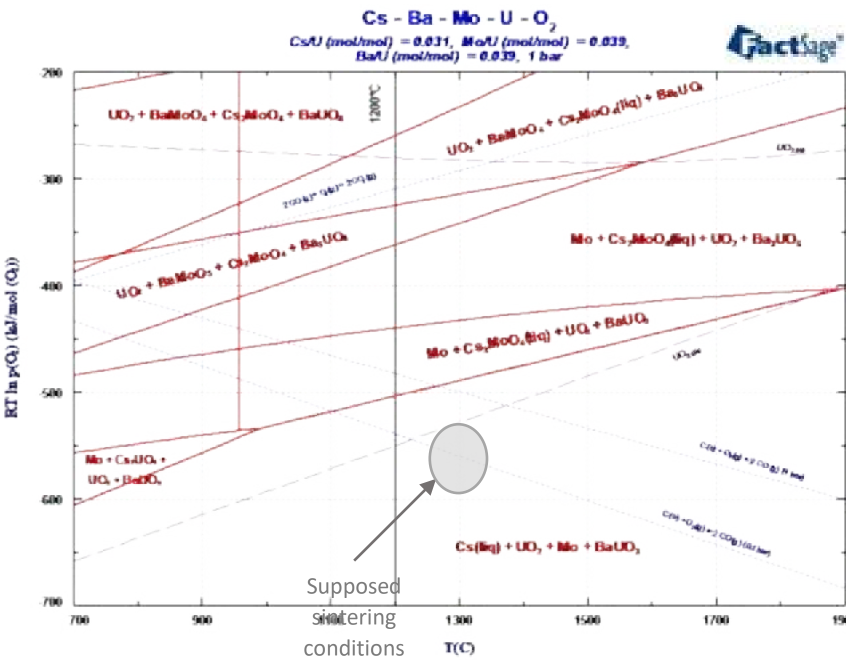


Figure 21: Predominance diagram for the U-Cs-Ba-Mo-O2 system (Batch 8), considering the quantities of elements added before sintering, obtained using the SGPS database of FactSage [3], [4].

4. CONCLUSION

Two types of samples have been studied in detail in this study: irradiated MOX fuels and SIMFuels produced through sintering at high temperature (1650°C, 2h, H_2 atmosphere). The samples were submitted to thermal treatments in conditions representative of a PWR severe accident. This approach made it possible to cover a temperature range from 400°C up to 2530°C and oxygen potentials from -470 $kJ.mol_{(O2)}^{-1}$ to -100 $kJ.mol_{(O2)}^{-1}$. The samples were characterized before and after each test using complementary techniques like OM, SEM, EPMA and SIMS in the case of irradiated fuels. XANES measurements using synchrotron radiation facilities were also performed on SIMFuels and produced valuable results on FP speciation (oxidation state, crystallographic structures, etc.).

The main phenomena assessed in the scope of this work were:

Effect of fuel-cladding interactions on the fuel's melting temperature. It seems that the role of the oxygen potential in this phenomenon is to enhance the diffusion of species in oxidizing conditions. The $U_{1-x}Zr_xO_{2\pm x}$ composition for which the melting temperature is minimal is thus reached earlier than in the case of a reducing atmosphere

Interactions between Mo and the oxide phase containing Ba, which has been described in the present paper. These interactions were shown to occur at temperatures as low as 1000°C under oxidizing conditions. The formation of MoO_2 and its reaction with $BaZrO_3$ results in the breakdown of this phase into $BaMoO_4$ and ZrO_2

The composition and behaviour of metallic phases in severe accident conditions. Mo depletion of the Mo-Ru-Rh-Pd-Tc inclusions was observed to take place around 1000°C in oxidizing conditions because of the oxidation of Mo into MoO_2. In reducing conditions, no major composition changes were observed.

More generally, the principal limitation of this approach lies in the behaviour of volatile FP such as Cs. These FP are released relatively quickly during a severe accident and are totally released from the fuel above 2300°C. Thus, the characterizations performed on irradiated fuels before and after a full accident sequence provided very little information on volatile FP speciation. Much in the same way, volatile FP are volatilised during the sintering stage of the SIMFuel fabrication process produced at high temperature, thus preventing their study at intermediate temperature levels.

Thus, low-temperature sintering was investigated for the production of SIMFuel samples containing Cs, Mo and Ba. Cs proved to remain in the samples obtained through SPS (1200°C, 5 min, Ar atmosphere). Moreover, the chemical state of these three FP in the pellets is representative of that in the centre of PWR fuels under normal operating conditions. Despite these promising results, large Cs and Mo releases occurred during sintering and the additives in the pellets were not distributed homogeneously. These issues brought us to consider further development of this production route.

Throughout this study and beyond the results presented in this paper, thermodynamic calculations were performed to assess the FP and fuel chemical state in the different conditions and materials in question. These calculations proved to be a necessary tool to interpret the experimental data obtained. The key contributions of thermodynamics in this work are:

Interpretation of the VERDON-3 and 4 scenarios in term of FP speciation and fuel behaviour. The calculations coupled with the experimental data led to the proposal of a mechanism for FP speciation adapted to each test. However, the assumptions used in these calculations (considering the whole irradiated fuel-FP-cladding systems) showed some limitations.

Choice of the experimental conditions in which thermal treatments were led on SIMFuels so as to observe a chemical evolution of Ba and Mo in the samples.

Determination of the oxygen potential range within which the SIMFuels were manufactured in the SPS furnace, as detailed in the present paper. The sintering range was defined between -550 $kJ.mol_{(O2)}^{-1}$ to -475 $kJ.mol_{(O2)}^{-1}$ at 1200°C.

Today, there is no longer any doubt concerning the existing link between fission products' chemical behaviour in the fuel and their release. Although their behaviour in the fuel during a severe accident is mainly governed by thermochemistry, this work demonstrated that it cannot be separated from the kinetics aspect. Indeed, chemical reactions between the different elements are strongly impacted by the ability of the different fission products to diffuse through the fuel pellets, which is insufficiently taken into account in the release models.

REFERENCES

[1] J.-O. Andersson et al., Calphad, vol. 26, nº 2, p. 273-312, 2002.

[2] TAF-ID, working version of january 2018 », https://www.oecd-nea.org/science/taf-id/.

[3] C. W. Bale et al., Calphad, vol. 26, nº 2, p. 189-228, 2002.

[4] C. W. Bale et al., Calphad, vol. 33, nº 2, p. 295-311, 2009.

[5] A. Gallais-During et al., 21st International Conference Nuclear Energy for New Europe, 2012.

[6] C. Le Gall, Ph.D. thesis, Université Grenoble Alpes and CEA Cadarache, 2018.

[7] « Cesar 5.1, developed by DEN/DER/SPRC », CEA Cadarache.

[8] P. G. Lucuta et al., J. Nucl. Mater., vol. 178, nº 1, p. 48-60, 1991.

[9] Z. Hiezl, Ph.D. thesis, Imperial College London, 2015.

[10] Y. Pontillon et al., European Working Group « Hot Laboratories and Remote handling », 2005.

[11] Y. Joly, Phys. Rev. B, vol. 63, nº 12, p. 125120, 2001.

[12] V. Tyrpekl et al., Sci. Rep., vol. 7, art. n°46625, 2017.

[13] D. W. Osborne et al., Journal of Chemical Thermodynamics, p. 361-365, 1976.

[14] A. Labet et al., European Winter Conference on Plasma Spectrometry, 2019.

[15] E. Geiger et al., J. Nucl. Mater., vol. 495, Supplement C, p. 49-57, 2017.

[16] H. Kleykamp, J. Nucl. Mater., vol. 131, nº 2-3, p. 221-246, 1985.

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DEBRIS BED FROMATION IN DEGRADED CORES OF LIGHT WATER REACTORS

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Abstract: During a hypothetical Severe Accident in Light Water Reactors, degraded core materials released from the Reactor Pressure Vessel (RPV) after its failure will be fragmented and quenched by contact with the water pool in the cavity below. The solidified particles will settle on the bottom forming a porous bed. However, this strategy succeeds only if the residual decay heat is sufficiently removed and the bed is thermally stabilized and will not re-melt again damaging the containment integrity.

One of the main factors determining the ability of decay heat removal and long-term coolability of debris bed is its geometrical configuration. A flatter and broader bed can be easier cooled than a higher bed with the same mass of debris. For this purpose, the present work focuses on the development of a two-dimensional continuum model describing the formation process of the debris bed resulting from the deposition of the settling particles and their relocation along the surface of the heap. The mathematical model is based on a hyperbolic system of partial differential equations determining the overall bed height, the distribution of the flowing particles layer depth and the depth-averaged velocity component tangential to the sliding layer. Because of the hyperbolicity of the system, a successful implementation of a solver is challenging, notably when large gradients of the physical variables appear, e.g., for a moving front in the flowing layer or possibly formed shock waves during the deposition.

In this paper, the Riemann's Roe-solver is implemented providing promising results, which are verified with analytical solutions in the steady state. A dedicated test facility, named BeForE, is designed and built in the framework of this study, with the aim of providing the necessary experimental data for the model validation. The comparison between the numerical and the experimental results has shown a relatively good agreement.

Moreover, the test facility could also be used to gain an insight into the influence of steam production on the particulate bed spreading. The decay-heat-induced coolant boiling, and the resulting two-phase flow serve as a source of mechanical disturbance, which might lead ultimately to levelling of the debris bed (a.k.a. self-levelling). Lastly, it was mathematically described how the steam production could reduce the characteristic angles of repose of a debris bed, putting forth a physical explanation of the self-levelling phenomenon. With the coupling of the developed continuum model with a

model simulating the two-phase flow within the bed, a full numerical simulation of the avalanche-like particles motion during the self-levelling process could also be successfully provided. This allows a more accurate simulation of the bed formation process under the influence of steam production, which is of great importance for the bed coolability and a decisive requirement for the nuclear accident progression and termination.

1. Introduction

As a severe accident mitigation strategy adopted in several designs of light water reactors and specifically in Nordic type boiling water reactors (BWR), a deep pool of water is foreseen in the cavity below the RPV. In fact, it is assumed that the corium jet pouring out of the broken vessel to a highly-subcooled (~80−90 K) deep water pool (7−11 m) is expected to break up by contact with water, and fragment into droplets, that solidify and settle down forming a porous debris bed. This interaction between the melt jet and water was underscored by the experimental results from the FARO-experiments (Fuel melt And Release Oven) [1] as well as by TMI-2 post-accident investigations [2, 3]. Depending on the reactor type and the corium composition, the formed particles beds could still include a specific power of 100-300 W/kg. The preeminent goal becomes how to prevent the re-melting of the debris in consequence of insufficient cooling and ensure long-term cooling of the bed by coolant ingress, and hence protecting the structural integrity of the containment.

The efficiency of heat removal from the formed beds is, however, contingent upon several parameters, including bed's height and its overall geometry among others [4]. A flatter and broader bed can be easier cooled than a higher bed with the same mass of debris. Despite its importance for the termination of severe accidents, very little studies and nearly no significant insights were found in the literature on the process of debris bed formation. The focus of most of the experimental and numerical studies in this stage of the SA lied on the steam explosion, on the molten fuel-coolant interactions (e.g., jet breakup, melt droplet fragmentation, premixing), or on the bed coolability and the two-phase flow inside already formed geometries, but not the formation process itself. The past most of the theoretical and experimental studies on debris coolability have taken the shape of the bed as predefined, and the particles are assumed to be fixed.

In addition to the bed formation process from particles deposition and relocation, the coolant boiling and two-phase flow caused by decay heat inside the hot debris bed, serve as a source of mechanical disturbance, which might lead ultimately to levelling of the debris bed [5] (as illustrated in Fig 1).

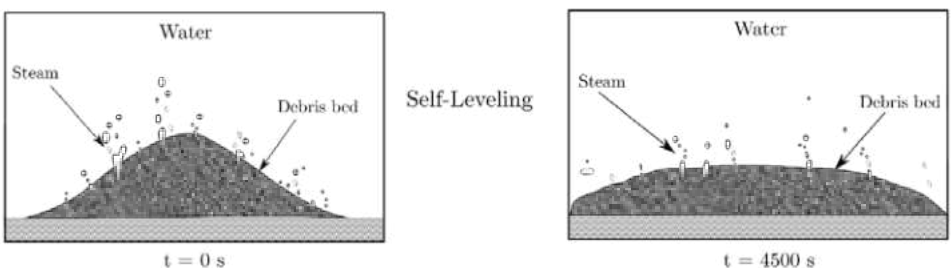


Fig 1. Debris bed levelling

Viewing the importance of this process and its influence on bed geometry and coolability, few experimental studies [6–10] and theoretical investigations [11–13] have been conducted on this subject, tough scanty. It should be noticed that all the proposed numerical models are based on empirical closures and assumptions, and the dynamics of the relocated particles induced by the boiling is still not sufficiently modelled and physically described.

Therefore, the paramount focus of the present paper lies on the mathematical description and development of a numerical model simulating the debris bed formation from deposition and relocation of the solidified melt particles under the consideration of the coolant boiling.

The remainder of the present paper is structured in two main parts:

(i) At first, a physical and mathematical description of a two-dimensional (2D) continuum model for the bed formation process without coolant boiling will be introduced in Section 2, in which the modelling approach and the main equations governing the particles dynamics will be then derived and explained in its first subsection. The implemented numerical solver used for the solution of the system equations will be explained, and the numerical results will be then presented in sub-section 2.2. To check the validity of the implemented model, the numerical modelling will be first verified through a comparison with analytic solutions in the steady state, and subsequently, validated and compared to experimental data in sub-section 2.3.

(ii) Second, the influence of the coolant boiling will be considered in Section 3. In subsection 3.1, a theoretical investigation of this phenomenon will be then outlined, and the continuum model developed in Section 2 will be adapted to consider the interaction between the two-phase flow and the bed formation process. Then, the numerical results underlying this influence will be presented and compared with the experimental results in the last subsection 3.2.

2. Debris bed formation from particles deposition and relocation

2.1. Modelling approach

In the present model, it is assumed that the fully fragmented and solidified debris particles are behaving like cohesionless granular material. When such particles are poured onto a horizontal flat surface from a single point, they form a conical shaped pile characterized by the slope angle. The value of this angle stays between two critical values. An avalanche starts to flow when the slope exceeds the angle of movement βm. The second characteristic angle is defined as the angle of settlement βs (often called static angle of repose), with tan(βs) taken to be the effective coefficient of dynamic friction in granular flows [14]. By exceeding the maximum value of βm, the pile cannot sustain the steep surface, and a flow of particles occurs within a thin surface layer on the top of a nearly quiescent bulk region [15].

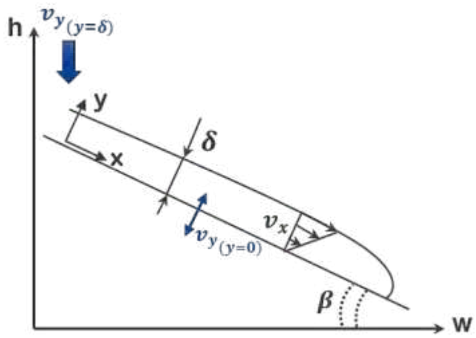


Fig 2. Sketch of the flowing layer and the used coordinate system

In the present model, it is considered that the non-cohesive granular particles are flowing uni-directionally in a thin surface layer (as shown schematically in Fig 2). The mass and momentum conservation equations in the flowing layer are as follows:

$$\frac{\partial \delta}{\partial t} + \frac{\partial(\delta u)}{\partial x} = v_{y\,(y=0)} - v_{y\,(y=\delta)} \tag{1}$$

$$\frac{\partial}{\partial t}(\delta u) + \frac{4}{3}\frac{\partial}{\partial x}(\delta u^2) = -6 d_p \frac{u^2}{\delta} + g\delta \frac{\sin(\beta - \beta_s)}{\cos \beta_s} - 2uv_{y\,(y=\delta)} \tag{2}$$

Where $\delta = \delta(x, t)$ is the local thickness of the flowing layer and $u = \frac{\delta v_x}{2y}$ is the downslope mean velocity, and d_p is the mean particle diameter. The first velocity term on the right side of the mass conservation denotes the absorption and erosion rate of particles into and from the static pile, and the second term $v_{y\,(y=\delta)}$ represents the velocity of the falling particles from the top.

The shear stress at the bed layer interface can be defined as the linear sum of the Bagnold's collisional τ_{xy_B} and Coulombic frictional stresses τ_{xy_C} ::

$$\tau_{xy} = -1.5\rho\delta d_p \left(\frac{\partial v_x}{\partial y}\right)^2 - \rho g \delta \cos(\beta)\tan(\beta_s) \tag{3}$$

On the other side, the shear stress imposed by the flowing layer on its surface with the static particles is balanced by friction. The shear stress can be then described according to the Mohr-Coulomb failure criterion as:

$$\tau_{xy_{y=0}} = -\rho g(\delta + d_p)\cos(\beta)\tan(\beta_m) \tag{4}$$

From Equations (3) and (4), a direct dependency between the mean velocity (u) and the layer thickness (δ) can be found under the assumption of having a thick layer ($\delta \gg d_p$):

$$u = \sqrt{\frac{g\cos(\beta)\sin(\beta_m - \beta_s)}{1.5d_p\cos(\beta_m)\cos(\beta_s)}}\frac{\delta}{2} = \gamma\frac{\delta}{2} \tag{5}$$

The dynamics of the bed-layer-interface $\boldsymbol{h}(x,t)$ can be geometrically deduced from Fig. 2 as below:

$$\frac{\partial \boldsymbol{h}}{\partial t} = -v_{y_{(y=0)}}\cos(\beta);\ \frac{\partial h}{\partial x} = -\sin(\beta) \tag{6}$$

The equations (1) - (6) define a two-dimensional continuum model for the description of the debris bed formation. The temporal evolution of the bed height as well as the avalanche thickness and the local particles mean velocities can be numerically solved with the indication of the appropriate boundary and initial conditions in regard of the real case conditions. A more detailed derivation of theses mathematical equations can be found in [4].

2.2. The numerical solution

The system of governing equations is of hyperbolic type (see Equations (1) and (2)) akin to the shallow water equations and it can be written in general vector form as:

$$q_t + f_x = S \tag{7}$$

With:

$$q = \begin{pmatrix}\delta \\ \delta u\end{pmatrix},\ f = \begin{pmatrix}\delta u \\ \frac{4}{3}\delta u^2\end{pmatrix}, and\ S = \begin{pmatrix} v_{y_{(y=0)}} - v_{y_{(y=\delta)}} \\ -4Md_p\frac{u^2}{\delta} + g\delta\frac{\sin(\beta-\beta_s)}{\cos\beta_s} - 2uv_{y_{(y=\delta)}}\end{pmatrix} \tag{8}$$

This hyperbolic equation system in its vector form is discretized locally on a one-dimensional regular grid along the x-axis. By knowing the vector q_i^n at the time step (n) and at the point (i), we compute its value at the time (n+1) with an explicit numerical scheme as follows:

$$q_i^{n+1} = q_i^n - \frac{\Delta t}{\Delta x}\left[f_{i+\frac{1}{2}}^n - f_{i-\frac{1}{2}}^n\right] + S_i^n\Delta t \tag{9}$$

The vector $f_{i+\frac{1}{2}}^n$ denotes the convection flux at the cell boundary ($i+\frac{1}{2}$). A Riemann problem is present at each interface $x_{i+\frac{1}{2}} = \frac{x_i + x_{i+1}}{2}$ separating adjacent states x_i and x_{i+1}. There is a broad range of finite volume schemes for the solution of hyperbolic systems based on Riemann solvers (Godunov-type schemes) [4, 16, 17]. One of the most popular techniques is the Roe-scheme [18] calculated with the following averaged states at every inter-cell boundary:

$$\tilde{u} = \frac{\sqrt{\delta_R}u_R + \sqrt{\delta_L}u_L}{\sqrt{\delta_R} + \sqrt{\delta_L}}\ and\ \tilde{\delta} = \sqrt{\delta_R\delta_L} \tag{10}$$

Note that $(\cdot)_R$ and $(\cdot)_L$ denote respectively the right and left states of the primitive variable at each inter-cell boundary. The conditions for applying this solver are listed and discussed in [4]. The averaged Roe-flux is then given by the following equation:

$$\tilde{f}_{ROE} = \frac{1}{2}\left[f(w_R) + f(w_L) - \sum_{i=1}^{2} |\tilde{\lambda}_i| \tilde{\alpha}_i \tilde{r}_i\right] \tag{11}$$

With $$\tilde{\alpha}_i = \tilde{l}_i(w_R - w_L) \tag{12}$$

where $\tilde{\lambda}_i$, $\tilde{r}_i$ and $\tilde{l}_i$ are respectively the eigenvalues, right and left eigenvectors of the locally averaged Jacobian matrix $\tilde{A} = A(\tilde{w}) = {\partial f}/{\partial w}$.

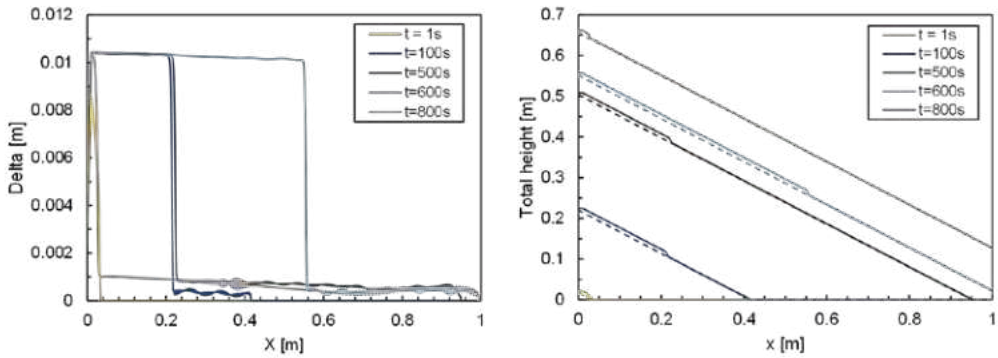
2.3. Verification and validation

In the context of developing an accurate and credible simulation code, it is a major concern whether the presented model and its results are "correct." This concern is addressed through model verification and validation (V&V).

2.3.1. Numerical results

Two numerical experiments including the debris bed formation in a closed system (i.e., with closed boundary conditions) and bed formation in an open system (characterized by an open boundary on its right side) are considered in the present section for its numerical evaluation. Both geometries have closed boundaries on the left side, representing the symmetry axis of the bed. For both test cases, A homogeneous continuous mass of mono-dispersed particles (mean diameter $d_p = 5\,mm$) is released at $t = 0\,s$ from the top into the systems with a constant flowrate $v_y(y = \delta) = -10^{-2} m s^{-1}$. The poured jet of particles has the width of six cells (with $\mathbf{\Delta x} = \mathbf{10^{-3}}$). The material has the angle of settlement $\beta_s = 28°$ and the angle of movement is equal to $\beta_m = 40°$ .The computation domain is $\mathbf{x} \in [0,1]$ in dimensionless length unit.

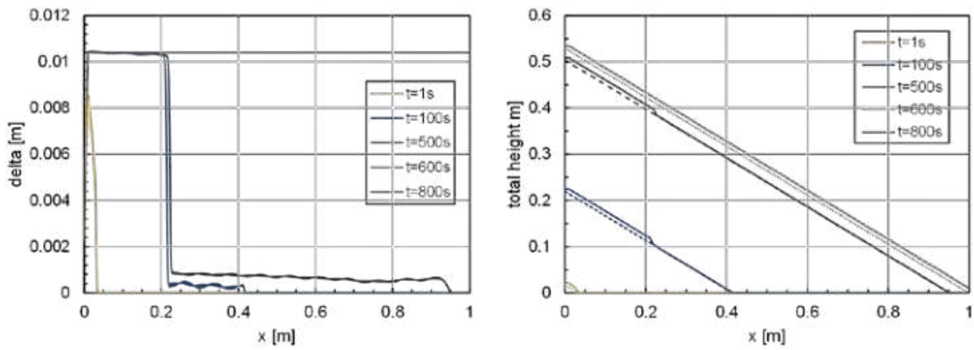
The results of the first test case in the closed system are displayed in Fig 3, where Fig 3(a) represents the growth of the layer thickness in time, and on the right side, the total height (the sum of $\mathbf{h}$ and δ) is depicted in Fig 3(b). It can be deduced that the bed height and the layer thickness are increasing over time. A moving layer front can be seen as a result of the new deposed particles on the static bed. It is moving down the slope in the form of small avalanches until reaching the bottom, leading to a corresponding increase in the bed height. By reaching the closed boundary on the right side of the system, a reflection on the wall can be obviously seen, and the bed height continues to increase in time, preserving the same angle of settlement.



(a) Layer thickness

(b) Bed height

Fig 3. Bed formation in a closed system



(a) Layer thickness

(b) Bed height

Fig 4. Bed formation in an open system

The results of the second test case in the open system are displayed in Fig 4. Similarly to the closed system in the first 528 s, the bed is growing in time until reaching the open boundary, where it remains constant, and the new deposed particles are flowing within a constantly thick layer down the slope without being eroded or absorbed by the static bed, until reaching the open boundary and leaving the system. It can be concluded from Fig 4(b), that a steady state is achieved. This particular steady state will be of great importance in the following subsection for the analytical verification of the model.

2.3.2. Analytical verification

As shown in Section 2.3.1, the height of the bed in an open system will remain constant after a certain time. When reaching the open boundary, a steady state is achieved. This state is characterized by a constant thickness and constant particles velocity in the flowing layer. In a steady state ($\partial\delta/\partial t = 0$, $\partial u/\partial t = 0$) and according to Equation (5) (for sufficiently thick layer), the conservation equations system (1) and (2) is simplified to the following system:

$$\begin{cases} \gamma\delta \dfrac{\partial \delta}{\partial x} = v_{y\,(y=0)} - v_{y\,(y=\delta)} \\ \gamma^2 \delta \dfrac{\partial \delta}{\partial x} = -g \dfrac{\sin(\beta_m - \beta)}{\cos \beta_m} - \gamma v_{y\,(y=\delta)} \end{cases} \tag{13}$$

Combining both equations of the system yields:

$$v_{y\,(y=0)} = \frac{-g \sin(\beta_m - \beta)}{\delta \cos(\beta_m)} \tag{14}$$

Figure 3.7b shows the solution with the Roe-solver of the total height ($h + \delta$) growth over time. In this numerical experiment, a steady state is achieved for $t > tc = 528s$, where particles are neither eroded nor absorbed. According to Equation (14), the angle β should be constant and equal to β_m and the particles are flowing with a constant velocity in a constantly thick layer ($\frac{\partial \delta}{\partial x} = \frac{\partial u}{\partial x} = 0$). These results are satisfyingly confirmed with the observations of the present numerical experiment.

Furthermore, it can be concluded that the flow rate of the poured particles $\dot{m}_{in}$ into the system through the opening Δw is equal to the flow rate of the flowing particles in the layer on the top of the steady heap. The layer thickness in the steady state can be analytically solved as follows:

$$|v_{y\,(y=\delta)}|\Delta w = \delta u \xrightarrow{yields} \delta = \sqrt{\frac{2|v_{y\,(y=\delta)}|\Delta w}{\gamma}} \tag{15}$$

As shown in Tab 1, the numerical simulations with the Roe-solver are in excellent agreement with the analytical solution in Equation (15).

Tab 1: Comparison of the numerical simulations and the analytic solution in an open system

	$\delta\,[m]$	$u\,[m/s]$
Numerical	$1.04 \cdot 10^{-2}$	$5.286 \cdot 10^{-2}$
Analytical	$1.04 \cdot 10^{-2}$	$5.286 \cdot 10^{-2}$

2.3.3. Experimental validation

The primary goal of the BeForE-facility (**Be**d **For**mation **E**xperiment) is to study visually phenomena of particles deposition and relocation forming debris bed with the water presence and an upward-flowing gas. The whole set-up of the experimental facility is depicted in Fig 5. The apparatus consists of three major parts: **(i)** the viewing bin, **(ii)** the particles pouring system, and **(iii)** the compressed air injection system. To permit visual observation and video recording, the viewing bin consists of a transparent tank made with two vertical Plexiglas walls with the dimensions of 1450 mm in width and 1950 mm in height. The two walls are separated by a gap of 100 mm. Water was poured into the vessel from the top and water-depth was adjusted at a constant height of 1800 mm. The upper side of the vessel is connected to the pouring system via a flexible cylindrical tube with a variable diameter. Aiming at isolating the viewing bin from the vibrations caused by the motor, the pouring system is placed at the height of 3200 mm on a separate structure. It is composed mainly of a feed hopper and a motor-driven screw conveyor, serving as variable rate feeder of solid particles. In the present work, water and compressed air were employed to simulate the coolant and generated steam caused by the boiling inside the bed respectively. For that purpose, an injection system is mounted at the height h=450 mm inside the transparent vessel to hold the falling particles from the pouring system and to control locally the air injection into the porous bed. As shown in Fig 5(a), the air injection system is made up of seven separated Plexiglas air chambers (perforated on its upper side with Φ 0.5mm holes). Depending on the granular mass on the top of each chamber, the airflow rate in every chamber is monitored separately and adjusted in time, with the use of real-time image processing and motor-driven control valves.

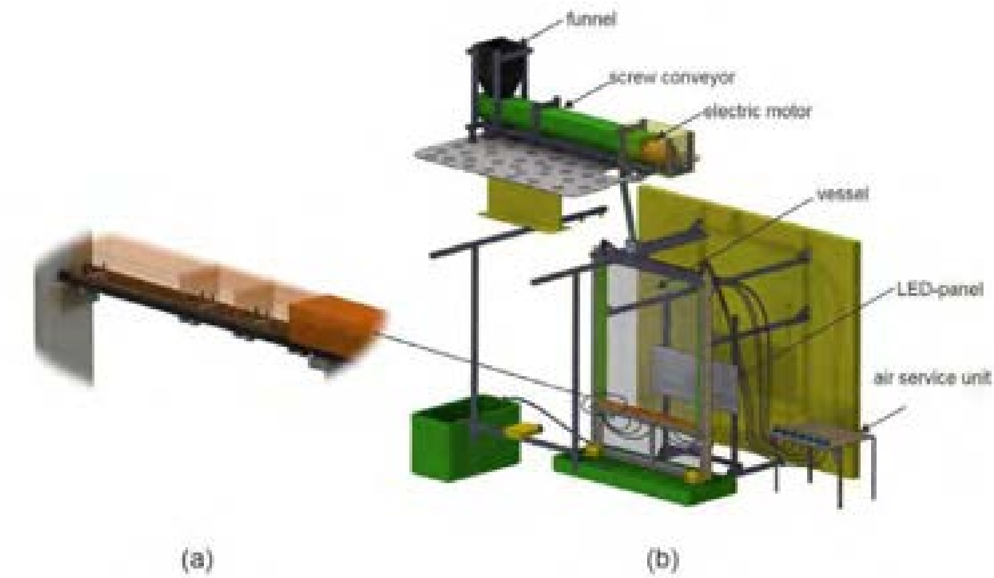


Fig 5. CAD-model of the BeForE facility: (a) the air injection cubes (b) the main apparatus

To simulate the fuel debris, 4 kinds of particles with different sizes and shapes were used. A series of experiments were conducted using gravel and aluminium particles, the properties of which are listed in Tab 2. In order to have a reliable validation, the main physical properties of particles influencing the developed model are measured and determined in other dedicated small facilities [4].

Tab 2: Physical properties of particles

	aluminum	sand	fine gravel	coarse gravel
Particles morphology	irregular		edge rounded	
Bulk density $\left[\frac{g}{cm}^3\right]$	2.33		2.54	
Size distribution $[mm]$	2.0 - 4.0	1.0-2.0	2.0 - 3.15	5.6 - 8.0
Eqv. diameter $[mm]$	3.75	1.45	2.13	6.48
Static angle of repose	40°	30°	32°	35°
Porosity ε	35.3%	38%	40%	39.3%

In order to gain first insights into the bed formation process, a series of experimental runs are initiated, by discharging the same amount (20 l) of particles with various sizes (coarse gravel: 5.6−8 mm/ aluminium: 2−4 mm/ fine gravel: 2−3.15 mm /sand: 1 − 2 mm) and shapes (rounded edges and irregular shaped) into the two-dimensional water vessel. Fig 6 depicts the effect of particle diameter [(a)-(c)] and the shape [(b) and (d)] on the bed formation process and the motion of the particles in the water. Based on the quantitative observations of the recorded runs, characteristics of the bed formations behaviour were analysed and compared. It is found, that due to the various interactions between solid particles and the water vessel, different particles deposition and relocation regimes could be identified.

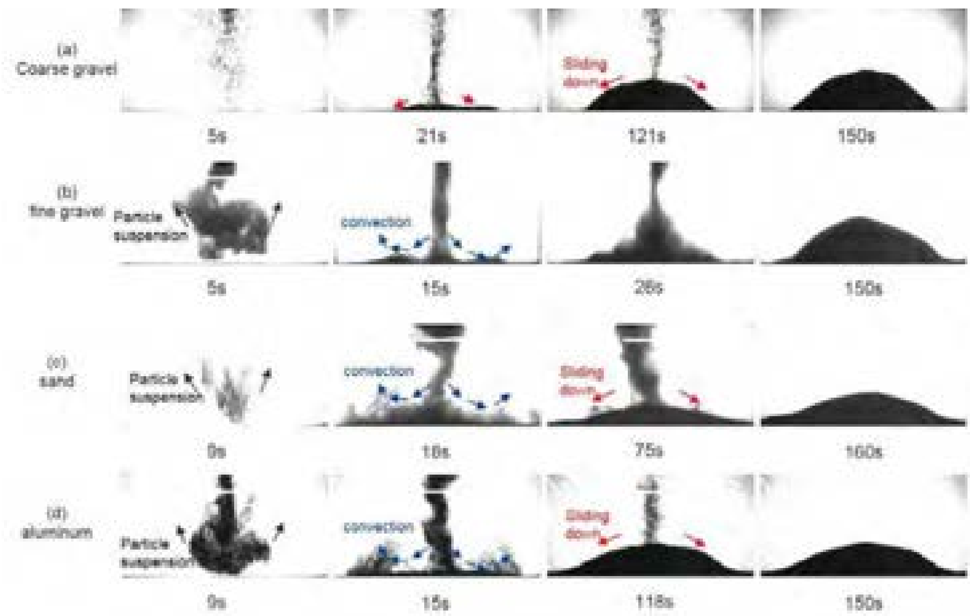


Fig 6. Time sequence snapshots of bed formation for several particles (V = 20L)

Three different regimes could be recognized depending on the particle's diameter and density. Depending on our observations, each regime is characterized as follows:

- **Sliding regime (inertial-dominant regime)**: this regime can be observed for gravel particles with d_p ≥ 3 mm approximately. Due to their inertia, particles are falling down vertically in the water vessel and form a delta-shaped bed until reaching the critical angle of repose. Then the slope will remain constant, and the particles are "sliding" down the slope within a thin layer on the top of the nearly quiescent heap, as initiated and assumed in section 2. Unlike the below presented regimes, the sedimentation was not heavily influenced by the fluid convection flows inside the vessel or by the following particles jet. This regime is dominated by the particles inertia and the particle-particle interactions (friction, collision) listed in section 2.1.
- **Convection-dominant regime:** this regime is found to exist for gravel and aluminium particles with 1.5 mm< d_p < 3 mm. Forced by the continuous inflow of particles, a pool convection can occur leading to a lateral displacement of the smaller (and lighter) particles. At the early stage, the pool convection may lead to the formation of (initially) concave beds with two mounds at its top. Depending on the mass flow rate and the jet diameter (more precisely depending on the ratio $\frac{d_p}{W_p}$, with W_p being the release pipe/jet diameter), the final mound top shape may change from concave to convex. The relative smaller particles can also be pushed away by the subsequent particles flow, leading to a decreasing of the bed height.
- **Particle-suspension regime:** for sand particles, this regime could be observed for d_p ≤ 1.5 mm. Due to their decreasing inertia, these light particles are more likely to be suspended in the water vessel. The poured particles tend to be ejected by the fluid convection inside the bed and to also be distributed (nearly in a uniform way) inside the vessel. The suspended particles will sediment gradually on the pool bottom leading to the flattering of the bed.

- Since the used samples are composed of poly-dispersed particles with different size ranges, it is possible that more than one regime can occur simultaneously during the formation process. Besides, **transitional** regions can also be seen between the different regimes, since its margins cannot be certainly and precisely determined.

In the present experimental work, the following conclusions can be drawn from the regimes identification above: in addition to the assumption taken in section 2.1 that the falling particles will settle around the centre to slide down the slope within a thin layer on the top of a nearly quiescent bed (see the red arrows in Fig 6), a pool convection could also be observed for smaller particles (see Fig 6(b)-(d)). This convection is caused by the entrainment of debris into the water driving the particles laterally in the vessel. The particles are also forced by the continuous inflow of the following particles to be pushed away from the centre forming two small mounds at the bottom (see Fig 6(b) t = 15s). This lateral relocation of the particles has a big influence on the final dimensions leading to the levelling of the bed and its extension horizontally. It could also be observed, that the smaller particles (< 1 mm) are ejected by the jet flow and suspended around the vessel due to their light weight and settle uniformly on the bottom. This small particles suspension leads to the flattering of the bed and diminution of the height.

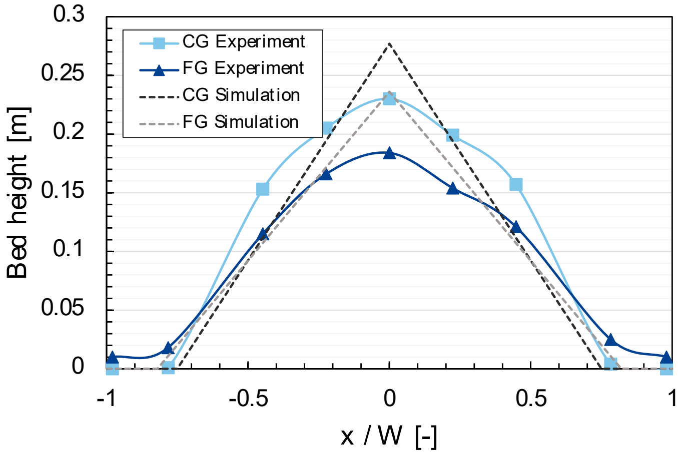


Fig 7. Comparison of the height profiles for the coarse (CG) and the fine (FG) gravel beds between the numerical and experimental results

Fig 7 shows a comparison between the experimental results and the numerical simulations for the fine and coarse gravel. The model could give a good numerical prediction of the bed height (with a mean error of 17.5% for coarse gravel and 27% for fine gravel). The model is overestimating the bed height and underestimating its width. In addition to the measurement uncertainties, this deviation between the numerical model and experimental data can be explained by the fact that this continuum model is only taking into account the particles sliding and cannot simulate the convection flow or the suspension of individual particles. Therefore, the numerical simulation is in better agreement with the reality for the case of the bigger particles (i.e., for d_p ≥ 3 mm approximately → mainly for coarse gravel), which should be owing to the absence of these phenomena. Nevertheless, it can still deliver a very good prediction of the reality for smaller particles.

3. Boiling effect on debris bed formation

In this section, the gas inflow effect on the debris formation process will be investigated theoretically and validated experimentally using the BeForE-facility (already presented in Section 2.3.3). Steam bubbles generated from the decay heat in the corium particles were simulated using locally controlled injection of compressed air into the bottom of the bed. The dynamics of the porous bed under the influence of "space-" and "time-dependent" natural convection with an increasing rate of airflow resulting from the increased quantity of settled particles was simulated in a stepwise manner thanks to a real-time image processing and control system.

3.1. Influence of the two-phase flow on the mathematical modelling

When vertical stream of gas is passed through a granular bed, an additional drag force as a result of the gas pressure gradient is acting on the surface layer of the moving particles, which alters its movement. The balance between the main forces is shown schematically in Fig 8.

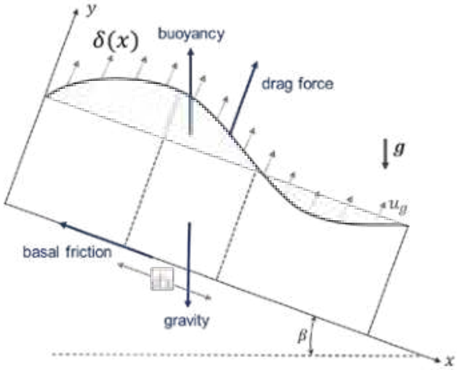


Fig 8. Schematic of the main forces acting on the surface flow of the moving particles

This additional drag force, changing the acting normal forces in the flowing layer, will influence the shear stress on the boundary between the layer and the quiescent bed. The Coulombic frictional stress (as defined originally in Equation (3)) can be then defined as follows:

$$\tau_{xy_C} = -\delta \tan(\beta_s) \cdot (\cos(\beta)\rho_s g - \nabla p_g) \tag{16}$$

Where ∇p_g is the pressure gradient induced by the gas flow into the porous particles layer. The calculation of the pressure drop is performed with a dedicated numerical model simulating the two-phase flow within the bed. Both A modified static angle of repose $\widetilde{\beta}_s$ can be calculated as a function of the bed height and the resulting gas flow according to the following definition:

$$\tau_{xy_C} = -\delta \rho_s g \cos(\beta) \tan\left(\widetilde{\beta_s}(x,t)\right) \tag{17}$$

It yields:

$$\tan\left(\widetilde{\beta}_m(x,t)\right) = \tan(\beta_m) \cdot \left(1 - \frac{\nabla p_g(x,t)}{\cos(\beta)\rho_s g}\right) = f_s \cdot \tan(\beta_m) \tag{18}$$

The new definition of the angle implied that the characteristic angle of settlement is no more a material property, which is constant across the entire calculation domain. However, the local angle of settlement will decrease in time with higher beds under the influence of the increasing coolant boiling leading to a reduction of the friction forces and hence to an increase of the avalanche thickness on the mound top surface. According to this mathematical description and the experimental observations in the BeForE-facility, the self-leveling of the particles bed will occur on the top surface of the bed in the form of episodic avalanches down the slope leading to a flatter and wider bed than the one built under quiescent conditions.

The same applies for the definition of the shear stress at the bed-avalanche interface $\tau_{xy}(y=0)$ as described by Equation (4). It implies that the angle of movement βm will be also similarly reduced with the same reduction factor f_s. Thus, the new definition of the reduced angle of movement is obtained:

$$\tan\left(\tilde{\beta}_m(x,t)\right) = \tan(\beta_m)\cdot\left(1 - \frac{\nabla p_g(x,t)}{\cos(\beta)\,\rho_s g}\right) = f_s \cdot \tan(\beta_m) \quad (19)$$

A two-way coupling is considered between the model simulating the two-phase flow within the bed (as described in detail in [4]) and the bed formation model (as defined in Section 2.1). This is illustrated in Fig 9. The bed height function h(x) is updated with the bed formation model at each time step. Based on the local height and the particles volume in each cell, the pressure drop ∇p will be actualized separately with the two-phase flow model, and the characteristic angles will be changed according to Equations (18) and (19). With these modified values, the bed formation model will be executed correspondingly at the subsequent time step.

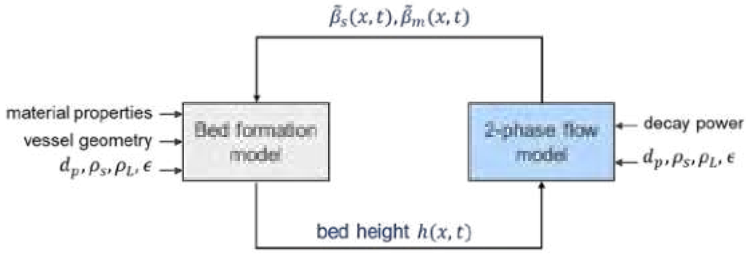


Fig 9. Coupling of the bed formation model with the two-phase model

Since the angle of movement β_m is defined as the maximum angle of repose, at which an avalanche starts flowing when exceeding it, it can be deduced from Equation (19) that the formed bed under two-phase flow conditions will settle at lower slope angles than the material's characteristic value. The slope angle at the mound top will be smaller than the angle of repose at its bottom, which will lead to an alteration of the bed overall shape (as depicted clearly in the numerical results in Fig 10).

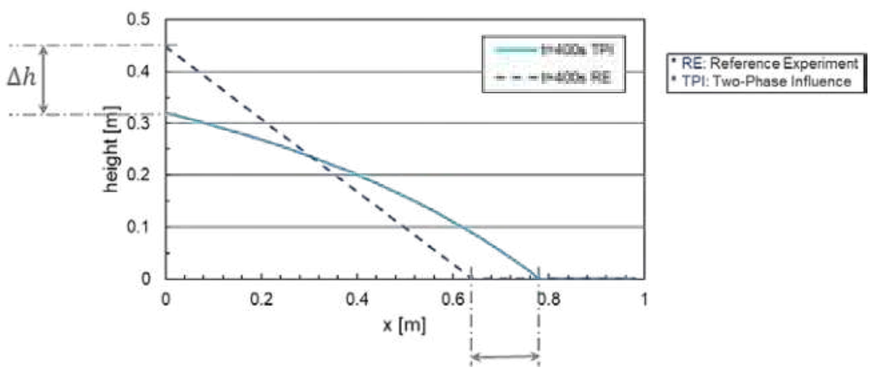


Fig 10. Comparison of the numerical result of the bed height with and without the influence of coolant boiling (closed system)

3.2. Experimental results and validation

Background (gray) without boiling (RE), foreground with 2-phase flow (TPI)

Fig 11. Comparison of the formed bed with and without the two-phase flow

Fig 11 shows a comparison between the cross-sectional profiles of debris beds formed with (TPI) and without (RE) the influence of interstitial gas flow for aluminium particles. It can be concluded that, in the absence of the gas inflow the particles are falling (mostly) in a narrow area in the centre of the viewing bin, and the bed grew rapidly (see Section 2 for bed formation without coolant boiling). In the TPI tests, the upward gas flow was intersecting with the downward particles flow, altering its trajectory and broadening the particles over a wider region of the vessel. The resulting bed is then flatter and broader and rises slower than in the reference test. On top of the influence on the falling particles jet, the two-phase flow induces a movement of the upper surface of the already formed bed, which will start flowing in the form of episodic avalanches within a thin layer down the slope, contributing to the flattering of the bed. These experimental results concur with the theoretical description alluded in Section 3.1, which has shown that the coolant boiling will lead to the flattering of particulate beds.

For the comparison of the experimental results with the numerical simulations, the height levelling will be defined as follows:

$$Height\ leveling = \frac{\boldsymbol{h}_{bed}(RE) - \boldsymbol{h}_{bed}(TPI)}{\boldsymbol{h}_{bed}(RE)} \tag{20}$$

By comparing this height levelling percentage for the different kinds of particles in Fig 12, it can be concluded that:

- First, a qualitative good agreement for the coarse and fine gravel and the aluminium can be depicted. However, the experimental results for the sand bed are not compliant with the numerical model, which can be explained by the higher influence of the water-particle interaction for such light particles, as illustrated also in Section 2.3.3.
- Second, it can be evinced, that the height levelling in the numerical model is stronger than in the experiments due to the fact of having higher beds in the reference experiment (RE) without coolant boiling (see Fig 7).

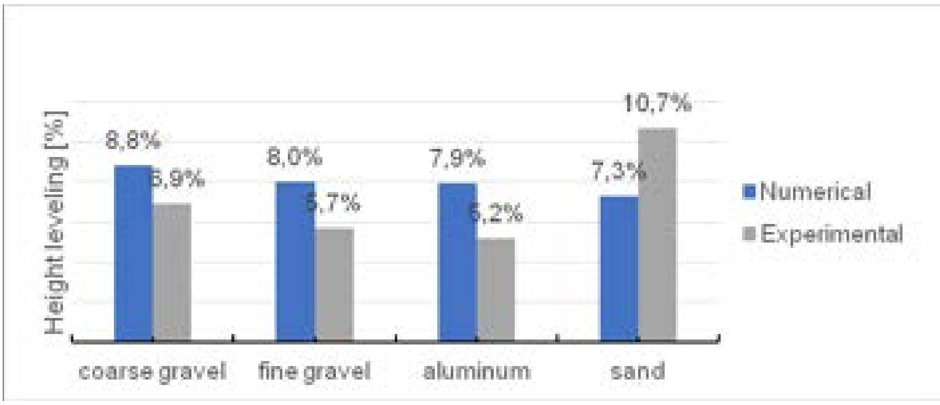


Fig 12. Comparison of the height levelling between the numerical and experimental results

4. Conclusion

The understanding of the bed formation process is of interest in the field of the nuclear safety analysis for the assessment of debris bed coolability. Since most previous numerical studies of ex-vessel severe accidents were limited to the assumption of the whole bed, being fixed and also initially established at a uniform temperature is not realistic, the present work concentrates on the development of a numerical module, simulating solid particles dynamics with and without the influence of coolant boiling, and on its validation with experimental data, with the final aim of clarifying the bed formation mechanism.

A new numerical model for the deposition and relocation of solidified particles was developed in the framework of the present study. It is based on the depth averaging of the conservation equations in the flowing layer of the newly deposed particles over the bed. The hyperbolic system of differential equations could be discretized and implemented with the use of the Riemann's Roe solver, which was also verified with an analytical solution in the steady state. A series of experiments have been conducted in order to study the key parameters of the bed formation and to validate the numerical model. It could be evinced, that in addition to the modelled particles sliding the smaller particles (<3mm) are subject to the influence of a suspension and convection flows inside the water vessel, which is influencing the final bed form. The comparison between the numerical and the experimental results has shown a very good agreement between them especially for the cases where the two last mentioned phenomena are not present.

Moreover, the geometrical configuration of the porous bed, and hence its ability of decay heat removal, can also change due to the particles redistribution induced by steam production within the bed. In this work, the influence of steam production on bed formation was investigated experimentally with the same BeForE-facility and the modelling approach could be successfully adapted and experimentally validated to take into account the self-levelling phenomenon by coupling the developed continuum model of particles deposition and relocation with a numerical model simulating the two-phase flow within the bed. This two-way model-coupling and the consideration of the reduced angles of repose enable more accurate numerical simulations of the bed formation process in degraded cores of light water reactors.

References

[1] N. Reinke, T. Drath, T. v. Berlepsch, H. E. Unger, and M. K. Koch, “Formation, characterisation and cooling of debris,” Nuclear Engineering and Design, vol. 236, no. 19-21, pp. 1955–1964, 2006.

[2] D. Magallon, “Formation and characterisation of corium debris arising from fuel-coolant interaction,” Nucl. Eng. Des, vol. 236, pp. 1998–2009, 2006.

[3] D. Magallon and H. Hohmann, “High pressure corium melt quenching tests in FARO,” Nuclear Engineering and Design, vol. 155, no. 1-2, pp. 253–270, 1995.

[4] W. Hilali, “Debris bed formation in degraded cores of light water reactors,” 2019.

[5] B. Zhang et al., “Self-leveling onset criteria in debris beds,” Journal of nuclear science and technology, vol. 47, no. 4, pp. 384–395, 2010.

[6] H. D. T. Y. G. Y. M. T. M. K. F. K. Cheng S., Ed., Experimental study of bubble behavior in a two-dimensional particle bed with high solid holdup, 2010.

[7] J. D. Gabor, “Simulation Experiments for Internal Heat Generation,” Reactor Development Program Progress, Report, vol. ANL-RDP-32, pp. 7–50, 1974.

[8] S. Basso, “Experimental and Analytical Investigation of Particulate Debris Spreading,” Master Thesis, KTH Engineering Sciences, Stockholm, Sweden, 2011.

[9] U. Müller and C. Günther, Post accident debris cooling: Proceedings of the Fifth Post Accident Heat Removal Information Exchange Meeting, July 28-30, 1982, Nuclear Research Center Karlsruhe, Karlsruhe. Karlsruhe: G. Braun, 1983.

[10] B. Zhang et al., “Experimental investigation on self-leveling behavior in debris beds,” Nuclear Engineering and Design, vol. 241, no. 1, pp. 366–377, 2011.

[11] S. Basso, “Particulate Debris Spreading and Coolability,” KTH, Nuclear Power Safety, 2017.

[12] S. Basso, A. Konovalenko, and P. Kudinov, “Empirical closures for particulate debris bed spreading induced by gas-liquid flow,” Nuclear Engineering and Design, vol. 297, pp. 19–25, 2016.

[13] S. Cheng et al., “Experimental Studies and Empirical Models for the Transient Self-Leveling Behavior in Debris Bed,” Journal of nuclear science and technology, vol. 48, no. 10, pp. 1327–1336, 2011.

[14] M. Y. Matsuo, D. Nishiura, and H. Sakaguchi, “Geometric effect of angle of repose revisited,” Granular Matter, vol. 16, no. 4, pp. 441–447, 2014.

[15] T. S. Komatsu, S. Inagaki, N. Nakagawa, and S. Nasuno, “Creep motion in a granular pile exhibiting steady surface flow,” Physical review letters, vol. 86, no. 9, pp. 1757–1760, 2001.

[16] R. J. LeVeque, Finite volume methods for hyperbolic problems. Cambridge and New York: Cambridge University Press, 2002.

[17] J. E. Marsden, L. Sirovich, F. John, E. Godlewski, and P.-A. Raviart, Numerical Approximation of Hyperbolic Systems of Conservation Laws. New York, NY: Springer New York, 1996.

[18] P.L. Roe, “Approximate Riemann solvers, parameter vectors, and difference schemes,” Journal of Computational Physics, vol. 43, no. 2, pp. 357–372, 1981.

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HYDRAULIC AND STATISTICAL STUDY OF METASTABLE PHENOMENA IN PWR ROD BUNDLES

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Abstract: The analysis of fuel rod bundle flows constitutes a key element of Pressurized-Water Reactors (PWR) safety studies. The present work aims at improving our understanding of nefarious reorganisation phenomena observed by numerous studies in the flow large-scale structures. 3D simulations allowed to identify two distinct reorganisation consisting in a sign change for either a transverse velocity in rod-to-rod gaps or for a subchannel vortex. A Taylor "frozen turbulence" hypothesis was adopted to model the evolution of large-scale 3D structures as transported-2D. A statistical method was applied to the 2D field to determine its thermodynamically stable states through an optimization problem. Similarities were obtained between the PWR coherent structures and the stable states in a simplified 2D geometry. Further, 2D simulations allowed to identify two possible flow bifurcations, each related to one of the reorganisations observed in 3D simulations, laying the foundations for a physical explanation of this phenomenon.

1. Introduction

Insufficient flow thermal mixing in the rod bundles within a Pressurized-Water Reactor (PWR) can lead to a boiling crisis, which is nefarious for the reactor operational safety. Mixing grids are typically used to enhance the thermal mixing inside fuel arrays, mostly through the intensification of the secondary flows. These secondary flows have a tendency to organize into large-scale structures in the plane normal to the tube axes. Numerous experimental or numerical studies have shown the existence of reorganisation phenomena in the transverse flow large-scale structures (see the review in appendix A from Kang and Hassan [8]). In particular, the AGATE experimental results [3] featured a global 90° rotation of the cross-flow pattern between the near and the far wake of a mixing grid. This reorganisation is shown in figure 1: a sketch of a 5 x 5 rod bundle fitted with a mixing grid, as well as colour plots of the transverse flow downstream a mixing grid are shown. The cross-flow is aligned with a 45° angle in the first one, but has rotated by 90° in the second one.

Such reorganisations are very significant for reactor safety studies: due to the points with zero cross-flow they induce, they lead to drops in the thermal mixing as demonstrated by

Shen et al. [6], which can pose a serious risk to the PWR reactor operational safety. This work aimed at improving our understanding of these phenomena, both for enhancing their characterization and for identifying their origin, with the long-term goal of developing small-scales models suited for this type of flow.

Little concrete information can be found in the literature on the reorganisation phenomenon. This is due to the lack of high-quality experimental where the phenomenon typically occurs, and to the fact that, among the variety of Computational-Fluid Dynamics (CFD) numerical simulations performed for rod bundle flows, few were conducted for the entire rod bundle axial span and with high-fidelity turbulence models. Attempting a new method, we focused on a physical approach to the reorganisation phenomenon by proposing an original method for the study of the rod bundle flow. A similarity was noticed between PWR rod bundle flow reorganisations and some phenomena typically experienced by quasi-2D geophysical flows, such as the Jupiter Red Spot or the Gulf Stream [13]. Indeed, the latter sometimes display important changes in their structure, leading to oscillations between very distinct solutions. These phenomena can be interpreted as phase transitions between different equilibrium states which become metastable.

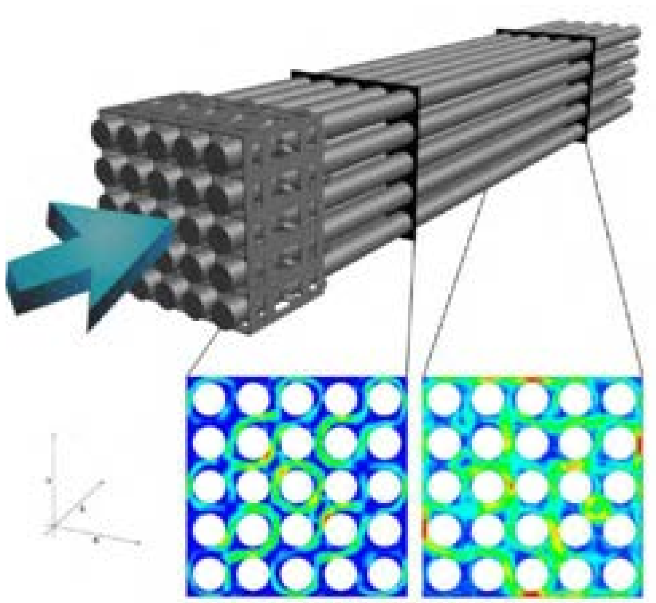

Fig 1. Sketch of a rod bundle and colour plots of the transverse velocity field downstream the mixing grid.

In order to study the reorganisation phenomena from the perspective of this similarity with 2D flows, the following steps were taken. 3D simulations were first performed in order to decompose the large-scale reorganisations into local inversions, and to justify a Taylor "frozen turbulence" hypothesis, as described in section 2. Section 3 details the 2D statistical method that was applied in simplified geometries with obstacles based on this hypothesis. The stable states obtained through this method are then used in 2D free decay simulations in section 4, highlighting similarities between their phase transitions and the 3D reorganisation phenomenon. Section 5 provides a conclusion on the physicality of the reorganisation phenomenon.

2. 3D CFD simulations

We performed 3D CFD simulations in rod bundles using the TrioCFD [1] code along with a WALE sub-grid scale turbulence model, in a tetrahedral mesh of 34.4 million cells and using in parallel 1000 CPU cores. Details on the numerical performance of this code were discussed by Angeli et al. [2]. The flow was characterized by a Reynolds number Re = 96000. Cross-flow reorganisations were observed in the simulation results, as depicted in figure 2: the averaged transverse flow at 30 mm downstream the mixing grid in the first plot displays a 45° orientation, while that at 150 mm in the second plot is aligned with the 135° diagonal. A significant impact of the numerical schemes used was also noted, which is a topic still under investigation by the community. Most importantly, we could distinguish two particular types of local cross-flow reorganisations.

The cross-flow can undergo an inversion of the transverse velocity between two rods, or a sign change for a vortex in the center of a subchannel (the vacant space between four rods). Different combinations of “velocity inversions” around a subchannel (e.g. one to four inversions) can lead to a variety of pattern changes, one of which is a global 90° rotation of the cross-flow pattern. This type of inversion was already noted in previous work by Shen et al [6].

Besides, we also observed in the 3D simulation results multiple sub-channels featuring a cross-flow pattern change without any gap flow inversion. Instead, the circulation inside these sub-channels seemed to vary greatly. This increase consisted either in a sign change for the subchannel vortex if one was present, or the apparition of a vortex in a pure shear flow. One of the possible large-scale pattern changes obtained was the 90° rotation of the subchannel cross-flow pattern.

Remarkably, the same final patterns can be obtained after each of these two reorganisations through two different flow evolutions, providing a more nuanced view of the possible reorganisations in rod bundle cross-flows.

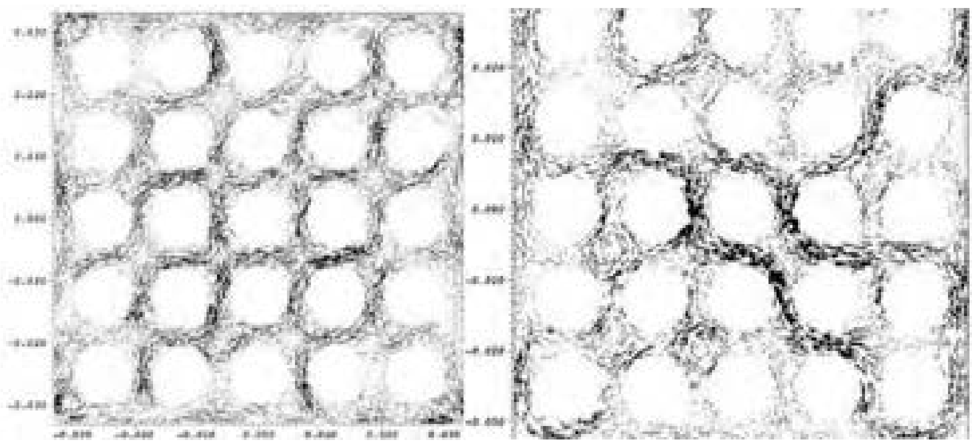

Fig 2. Averaged transverse velocity field from a LES simulation of the flow in a 5 x 5 rods fuel assembly, at 30 mm (left) and 150 mm (right) downstream a mixing grid.

In order to tackle the reorganisation phenomenon, it was decided to adopt an approach based on a statistical fluid mechanics point of view and relying on a Taylor "frozen turbulence" hypothesis. This hypothesis is commonly used in meteorological flows (see Higgins et al. [7]) where local turbulent eddies are advected by a mean wind and are considered "frozen" at a fixed position. Under this hypothesis, one can consider that a rod bundle cross-flow behaves as a quasi-2D flow transported by the axial component of the velocity field. This hypothesis allows to decompose the 3D velocity field $\boldsymbol{u}(x,y,z,t)$ into:

$$\boldsymbol{u}(x,y,z,t) = \overline{u_z}\boldsymbol{z} + \overline{\boldsymbol{u}_{x,y}}(x,y,\overline{u_z}t) + \boldsymbol{u}'(x,y,z,t).$$

Here $\overline{u_z}$ is a uniform axial component, and $\boldsymbol{u}'(x,y,z,t)$ denotes the 3D turbulent fluctuations. The $(\boldsymbol{x},\boldsymbol{y})$ components form a purely advected transverse 2D part $\overline{\boldsymbol{u}_{x,y}}(x,y,\overline{u_z}t)$ that is assumed to abide by the 2D Navier-Stokes equations. In order to verify this hypothesis, the flow must display very small variations of the axial component $\overline{u_z}$ compared to that of the transverse flow field $\overline{\boldsymbol{u}_{x,y}}$, and a high scale difference between the axial and transverse components.

These criteria were mostly fulfilled outside of boundary layers and past the near wake of the mixing grid, notably with a scale ratio between the axial and transverse components of up to 30. Although deviations from the hypothesis are observed and should be investigated further, such a decomposition allowed us to apply statistical methods inspired by geophysical flow studies to the transverse 2D part.

3. 2D statistical approach

Past studies on 2D turbulent flows through the lens of statistical fluid mechanics have tackled a broad set of physical fields, from thin oceanic layers to the Red Spot in the Jovian atmosphere and experimental soap films. A crucial part of the study of such 2D flows is the prediction of the steady stable structures emerging from given initial characteristics and depending on the domain geometry. In the framework of PWR rod bundle flows, this prediction consists in the determination of stable patterns for the transverse flow, following “initial conditions” set by its passage through the mixing grid.

Instead of an exhaustive application of a dynamical stability criterion to the infinite set of steady solutions to the 2D Euler equations, an equivalence can be used between such a dynamical stability criterion and a constrained optimization problem, usually on a measure of the entropy with conservation of a varying set of Euler invariants, following the work from Miller, Robert and Sommeria [9, 12]. This allows for the use of several tools coming from mathematical optimization theory, and to directly calculate the expected steady state in a given 2D physical configuration.

Multiple theories have been devised to determine these stable states, leading to various constrained optimization problems. We have focused on the Minimum-Enstrophy-Principle (MEP) due to its relative simplicity and the linear equations it leads to. This principle was proposed from phenomenological considerations (see Bretherton and Haidvogel [4]), and it states that the stable flow regimes minimize the enstrophy of the system under constant energy and circulation. The enstrophy is defined as $\Gamma_2 = \int_\Omega \omega^2 \, \mathbf{dr}$, with ω the flow vorticity field and Ω the physical domain.

A resolution method for this problem was devised and proposed by Naso et al. [11], applicable to simply-connected domain geometries. We adapted this method to geometrical domains with internal obstacles in order to allow the consideration of typical rod bundle cross-section geometries. Each obstacle adds the conservation of the flow circulation around itself and thus another degree of freedom to the problem.

The minimization of the enstrophy under multiple constraints leads to a variational problem solved in our method through a projection on the Laplace eigenbasis. Scanning the parameter space and interpolating for constant energy, circulation and circulation around the obstacles allows to determine the stable solutions for any combination of the integral constraints. Details on the derivation of the solutions and on the method followed to explore the solution ensemble are available in Muller et al. [10].

Our method has been validated first through numerical convergence studies and recovery of literature results [5], before being applied in the case of a square domain with two diagonally-opposed obstacles. This simple geometry was designed as a basic model for a PWR rod bundle cross-section. In order to reduce the number of degrees of freedom in the problem, we assumed equal circulations around the two obstacles, justified by the typical cross-flow patterns observed downstream mixing grids in PWR rod bundle flows and shown in figure 1.

This approach resulted in the stability map shown in figure 3. Therein, $\Lambda^2 = \frac{\Gamma^2}{2E}$ with E the total flow energy combines the energy and circulation into one parameter, while Γ_1 is the circulation around the obstacles in this geometry. The thick black line indicates the minimal-enstrophy state, solution of our multiply-constrained optimization problem. Under the MEP, this solution is a stable flow for given values of the parameters $(\Gamma, \mathbf{E}, \Gamma_1)$. The light and dark grey areas respectively indicate areas of lower-enstrophy for 1- and 2-vortices solutions, but their enstrophy is systematically higher than that of the solutions on the black line. In the graph, β is related to the energy E and a_1 to the boundary condition on the obstacles. Interestingly, a single solution is stable for $\Lambda^2 > \Lambda^2_{crit}$, while two branches are stable for $\Lambda^2 < \Lambda^2_{crit}$. Further, the single branch features a central vortex aligned with the diagonal without obstacles and one vortex around each obstacle, while the upper branch for $\Lambda^2 < \Lambda^2_{crit}$ displays a single vortex around both obstacles on the opposite diagonal.

Therefore, two stable regimes differing by a 90° angle were obtained, which recalls the pattern reorganisations observed in PWR rod bundle cross-flows. Although in the 2D statistical approach, the parameters $(\Gamma, \mathbf{E}, \Gamma_1)$ are fixed due to their conservation by the Euler equations, they can be dissipated by viscosity in physical systems, leading to changes in the minimal-enstrophy solution and thus stable states. Phase transitions can thus occur between these states, which was investigated further in our study.

4. 2D free-decay CFD simulations

To further validate the methodology and the computational code for the statistical approach and check if a link could be established between the statistical approach and the CFD calculations, the case of the free relaxation of turbulent 2D flows has been studied afterwards. The objective was to compare the flow reached in the long-run of a 2D CFD simulation and the stable state predicted by the statistical approach, from initial conditions either random or designed to investigate particular flow regimes.

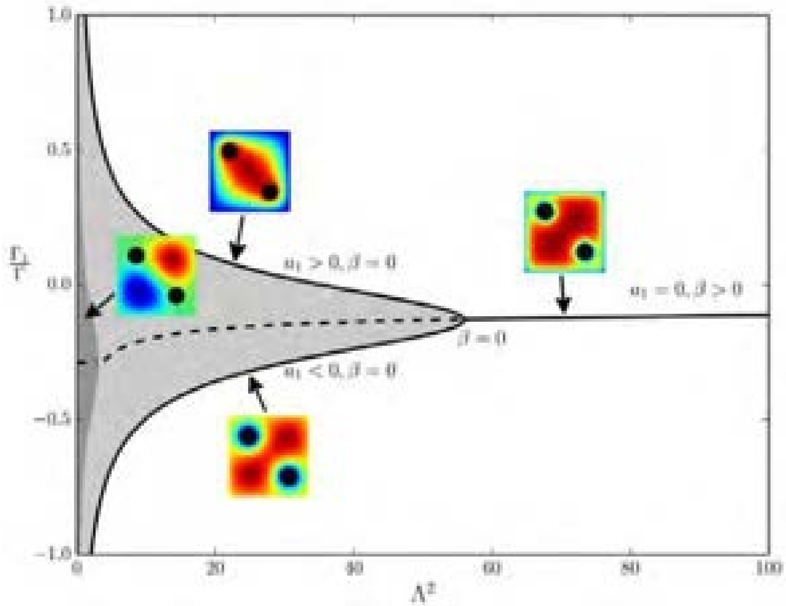

Fig 3. Stability map obtained in a square geometry with two obstacles, following the application of the Minimum-Enstrophy Principle. Depending on the value of the parameter Λ^2, one or two flow regimes can be stable in the domain.

The simulations were set up to feature as little diffusion as possible in order to conserve energy relatively well when compared to the spontaneous enstrophy dissipation. Similarly to the 3D simulations, the 2D simulations conducted in this study were based on the code TrioCFD [1]. They did not use any turbulence model. In order to allow the capture of most flow scales, moderate Reynolds numbers were chosen ($Re = 3000$). When choosing the numerical schemes, we opted as much as possible for the less dissipative ones: only slightly upstream convection schemes, a third-order Runge-Kutta time advancement method and a resolution of the pressure equation through a Cholesky method [2]. Regarding the boundary conditions, we used "stress-free" boundary conditions, which in practice amounted to a nullity condition on the normal velocity component at the boundary. We found this method to be the closest one to the physical framework of the statistical approach, where the existence of a non-zero circulation Γ_1 around the internal obstacles requires in turn the tangential velocity at the boundary of the obstacles to be non-zero.

We first validated the process by recovering final states in square and rectangular domain geometries in accordance with statistical mechanics literature results, and by capturing plausible turbulent cascades for the kinetic energy. The decay process obtained in a square geometry is shown in figure 4. In this geometry, the Minimum-Enstrophy Principle approach (see Chavanis et al. [5]) leads to a single central vortex as the only stable solution. Having initiated our simulation with an array of Taylor-Green vortices, it underwent a phase of strong mixing, before converging towards the expected single-vortex stable state.

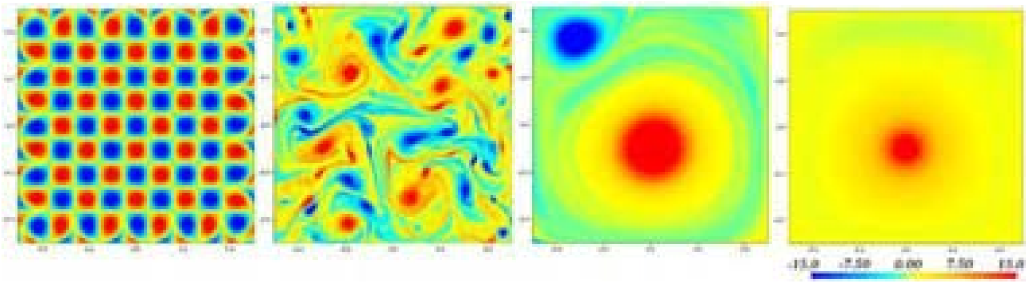

Fig 4. Colour plot of the vorticity field along a free decay 2D simulation in a square, from an array of Taylor-Green vortices to a minimal-enstrophy single vortex.

In the case of the square domain with two obstacles, the simulations were tailored to have initial conditions spanning the $\left(\Lambda^2, \frac{\Gamma_1}{\Gamma}\right)$ parameter space. This was performed through the initialization of the simulations with carefully designed analytical functions. Let $(\mathbf{O}, \boldsymbol{e}_r, \boldsymbol{e}_\theta)$ define a polar coordinate system with $\mathbf{O}$ the square center as origin point, $\boldsymbol{e}_r$ a unitary vector along the position vector $\boldsymbol{r}$ and $\boldsymbol{e}_\theta$ a unitary vector orthogonal to $\boldsymbol{r}$. The analytical functions for the simulation initial conditions were built through the addition of the following terms:

- A rigid body rotation term $\mathbf{u} = \Omega \mathbf{r} \boldsymbol{e}_\theta$ (with Ω an arbitrary angular velocity and $\mathbf{r}$ the distance to the origin $\mathbf{O}$) leading to a background vortex in the entire square domain.
- A single vortex around each obstacle, built for each one from the combination of a 2 × 2 array of Taylor-Green vortices with damping functions depending on the distance from the obstacle center.

The rotation sign of the obstacle vortices were set opposite to that of the central vortex, and the relative intensity of the two counter-rotating phenomena was varied between the different tests in order to adjust the initial value of $\frac{\Gamma_1}{\Gamma}$. The simulations were performed using two mesh refinements, both with 21,000 or 237,000 triangular cells. These limited resolutions were imposed by the limited resources available due to the large number of cases tested and the long simulated time required in each case. The starting points were all placed in the right-hand side of the stability map shown in figure 3, i.e. in the zone where the system should only present one stable solution. We thus hoped to observe the flow select either of the two branches when following the free decay process and having a decreasing Λ^2.

The energy, total circulation and circulation around the obstacles were calculated in order to observe the evolution of the freely-decaying 2D simulations in the $\left(\Lambda^2, \frac{\Gamma_1}{\Gamma}\right)$ stability map. The resulting evolutions are superimposed on the stability map in figure 5. Note that the flow remained quite symmetrical during the simulations, to the extent that the circulations around the two obstacles remained about equal. This allowed a comparison with the similar case of the square with two obstacles of equal circulations in section 3.

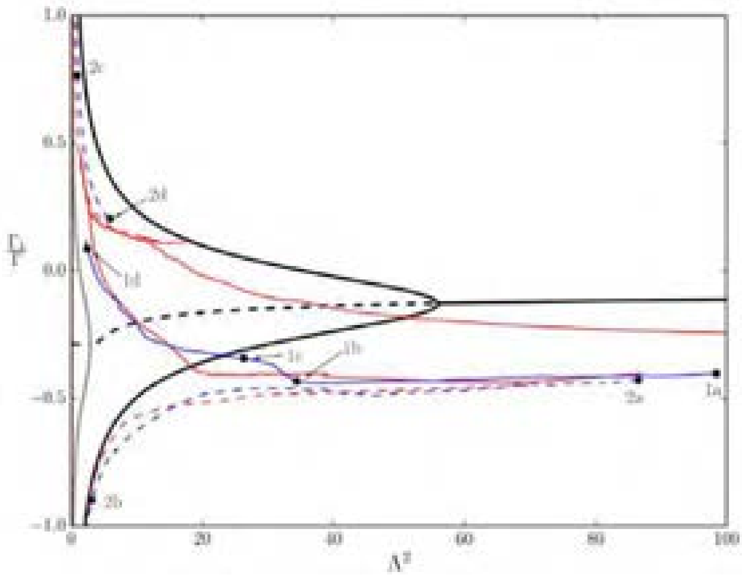

Fig 5. Decay processes (red and blue plots) in a square geometry with two obstacles, within the related stability map (fig 3). Two possible bifurcation paths were identified.

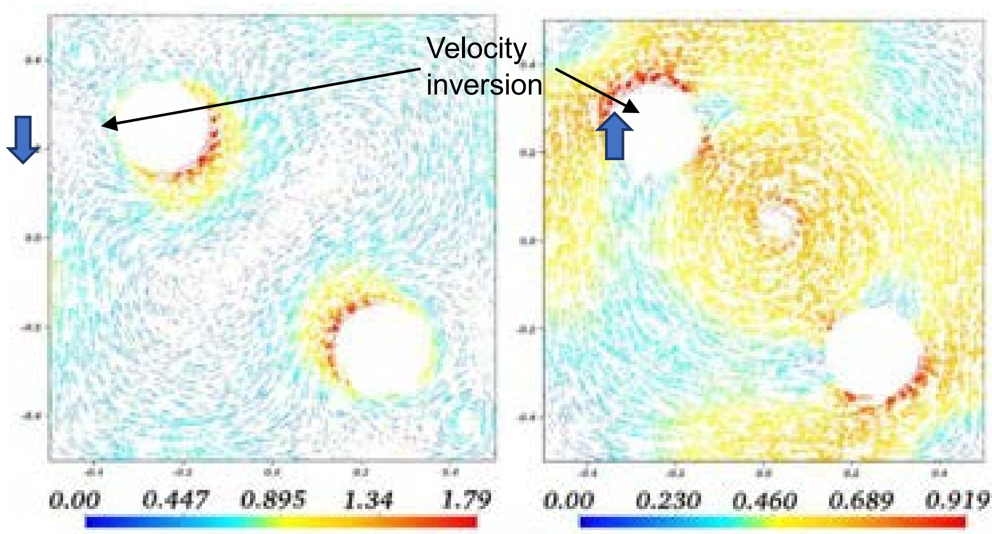

Fig 6. Decay process in a square geometry with two obstacles and with a type 1 inversion; each vortex around an obstacle switches its sign. The left and right plots correspond respectively to points "1b" and "1d" in figure 5.

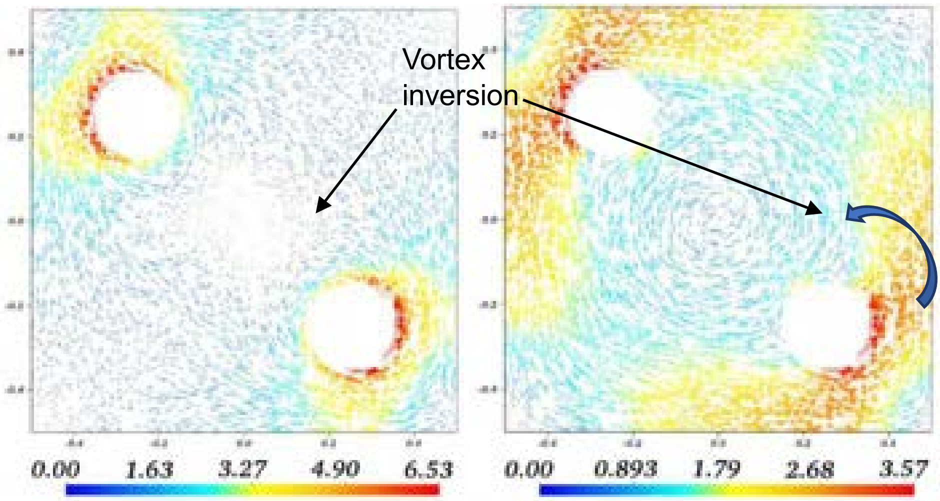

Fig 7. Decay process in a square geometry with two obstacles and with a type 2 inversion; the central vortex switches its sign. The left and right plots correspond respectively to points "2b" and "2c" in figure 5.

Among the 30 simulations tested from various initial points, two types of bifurcations were observed, respectively displayed as continuous and dashed lines in figure 5.

- Either the central vortex of negative vorticity was conserved while the vortices around the rods switched their rotation direction, implying a better conservation of Γ than Γ_1. This bifurcation is displayed in the velocity vector fields in figure 6, and is annotated from "1a" to "1d" in figure 5. Such a bifurcation implies a sign change for the velocity between obstacles and walls, recalling the "velocity inversion" phenomenon observed in our simulations in section 2 or from the work of Shen et al. [6].
- Or the central vortex switched its rotation direction, "forced" by the vortices around the obstacles which in this case are conserved. This bifurcation is displayed in the velocity vector fields in figure 7 (with a near-zero vorticity for the initial central vortex), and is annotated from "2a" to "2d" in figure 5. This bifurcation is comparable to the sign change for a subchannel vortex observed in our simulation results for rod bundle flows.

To assess the "pertinence" of the adopted approach based on 2D equations, different approaches were considered to establish links between flows obtained from 2D simulations and the cross-flows observed in planes orthogonal to the main axial direction in 3D simulation results.

First, initial and intermediary states from 2D free-decay simulations were inserted as a cross-flow into a 3D flow with a large advection velocity in order to observe the decay process in a quasi-2D setup. Similarities were observed between the transported-2D and 2D evolutions; in particular a comparable final state was observed in some cases. However this approach encountered significant challenges such as 3D diffusion, computational domain design and boundary layer effects. Second, a 2D simulation with an initial condition as the cross-flow taken directly after a 3 × 3 rod bundle mixing grid in a 3D flow has been realized. Parallels could be drawn between its resulting decay process and that observed in the 3D cross-flow, but the 2D simulation was observed to reach in the long run a symmetrical state definitely not achievable by the 3D flow due to the shortness of the rod bundle axial span.

The conclusion from these attempts is that the results obtained in 2D are difficult to directly transpose in the full 3D flow. Among others, boundary layer effects and departures from the Taylor hypothesis require further investigation before clear quantitative parallels can be drawn between the 3D simulation and experimental results and the 2D theoretical and numerical results.

Conclusion

The various new learnings from this work can be synthesized as the following: the global reorganisation phenomenon observed in PWR rod bundle experiments and numerical simulations can be decomposed at the local level into sign changes for either the rod gap velocity or the subchannel vortex. Decomposing the flow into is axial and transverse parts based on a Taylor "frozen turbulence" hypothesis allows to study the transverse flow using tools from 2D statistical fluid mechanics. A resolution method was designed to allow for the identification of stable states in domains with internal obstacles based on the minimization of the system enstrophy. In a square with two obstacles modeling a PWR rod bundle cross-section, two particular flow regimes differing by a 90° rotation were observed, comparably to the PWR cross-flow patterns. Freely-decaying 2D simulations in this geometry lead to the identification of two bifurcation mechanisms, each related to an inversion phenomenon in PWR rod bundle flows. This comparison paves the way for a better understanding of reorganisations in nuclear cores coolant flows.

From an industrial point of view, this work should encourage members of the nuclear research community to intensify the investigation of PWR rod bundle cross-flow reorganisation phenomena. The phenomena can be observed in most rod bundle experimental results; the disturbances in thermal mixing they entail can raise significant safety issues. Further experimental data should therefore be acquired and published in the open literature. The numerical simulations performed in this work in 2D and 3D should be pursued and refined, in particular in order to improve the links between the 2D and 3D approaches through the inclusion of boundary layer effects and deviation from the quasi-2D framework.

As mentioned in section 4, results from the 2D analysis are challenging to directly transpose into a 3D framework. However, the idea a mixed approach should be considered. In the long term, a hybrid 2D-3D model could provide first-estimate results for 3D flows in a fraction of the computational costs, by combining:

- a 3D simulation of the flow in the near wake of a mixing grid, where the Taylor "frozen turbulence" hypothesis is invalid;
- a 2D simulation in the rest of the rod bundle using as initial condition the outlet cross-flow of the 3D simulation.

Numerous roadblocks still need to be lifted before such a model can be applied into industrial problems, but it could provide interesting perspectives in the study of PWR rod bundle flows.

References

[1] TrioCFD: http://www-trio-u.cea.fr/.

[2] Angeli, P.-E., Puscas, M.-A., Fauchet, G., and Cartalade, A. FVCA8 Benchmark for the Stokes and Navier–Stokes Equations with the TrioCFD Code—Benchmark Session. In Finite Vol.

Complex Appl. VIII - Methods Theor. Asp. (Cham, 2017), C. Cancès and P. Omnes, Eds., Springer International Publishing, pp. 181–202.

[3] Bieder, U., Falk, F., and Fauchet, G. LES analysis of the flow in a simplified PWR assembly with mixing grid. Prog. Nucl. Energy 75 (2014), 15–24.

[4] Bretherton, F. P., and Haidvogel, D. B. Two-dimensional turbulence above topography. J. Fluid Mech. 78, 01 (nov 1976), 129.

[5] Chavanis, P. H., and Sommeria, J. Classification of self-organized vortices in two-dimensional turbulence: the case of a bounded domain. J. Fluid Mech. 314 (1996), 267–297.

[6] Fen Shen, Y., Dong Cao, Z., and Gang Lu, Q. An investigation of crossflow mixing effect caused by grid spacer with mixing blades in a rod bundle. Nucl. Eng. Des. 125, 2 (feb 1991), 111–119.

[7] Higgins, C. W., Froidevaux, M., Simeonov, V., Vercauteren, N., Barry, C., and Parlange, M. B. The effect of scale on the applicability of Taylor's frozen turbulence hypothesis in the atmospheric boundary layer. Boundary-layer Meteorol. 143, 2 (2012), 379–391.

[8] Kang, S. K., and Hassan, Y. A. Computational fluid dynamics (CFD) round robin benchmark for a pressurized water reactor (PWR) rod bundle. Nucl. Eng. Des. 301 (may 2016), 204–231.

[9] Miller, J. Statistical mechanics of Euler equations in two dimensions. Phys. Rev. Lett. 65, 17 (1990), 2137–2140.

[10] Muller F., Burbeau A., Gréa B.-J., and Sagaut P., Minimum enstrophy principle for two-dimensional inviscid flows around obstacles, Phys. Rev. E 99, 023105 (February 2019)

[11] Naso, A., Chavanis, P. H., and Dubrulle, B. Statistical mechanics of two-dimensional Euler flows and minimum enstrophy states. Eur. Phys. J. B 77, 2 (2010), 187–212.

[12] Robert, R., and Sommeria, J. Statistical equilibrium states for two-dimensional flows. J. Fluid Mech. 229 (1991), 291–310.

[13] Schmeits, M. J., and Dijkstra, H. A. Bimodal behavior of the Kuroshio and the Gulf Stream. J. Phys. Oceanogr. 31, 12 (2001), 3435–3456.

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FISA 2019
EURADWASTE '19

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Annex I. Journal articles on FISA 2019 – EURADWASTE '19


FISA 2019
EURADWASTE '19
4-7 June, 2019
Pitesti, Romania

Koen Mortelmans
Science journalist

JOINT FORCES NEEDED FOR NUCLEAR WASTE MANAGEMENT AND NEW GENERATION REACTORS

Traditionally, the Euratom conferences Fisa and Euradwaste are jointly organised in the country that presides the European Union. This year, some 500 researchers, policy makers and other stakeholders gathered in Pitesti (Romania). Fisa focusses on research and training in the safety of reactor systems, Euradwaste on the management and disposal of radioactive waste.

Currently, worldwide 452 nuclear power plants are operational and 54 are under construction, while thirty countries consider introducing of nuclear power. From the 222 reactors in Europe, 128 are operational and 94 are destined for decommissioning. "It is our main concern to maintain the existing aged nuclear power park in a good condition. This way, we support the policy makers, without interfering with politics," says Stefano Monti (International Atomic Energy Association (IAEA)). "This support includes the development of innovations in safety and security, in a holistic view. We also need to open a dialogue about the role of the nuclear sector in the climate actions."

Nevertheless, parts of the discussion touched the political world. "In every EU-country, regulatory bodies have a different shape. We need to involve the energy market regulators in an early phase. This way they will be better prepared on what's coming," was a thinking track.

EU/Euratom initiatives are being capitalised

The European Atomic Energy Community (Euratom) Research and Training framework programmes are benefitting from a consistent success in pursuing excellence in research and facilitating Pan European collaborative efforts across a broad range of nuclear science and technologies, nuclear fission, fusion and radiation protection.

The European Commission helps to stimulate joint funding from Member States and/or enterprises, and benefits are being capitalised from the increasing interaction between European Technology Platforms (ETPs) launched during the 7th Framework Programme (2007-2013), namely the ‘Sustainable Nuclear Energy Technology Platform’ (SNETP incorporating NUGENIA Generation II III water cooled reactor technology, ESNII Generation IV fast reactors aiming at closing the fuel cycle, and NC2I Cogeneration of electricity and heat), the ‘Implementing Geological Disposal of Radioactive Waste Technology Platform’ (IGDTP), the ‘Multidisciplinary European Low Dose Initiative’ (MELODI association), the European Energy Research Alliance (EERA) Joint Programme in Nuclear Materials (JPNM), the Strategic Energy Technology Plan (SET-Plan) and other EU stakeholders (ENEF, ENSREG, WENRA, ETSON, FORATOM, etc.) as well as OECD/NEA, GIF and IAEA at international level.

Spirit of collaboration

"The treatment of spent fuel and the safe disposal of long living radioactive waste aren't major scientific nor technical problems any more, says Euratom policy officer Christophe Davies. "What we need now is trust and a spirit of collaboration. That's a political problem. The basic knowledge about the safe disposal of nuclear waste has been developed by individual countries. Finland has procured a building license for a deep geological repository, while Sweden and France make good progress towards licensing. But next steps should be taken in a spirit of union. A lot of work still remains to be done, also upstream. Amongst others, we need to find appropriate solutions for different specific waste streams, such as bituminized waste and graphite, regarding their disposability and long-term behaviour."

"We need to decide about the budget, location and social optimum for waste disposal before we start to dismantle nuclear plants," remarks Pierre-Marie Abadie (French agency for radioactive waste management Andra). Balint Nos (Public Company for Radioactive Waste Management, Hungary) draws a specific attention to the situation in Central- and Eastern-Europe. "In this region only a limited number of nuclear plants is operational. It makes sense to decide about a common deep geological solution for several countries."

Predisposal

"Predisposal is becoming a new pillar in the Euratom-program," Swedish expert and former IAEA-director Hans Forsström explains. "The results until now are promising. Further improvements in characterisation, minimisation and treatment of waste can be achieved. This might lead to even more safety and have commercial benefits."

Non-technical stakeholders

Nuclear safety and radioactive waste management also aren't exclusive territories for nuclear and technical specialists any more. "Social scientists want to be present in all projects where civil society is involved," Davies observed. "Therefore, the contributions of non-technical stakeholders need to be defined. Euratom can help to realise a synergy and to transfer the necessary knowledge."

"Monitoring the functioning of the disposal activities is not only a technical issue," Forsström remarks. "The involvement of civil society representatives has been very useful. It makes sense to consider during a further and more intensive participation of stakeholders from civil society in setting up a monitoring programme."

Building competence

"We can choose to be leaders in nuclear energy technologies or to become intelligent consumers of Russian or Chinese technology," says Martin Murray (UK Environment Agency). "In both scenarios, we need our own independent research, for instance to evaluate the impact of nuclear accidents. This is important even for countries which don't use nuclear systems, because they also can be affected by accidents in nearby countries."

Murray is a member of Euratom's scientific and technical committee. This body was established in 1957, to provide independent scientific and technical advice to the European Commission. "We need to be prepared to create a carbon free economy by 2050," he argues. "It is often said that the road to an operational fusion reactor will take another forty years. Within the 2050-horizon, fission-based reactor systems will continue to be an important technology. So, parallel research in fission technology remains necessary," Murray explains.

"However, research budgets are limited and choices will need to be made on priority areas for research funding. There is a consensus about the importance of the provision in radio-isotopes for medical use. With limited funding the importance of finding synergies with fusion, medical and other research programmes cannot be ignored."

Several reactors that produce medical isotopes are ageing and are coming to the end of their operational life, Murray warns. "In 2018 some of them were shut down for maintenance. Particle accelerators can't produce the full range of necessary isotopes." He thinks new, specialised reactors will be needed in Europe as. "Isotopes with a short half-life can't be transported over long distances. We need to remember that even countries which don't want to have nuclear power plants need access to medical isotopes!"

Interaction between researchers

Johan Andersson (Swedish Nuclear Fuel and Waste Management Company) agrees it is important to build up own European competences, especially for the management of radioactive waste. "This must allow us to find the ideal disposal and depository locations and enables us to communicate very openly about it, so no unrest will be created." Sweden has some experience, as it already decommissioned two reactors. About the European funding, he is not worried. "From our Swedish point of view the amount of the funding is not important. What matters is that the European project funding creates interaction with other researchers. This is a key aspect that can be found nowhere else."

Forsström agrees. "The Euratom programme remains very important, in spite that more than 90% of the research and development funding is national. It helps to coordinate research and development (r&d) and to transfer knowledge and experiences and foster cross-fertilisation between front runner countries and countries with a longer time scale, beyond 2050. All countries need to keep abreast of knowledge development. However, the long-time schedules for construction and operation of disposal facilities – more than hundred years– puts important strains on knowledge management and to the ensured availability of capable people in the long future. Furthermore, waste is not a very sexy theme. To attire a next generation of young people, r&d-incentives are indispensable."

Michel Pieracini (Electricité de France) underlines the importance of practical knowledge transfer from the generation that now is retiring and, as young engineers, experienced the construction of the current nuclear park. "This patrimony is very diverse: since 2010 we decommissioned nine reactors of four different types on six different sites."

Financial support

Forsström also makes a comparison with India. "In India, every single researcher is very much aware where exactly his own work fits in the Indian nation strategy. We, in Europe, have failed to show the individual scientists the broad picture of their efforts. Nevertheless, the existence of a European funding system enabled them to collaborate and to perform good research.

In this perspective, conference participants with management functions spent much attention on the information given about the new European funding frame for radioactive waste management. Instead of many small r&d projects the European Commission is now funding a large program, Eurad, that will be based on a European Joint Programming (EJP). Eurad will propose, plan and manage most EU funded projects. Also, representatives from the civil society will be involved. In a second step waste producers will be included. In a first round Eurad will run seven collaborative research and development projects, two strategic studies and three knowledge management projects.

Administration

"We received an important amount of information about European funding during the conference," comments researcher Zbynek Hlavac (Czech Research Centre Rez). "This knowledge can be very useful for us. Only recently, we stepped in the Eurad work packages, Cori (Cement-organics-radionuclide Interactions). Now we are seeking suitable topics for Czech companies. We noticed several projects include dozens of institutions and several institutions participate in a large number of projects. This requires they can rely on a specific and efficient administration."

Brexit no issue

The Brexit was no issue on this year's conferences. "The nuclear theme is complicated, but not political sensitive, such as the Irish-Irish border," explains William Nuttall (Open University, UK). "I think there it's possible to establish a kind of association between the UK and Euratom."

EURADWASTE

Euradscience is a growing network for research organisations studying science in radioactive waste management in Europe. At the moment, it has 28 members, representing fourteen countries. "Its emergence is logical consequence of the market evolution," says Christophe Bruggeman (Belgian Nuclear Research Center). "We are coming from single contracts with single partners to large numbers of contracts with many partners, working within very long-time frames. We want the research centres to be recognised as individual partners and to establish credibility for independent science."

http://www.engineeringnet.be/belgie/detail_belgie.asp?Id=22321&category=nieuws

CAN RESEARCH AND DEMONSTRATI ON GO TOGETHER?

In the development of a fourth generation of nuclear systems, liquid metal cooled reactors are envisaged to play an important role, because of their possibility to use natural resources efficiently and to reduce the volume and lifetime of nuclear waste. Liquid lead, lead-bismuth-alloys and liquid sodium are candidates for cooling such reactors.

An earlier version of cooling by liquid lead-bismuth was already used by Russian submarines during the seventies and eighties. The initiators of the European project Alfred (Advanced Lead Fast Reactor European Demonstrator) are convinced that the lead fast reactor technology (LFR) will open the possibility, on a relatively short term, to deploy commercially viable LFR-based small modular or large reactors. Therefore, they want to construct, in Romania, a European LFR-demonstrator. They also intend to use this reactor for research. For Romania this is an important project, because the political opinion greatly values the role of the nuclear sector in the energy transition from 2030.

ALFRED

As a strategic incentive, Alfred might also help to stop the brain drain the country currently is suffering. According the prognoses, this reactor can be ready in about fifteen years. "We identified 68 Romanian companies with competences to collaborate in this project," says Teodor Chirica (Romanian nuclear Forum Romatom). "42 of them already showed interest. Today 11.000 people are employed in the nuclear industry in our country. We can raise this number with 8.000 new jobs, mainly in construction."

MYRRHA

In Belgium, lead-bismuth cooling will be used by Myrrha (Multi-purpose hYbrid Research Reactor for High-tech Applications). Both projects have different operating environments. Alfred uses lead as pure as possible at 480 °C, Myrrha an alloy of lead and bismuth at 320 °C. This alloy is an eutectium, which means that its melting point is lower than the melting points of both components.

Myrrha will be the first prototype of a nuclear reactor, driven by a particle accelerator. This improves the safety, as the fission material mass is subcritical and the chain reaction immediately stop as soon as the accelerator is switched off. The first parts of Myrrha, the particle accelerator and the irradiation stations, should by operational in 2026, the complete installation in 2033.

Reluctancy

Alfred announced it is open for collaboration with America – the name Westinghouse was mentioned – and with China. During a conference workshop, this intention was firmly criticised by Hamid Aït Abderrahim, Myrrha's project director. "We need to be very careful with Westinghouse. In 2017, it announced it intends to replace its AP1000 by a LFR technology as main flagship. Westinghouse-representatives visited several European sites with knowledge of LFR-technology, including our Belgian Nuclear Research Centre and the Italian Brasimone Research Centre. They even started to speak about collaboration without being clear on the terms of innovative performance research valorisation and sharing."

Few months after these visits, Westinghouse was put under Chapter 11 to protect the company from the risk bankruptcy. "I was worried they were fishing for free access to knowledge we developed with European and national funding. We also have to be very cautious with China. As soon as a technology reaches an industrial level, China can move forward far more faster than we can. Look what happened with photovoltaic panels. We spent a lot of public money to subsidise them, but since the market grew mature, most panels are imported from China."

Aït Abderrahim also makes some comments about the dual use of a reactor for research and demonstration. "A research reactor such as Myrrha is designed specifically for research, with a large flexibility in operation. It can produce medical isotopes too. But when you design a reactor to demonstrate the efficient production of electricity this also has to be the final goal of your optimisation efforts. It is not productive to manifest it as a research reactor to attract more funding."

http://www.engineeringnet.be/belgie/detail_belgie.asp?Id=22321&category=nieuws

FLEXIBLE NUCLEAR ELECTRICITY BY COGENERATION SYSTEMS

The development of next generation nuclear power plants will also see emerging new focusses in nuclear safety. During the Fisa 2019 Conference, Grzegorz Wrochna (Polish National Centre for Nuclear Research), gave an overview of the Polish approach.

"Today, the production of electricity and heat in Poland is too much depending on very polluting coal. We want to phase out coal. However, we don't see natural gas as a suitable alternative, as this would make us too dependent from imported gas," Wrochna says. "A better solution is the use of high temperature gas cooled nuclear reactors (HTGR)." Therefore, Poland has strongly engaged itself in the European project Gemini+. This project aims the conceptual design of an industrial demonstration HTGR for the cogeneration of power and heat. Gemini+ builds on the knowledge, experimental data and modelling tools acquired in several earlier European research and development projects. "The first concrete result is a flexible nuclear boiler, connected with a cogeneration unit by a single-pipe system. Because of the use of the reactor for cogeneration instead of for baseload electricity, most parameters for the other parts of the system remain unchanged and it won't be necessary to change components." A first possible application is the replacement of coal fired boilers in chemical and other industries by HTGR, providing the heat by a pipe with hot steam. This way, no changes would be required in industrial installations."

By-product

In this application, Wrochna sees electricity as a by-product of heat. This vision reflects the current Polish situation – especially in Silesia –, with a large number of heat grids, powered by local cogeneration units. "Because of the cogeneration, the electricity production can be flexible. This way, those reactors can supply the necessary electricity when the irregular production from renewable sources, such as wind and solar, are low," Wrochna adds. "There is a large market for such cogeneration reactors. On the thirteen biggest chemical industrial sites in Poland together, a production capacity of about 6.500 megawatt (MW) is installed. Today, this capacity is coal or gas fuelled. We expect the costs for CO2-emissions will rise in the future."

Fitted for the demand

An enquiry about the energy needs of the chemical industry showed that the ideal reactor capacity is about 165 MW. For end users, the financial efforts to engage in HTGR are quite risky. "Therefore, public funds are required to support the design of the reactor, at a level of 50%. The decision to invest in a construction can be taken within five years, depending on the evolution of the coal and gas markets." Wrochna sees a local heat storage system close to the reactor as a cheap way to balance intra-day fluctuations in energy demand.

Safety and licensing

Foundations of a licensing framework for the development of any new nuclear cogeneration prototype should be laid down. They should address both requirements of Europe's nuclear safety directives and a safe coupling between nuclear and industrial applications. By involving at an early stage both designers and regulators, by using technology state-of-the-art and experience gained from existing dedicated nuclear cogeneration facilities, in Europe and overseas, it will benefit such safety and licensing challenges to enable a deployment at the horizon of 2040.

http://www.engineeringnet.be/belgie/detail_belgie.asp?Id=22321&category=nieuws

YOUNG RESEARCHERS: AWARDS AND NEW FOCUSSES

The 2019 Fisa-Euradwaste Conference 2019 in Pitesti was an excellent background for the presentations and the proclamation of the awards, granted by the European Nuclear Education Network (Enen). Overall, 12 PhD, MSc or young professionals' were awarded for Fisa, Euradwaste and ENEN, and peer-reviewed scientific papers will be published in highlights of the European Physical Journal (EPJ N, EPJ Nuclear Sciences & Technologies).

Enen organises this awards every year, in order to promote and to support the work of young scientists and researchers in Europe. Twelve participants were nominated to present their doctoral degree work before a jury of experts. Among those twelve, the jury selected three laureates.

The 2019 award winners are Claire Le Gall (Grenoble Alpes University), Wael Hilali (University of Stuttgart) and Florian Muller (Aix-Marseille University). Le Gall received her prize for her study about the release of the nuclear fission products caesium, molybdenum and barium from irradiated nuclear fuels during severe accident conditions. "Based on this research, we hope to ameliorate the calculation codes for and the performances of the data banks about fission products," Le Gall says. "However, I was surprised my presentation was awarded, because I had observed that the other participants' papers had a very high level."

Debris

Wael Hilali was awarded for his research about debris bed formations in degraded cores of light water reactors and Muller for his hydraulic and statistical study of metastable phenomena in pressurised water reactor rod bundles.

The award participants and some other young researchers presented their work with poster sessions. Their input in the conference also offered an impression of the current trends in academic research. Striking is the entry of bio-engineers and biologists in nuclear research. Several of them are focussing on the influence of organic matter in the long-term disposal of radioactive waste. An example is the possible degradation of steel waste vessels by micro-organisms.

Bio-scientists

The current input of the bio-scientists isn't limited to living organisms. "There is a large consensus about the safe disposal of high- and intermediate level radioactive waste in deep clay layers, says Elke Jacops (Belgian Nuclear Research Center), one of the award nominees. "The clays under consideration have a high fixation capacity to retain radionuclides, limited water flow by means of low permeability and high self-sealing properties by capillary sealing efficiency. On a microscale however, those layers are not all or completely homogenous. Within a geological repository, the production of gas is unavoidable. The dominant process here is the anaerobic corrosion of metals producing hydrogen. In a first stage, the gas will dissolve in the porewater and dissipate by diffusion. If the rate of gas generation is larger than the diffusive flux, a free gas phase will form which might have negative effects on the performance of the barriers. Diffusion coefficients in clay depend on the size of the gas molecules and the pores in the clay."

Jacops and her team investigated samples of different deep clay layers and carried experiments with different kinds of gasses. "In some levels of the clay layers the quartz grains are not homogeneously distributed. We think this is caused by fossil wormholes, created during the geological period when this clay was located at the surface. Later, those holes got filled up with quartz grains, resulting in distortions with larger pores and other diffusion properties. This became only visible by studying the micro-structure of the clay."

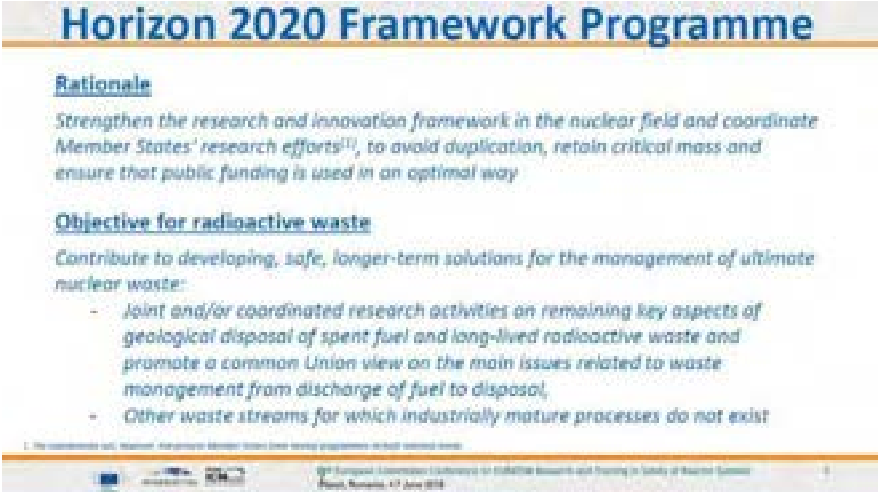
http://www.engineeringnet.be/belgie/detail_belgie.asp?Id=22321&category=nieuws

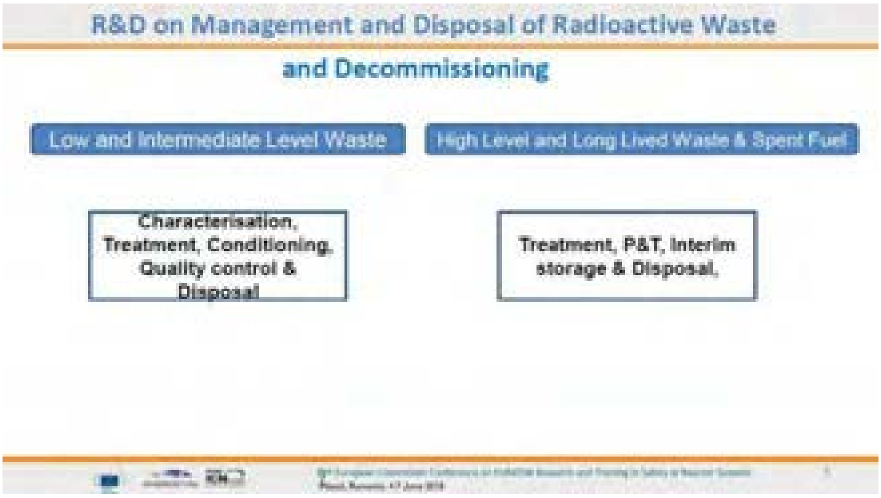
Annex II. EURADWASTE '19 PPT presentations

FISA 2019
EURADWASTE '19

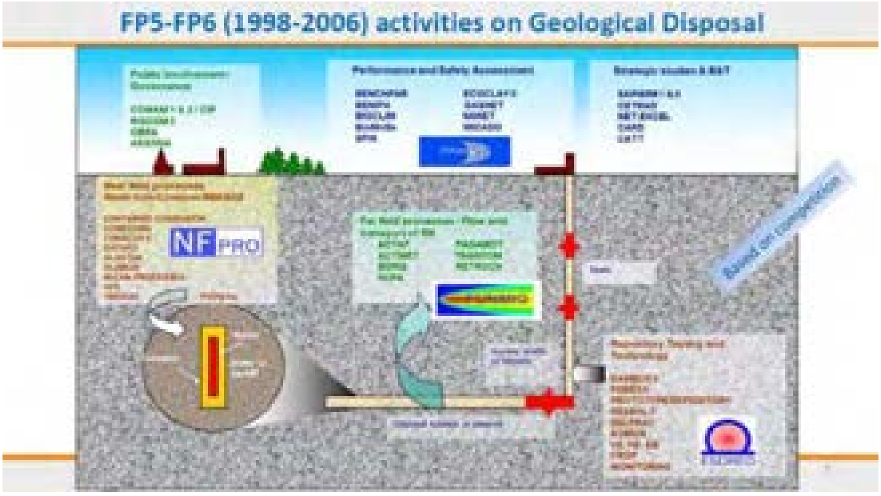
4-7 June, 2019
Pitesti, Romania

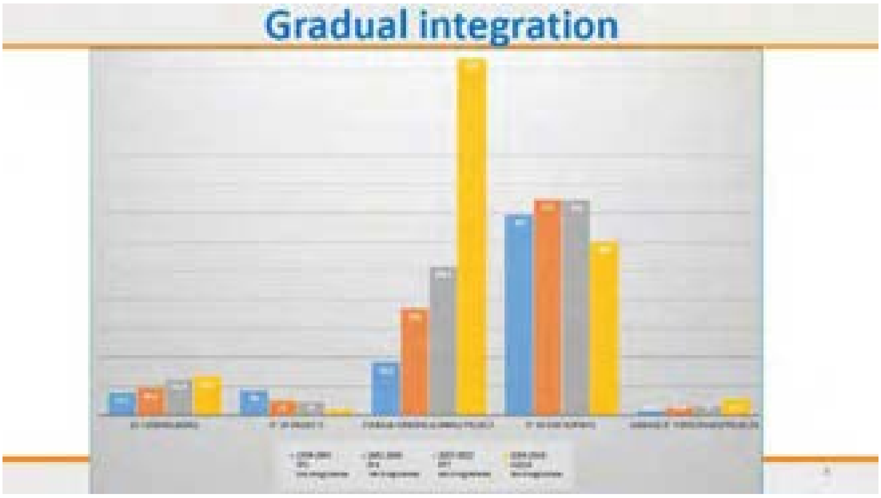
EURATOM R&D Programme in Radioactive Waste Management - *Christophe Davies (EC, DG RTD)*

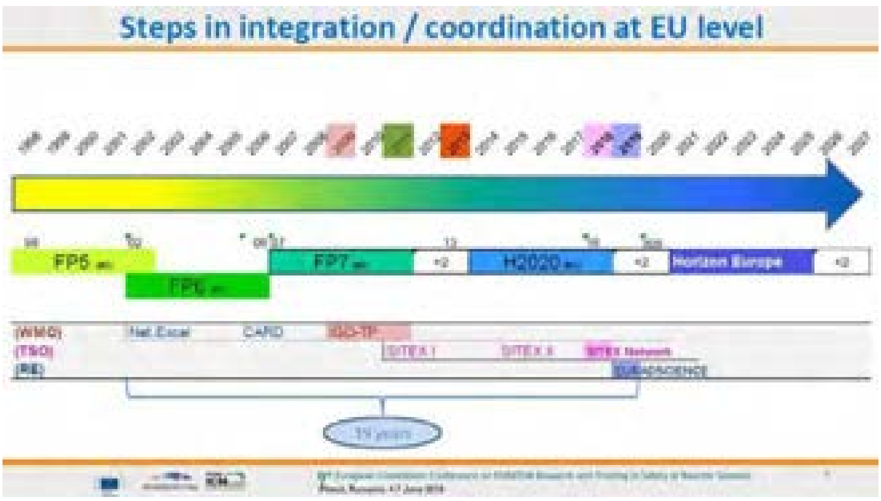

Horizon 2020 Framework Programme
Rationale
Strengthen the research and innovation framework in the nuclear field and coordinate Member States' research efforts[1], to avoid duplication, retain critical mass and ensure that public funding is used in an optimal way
Objective for radioactive waste
Contribute to developing, safe, longer-term solutions for the management of ultimate nuclear waste:
- Joint and/or coordinated research activities on remaining key aspects of geological disposal of spent fuel and long-lived radioactive waste and promote a common Union view on the main issues related to waste management from discharge of fuel to disposal,
- Other waste streams for which industrially mature processes do not exist

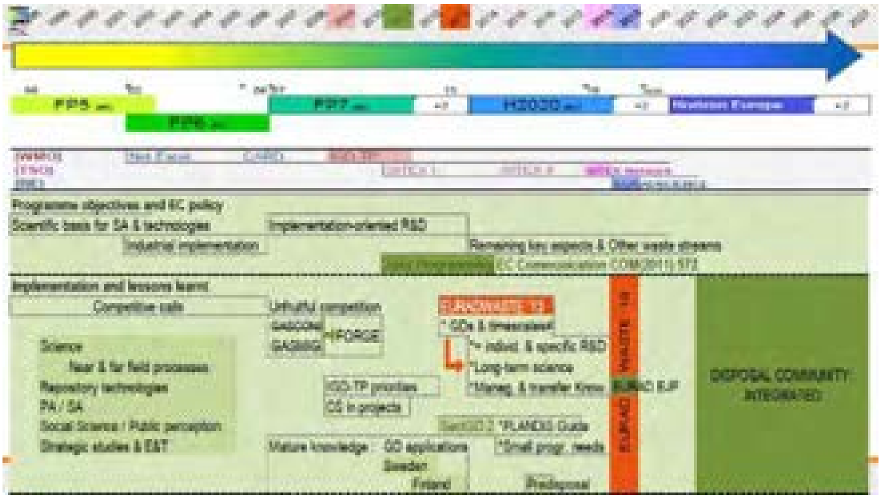

R&D on Management and Disposal of Radioactive Waste and Decommissioning
Low and Intermediate Level Waste
High Level and Long Lived Waste & Spent Fuel
Characterisation, Treatment, Conditioning, Quality control & Disposal
Treatment, P&T, Interim storage & Disposal,


Budgets on Radioactive Waste Management and Decommisssioning


FP5-FP6 (1998-2006) activities on Geological Disposal
NF PRO


Gradual integration


Steps in integration / coordination at EU level
FP5
FP6
FP7
+2
H2020
+2
Horizon Europe
+2
(WMO)
(TSO)
(RE)
CARD
IGD-TP
SITEX I
SITEX II



Strategy and questions at EU level

How to integrate waste producers with GD community

* on open R&D (shared ownership)
* competitive R&D compatible ?

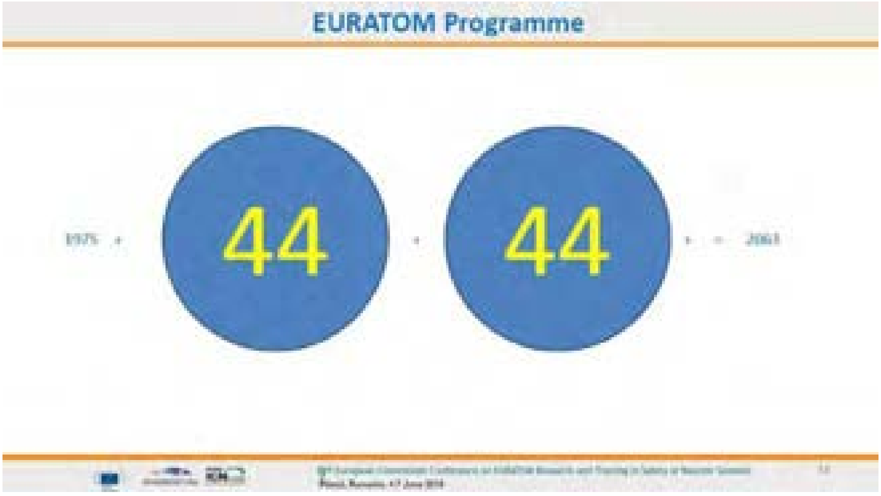
Ensure long-term KM plan (SoA, R&D guide, Training)

* Organise effective synergy with IAEA on KM
* How to involve academics not mandated actors

Which tasks for non-technical stakeholders

Conclusions

- "Raison d'être" of EURATOM is to help MSs develop solutions for the management of nuclear waste, jointly for possible common use,
- Together we can ensure synergies and effectiveness between all actors,
- Coordinated (non-competitive) R&D on open science for disposal in EJP seems more effective,
- Also cutting edge science, knowledge transfer between MSs and provisions of next generations of scientists (involving Academics "not mandated") should be the best way for EURATOM R&T sustainability,
- Contribution of non-technical stakeholders in R&D & EJP need to be defined


EURATOM Programme
44
44

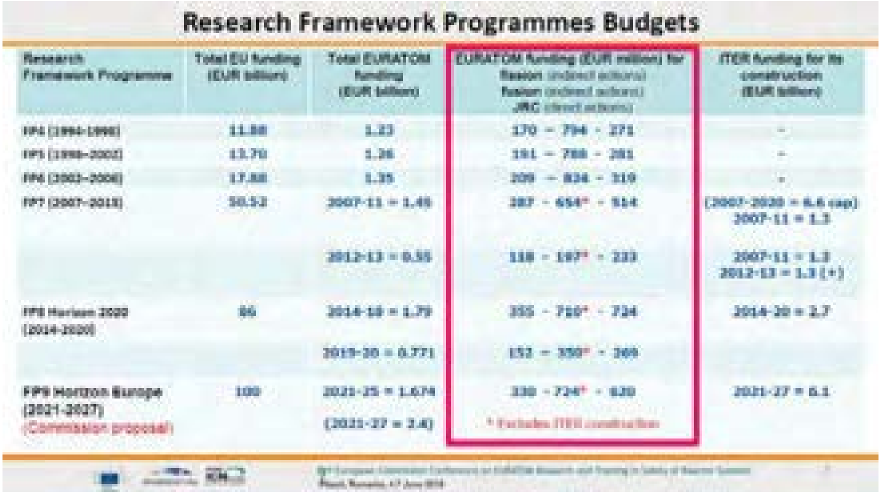

Dates for radioactive waste geological disposal

Euratom R&D Programme in safety of reactors systems - *Roger Garbil (EC, DG RTD)*


EU Decision Making Process (timeline)
FP9
WP2018
WP2019-20
WP2021-22

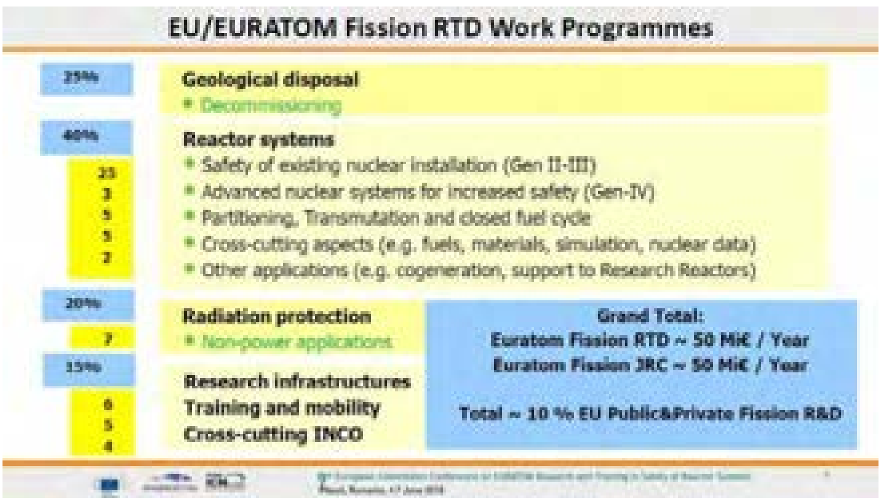

Multi-Financial Framework Budget Proposal (MFF 2021-27)
ALIGNED TO POLITICAL PRIORITIES
Simplification, transparency and flexibility
€1279.4


FP9 (2021-27) Horizon Europe Budget: €100 billion*
Euratom Research and Training
Indirect RTD
EUR 724 million
EUR 330 million
Direct JRC
EUR 620 million
ITER
EUR 6.1 billion
€2.1
€2.4
€13.5
€25.8
€52.7
Research & Innovation (7 years)
€ billion in current prices
Open Science
Global Challenges & Ind. Competitiveness
Open Innovation
Strengthening ERA
Euratom

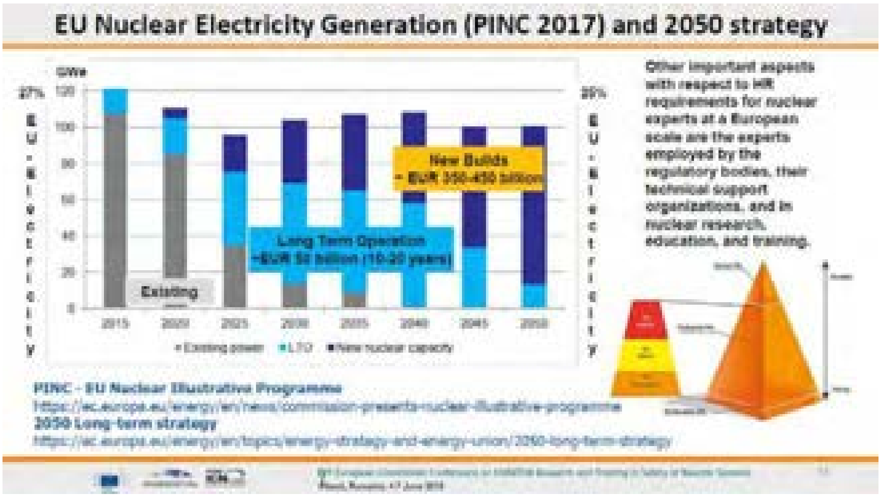


Research Framework Programmes Budgets

Research Framework Programme	Total EU funding (EUR billion)	Total EURATOM funding (EUR billion)	EURATOM funding (EUR million) for fission (indirect actions) fusion (indirect actions) JRC (direct actions)	ITER funding for its construction (EUR billion)
FP4 (1994-1998)	11.88	1.23	170 – 794 - 271	-
FP5 (1998-2002)	13.70	1.26	191 – 788 - 281	-
FP6 (2002-2006)	17.88	1.35	209 – 824 - 319	-
FP7 (2007-2013)	50.52	2007-11 = 1.45	287 - 654* - 514	(2007-2020 = 6.6 cap) 2007-11 = 1.3
		2012-13 = 0.55	118 - 197* - 233	2007-11 = 1.3 2012-13 = 1.3 (+)
FP8 Horizon 2020 (2014-2020)	66	2014-18 = 1.79	355 - 710* - 724	2014-20 = 2.7
		2019-20 = 0.771	152 – 350* - 369	
FP9 Horizon Europe (2021-2027) (Commission proposal)	100	2021-25 = 1.674 (2021-27 = 2.4)	330 - 724* - 620 * Excludes ITER construction	2021-27 = 6.1




EU/EURATOM Research and Training
TOGETHER
SINCE 1957
SUSEN
ALLEGRO
ALFRED
FALCON
SNETP
NUGENIA
ESNII
NC2I
PALLAS
EERA JPNM
EUROfusion


EU Nuclear Electricity Generation (PINC 2017) and 2050 strategy
GWe
27%
25%
EU-Electricity
New Builds
~EUR 350-450 billion
Long Term Operation
~EUR 50 billion (10-20 years)
Existing
2015
2020
2025
2030
2035
2040
2045
2050
Existing power
LTO
New nuclear capacity
Other important aspects with respect to HR requirements for nuclear experts at a European scale are the experts employed by the regulatory bodies, their technical support organizations, and in nuclear research, education, and training.
PINC - EU Nuclear Illustrative Programme
https://ec.europa.eu/energy/en/news/commission-presents-nuclear-illustrative-programme
2050 Long-term strategy
https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/2050-long-term-strategy


Global Perspectives
IEA – NEA Energy Technology Perspective 2015
https://www.oecd-nea.org/pub/techroadmap/techroadmap-2015-foldout-a3.pdf


1
2
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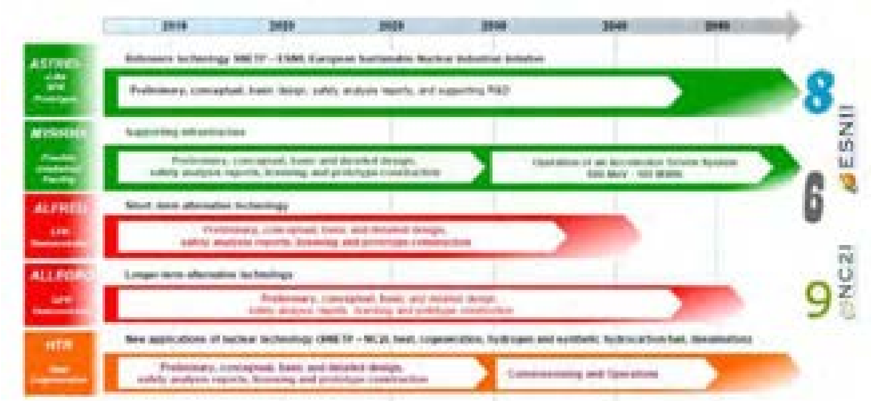
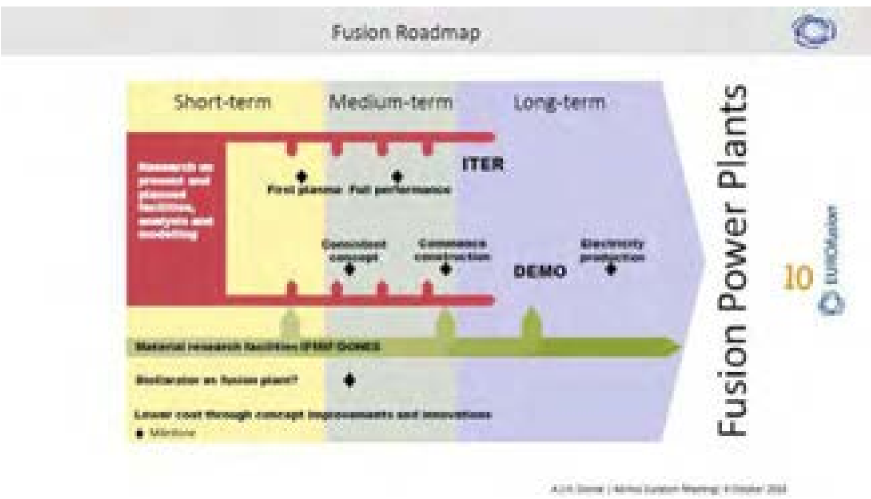
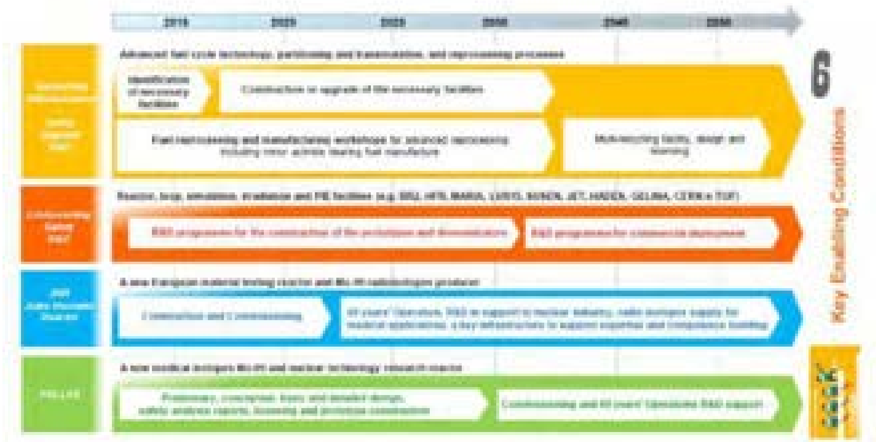
5
7
NUGENIA


ASTRID
MYRRHA
ALFRED
ALLEGRO
HTR
8
6
9
ESNII
NC2I


Fusion Roadmap
Short-term
Medium-term
Long-term
ITER
First plasma
Full performance
DEMO
Fusion Power Plants
10


6
Key Enabling Conditions

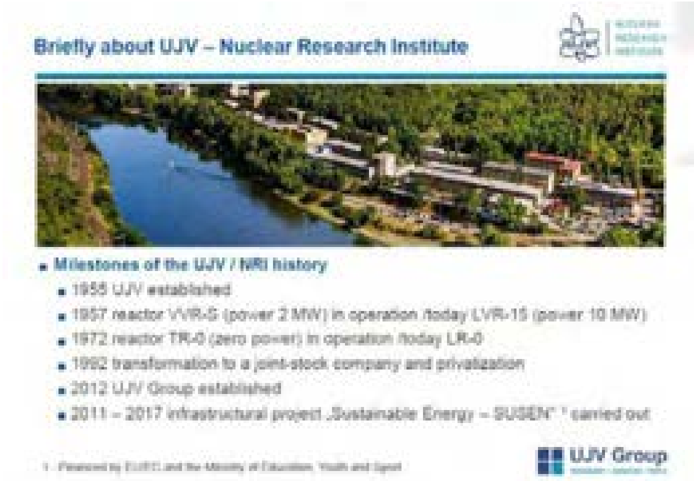

Key Enabling Conditions


Let's Capitalise ... All initiatives FP7, ETPs, ERA, INCO, H2020
Under Euratom, EC should promote and facilitate EU Nuclear safety R&D in MS, collab. IAEA, OECD/NEA, GIF
ETPs are industry led to promote R&D and demonstration of EU fission technologies
EU fora supporting nuclear policy, promoting stakeholders dialogue and safety improvements
ENEF from 2007 and WG Transparency, risks and opportunities
ENSREG from 2007, stress tests peer reviews
SNETP composed of NUGENIA, ESNII and NC2I pillars
SET-Plan Key action n.10 on nuclear fission and fusion
IGDTP on geological disposal, EURAD
MELODI with NERIS-TP, EURADOS and Alliance, CONCERT
ENEN European Nuclear Education Network
INCO structured dialogue on R&D policy and priorities
NUGENIA
EERA
ENSREG
ETSON
EHRO-N

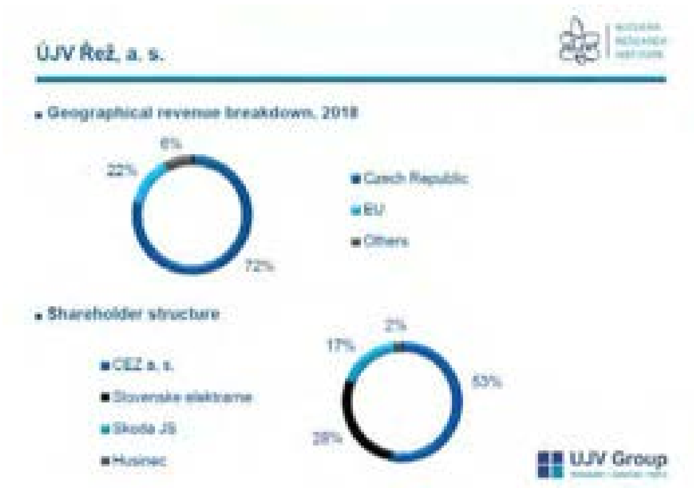

European Group of Ethics EGE Opinion 27 dated 16/01/2013
On January 16, 2013, the EGE adopted Opinion 27 on "Ethical framework for assessing research, production, and use of Energy"
The EGE recommends to achieve equilibrium between four criteria - access rights, security of supply, safety, and sustainability - in light of social, environmental and economic concerns.
2013 Symposium Proceedings
https://publications.europa.eu/en/publication-detail/-/publication/e92b20be-9163-4aee-b469-87828b10c0f1/language-en


Thank You!
SINCE 1957

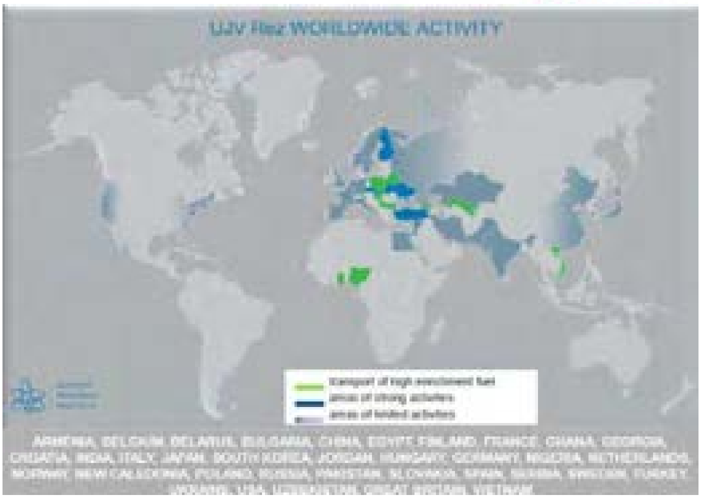
KEY NOTE: *Radek Trtílek (ÚJV Řež, CZ)*


Briefly about UJV – Nuclear Research Institute
Milestones of the UJV / NRI history
1955 UJV established
1957 reactor VVR-S (power 2 MW) in operation /today LVR-15 (power 10 MW)
1972 reactor TR-0 (zero power) in operation /today LR-0
1992 transformation to a joint-stock company and privatization
2012 UJV Group established
2011 – 2017 infrastructural project „Sustainable Energy – SUSEN" 1 carried out
UJV Group


UJV Group
UJV Group revenue in 2018 – € 98 mil
1200 employees
ÚJV Řež, a. s.
UJV Divisions
Nuclear Safety and Reliability
Integrity and Technical Engineering
Radioactive Waste and Decommissioning
ENERGOPROJEKT PRAHA
Radiopharmaceuticals
VZÚ PLZEŇ
Research and Testing Institute Plzen
Research Center Rez
ÚAM BRNO
Institute of Applied Mechanics, Brno
UJV Group


ÚJV Řež, a. s.
Geographical revenue breakdown, 2018
6%
22%
72%
Czech Republic
EU
Others
Shareholder structure
CEZ a. s.
Slovenske elektrarne
Skoda JS
Husinec
2%
17%
53%
28%
UJV Group


Main areas of the UJV activity
Technical and engineering support of safe operation of NPPs
Design and engineering services for energy sector
Radiopharmaceutical and PET centres
Radioactive waste management
R & D:
R&D support to main activities
Construction materials
Sorption materials
Hydrogen technology
Systems using renewable sources
Gen IV reactor technologies
DGR safety issues
UJV Group


UJV Rez WORLDWIDE ACTIVITY
ARMENIA, BELGIUM, BELARUS, BULGARIA, CHINA, EGYPT, FINLAND, FRANCE, GHANA, GEORGIA, CROATIA, INDIA, ITALY, JAPAN, SOUTH KOREA, JORDAN, HUNGARY, GERMANY, NIGERIA, NETHERLANDS, NORWAY, NEW CALEDONIA, POLAND, RUSSIA, PAKISTAN, SLOVAKIA, SPAIN, SERBIA, SWEDEN, TURKEY, USA, UZBEKISTAN, GREAT BRITAIN, VIETNAM


UJV as a RAW producer and processor
Processing of institutional RAW in the Czech Rep. (more then 95%)
Mostly „drum-in-drum" technology is used
Waste characterization and radiological monitoring
Decommissioning of old facilities (environmental liabilities)
Clearance measurement after decommissioning
Services and technologies for processing of RAW
Expertise and concepts
UJV Group

Institutional RAW processed in the ÚJV in 2014 - 2018

Producer	RAW form	unit	2014	2015	2016	2017	2018
ÚJV	solid	m^3	26.2	20.3	24.4	41.4	18.9
	liquid		60.3	9.9	8.0	9.2	9.4
External producers	solid		18.3	9.7	8.7	21.0	20.7
	liquid		4.25	14.4	23.8	14.0	5.4
Historical liabilities	solid		55.8	63.8	98.1	36.2	84.4
	liquid		2.95	4.3	8.2	3.0	3.0
Processed RAW together			164.8	122.5	173.3	124.8	141.6
Packages to dispose *	solidified	pcs	839	479	547	418	717

* [illegible]

UJV Group

Scope of other RWM activities

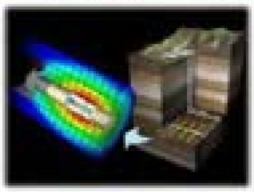
- Operational support of NPPs
  - Testing of final waste form
  - Processing of spent resins and sludge [1]
- Shipment of spent nuclear fuel from RR
  - BRRFR and MRRR Programs
  - 17 shipments from 12 countries
- Radiochemical analyses
  - Accredited testing lab
  - IAEA safeguard labs net
  - Support of characterization and D&D
- R&D for the DGR Project
  - Barriers, interactions, diffusion, migration
  - Modeling, WAC development, SA
- R&D of matrices and RW technology
  - Bitumen, cement, geo-polymer, mixed
  - Treatment of liquid waste after a severe accident
  - Nanomaterials applications

1 – in consortium with Chemcomex a.s. and ÚJV Energoservis s.r.o.

UJV Group

RWM – R&D activities

DGR development and L&ILW disposal



- Applied research on safety issues of DGR and engineering support for existing repositories
  - Barriers development and testing
  - Corrosion, diffusion, chemical interactions
  - Anaerobic conditions
  - Radionuclides migration
  - Hydrogeology and transport modelling
- General engineering support of DGR project
  - Designing
  - Communication
  - Safety assessment, safety scenarios, WAC development
- Participation in EU/EC projects
- URL Bukov Experimental Programme
- Engineering support for existing repositories

UJV Group

RWM – R&D activities

Pre-disposal - 1

- Applied research for pre-disposal WM and technology
- Bitumen matrix
  - > 24,000 drums disposed (NPPs chemical concentrate)
  - Complex testing of the concentrate - bitumen composition
  - Developed a matrix composed of pure raw materials [1]
- Geopolymer matrix
  - > 4,700 drums disposed (NPPs resins and sludge)
  - Mixed cement-polymer matrix developed using suitable properties of both matrices [1,2]
- Development of advanced technologies:
  - Molten Salt Oxidation (MSO) [1,2]
  - Polysiloxan matrix [1,2]
  - Application of nanostructures to sorption and to improve matrix properties [1,2]

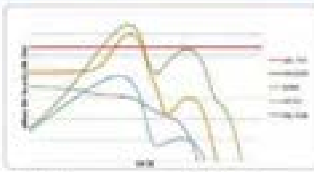
1 – Funded by the Ministry of Industry and Trade, Project No. FR-TI3 / 283
2 – It continues to be funded by public funds
3 – Cooperation with Chemcomex a.s.

UJV Group

RWM – R&D activities

Pre-disposal - 2

- The Dukovany repository filling model depending on: [1]
  - Operation of NPPs
  - Decommissioning time of NPPs
  - Time to commission of new units
- Model VLLW landfill and criteria [1]
- Development of new radioanalytical methods and their certification [1,2]
- Decontamination methods for D&D processes [1]
- Treatment of a large volume of liquid waste after a severe accident [1]



1 – Funded by the Ministry of Industry and Trade, Project No. FR-TI3 / 283
2 – It continues to be funded by public funds

UJV Group

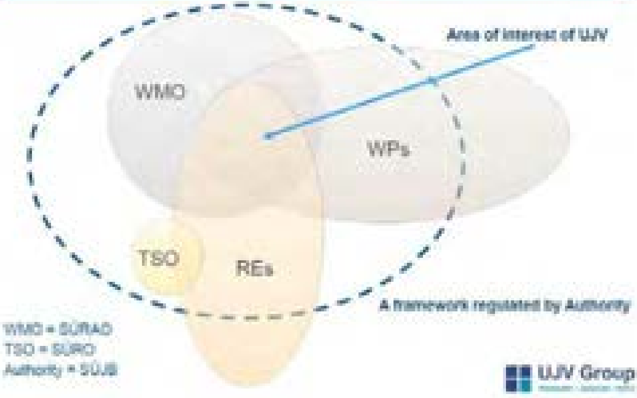
UJV relation to WMO

- Unique UJV Group know-how in the Czech Rep.
  - Complex research infrastructure
  - Working with open sources IR, irradiated and nuclear material
- RAW collection and processing (WP)
  - Incl. seizures of abandoned and orphan sources
  - NPPs operation support
- Long-term continuity in collaboration and support
  - Support for the establishment of the WMO (SÚRAO)
  - DGR Reference Design
  - Safety assessment, monitoring and upgrading of repositories
  - Studies for the National RAW and SNF Management Policy /Frame
- International collaboration and participation in > 20 EU/EC projects

➡ Frame Agreement on collaboration in applied research between SÚRAO and UJV, the FA includes both pre- and disposal management activities.

UJV Group

Relations of interests in the Czech Rep.



WMO = SÚRAO
TSO = SÚRO
Authority = SÚJB

UJV Group

R&D challenges for pre-disposal RWM

Objective	Task
Post-operational safety of repositories	Long-term stability of matrices
LTO of repositories	Ageing of structures and barriers
	Modernization and equipment up-grade
Waste from D&D and remediation historical liabilities	Final forms for waste unacceptable to existing repositories
	VLLW management and landfill
New builds	Technology selection
	Final product(s) testing and licensing
	Analysis and modeling of repositories capacity
Long-term SNF storage	Fuel properties (source inputs for DGR)

UJV Group

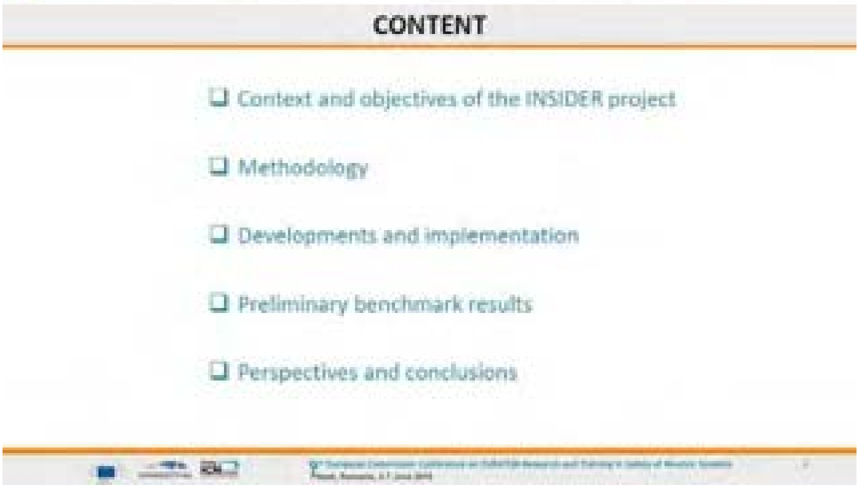
Conclusion

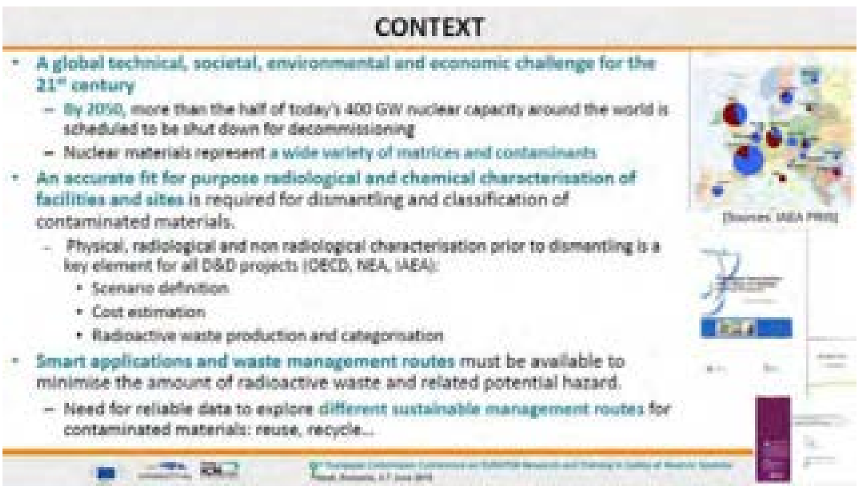
- **The Czech Republic remains a nuclear country**
  - Institutions and resources are established
  - RAW management is coherent and conceptual
  - L&ILW are continuously processed and disposed
- **A strong development and research base is available at UJV Group**
  - Includes RWM support (pre- and disposal) and institutional RAW processing
  - Working at a broad international level
- **WMO, WPs and REs interests:**
  - Complementary and coordinated
  - WMO and key WPs jointly define R&D needs and objectives
  - Guided by the principles of long-term safety and sustainability

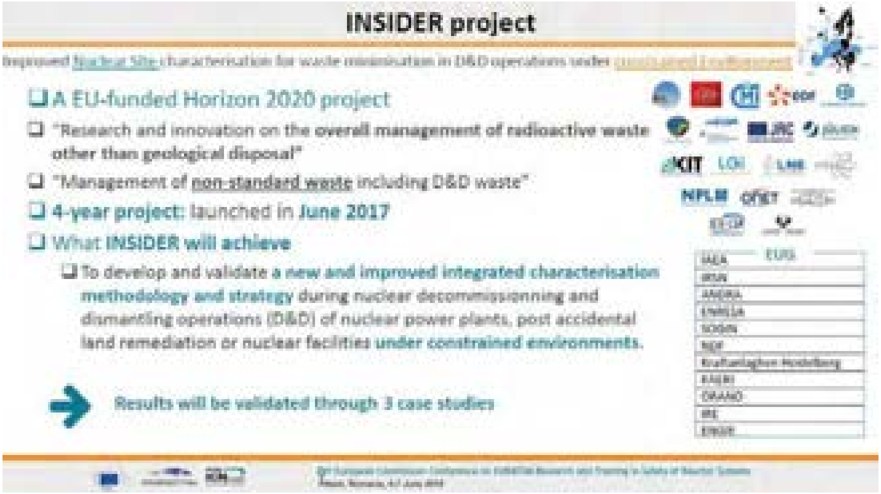
➡ Reflected in the proposals for R&D tasks including involvement in Horizon2020 projects (EJP1, NFRP10,event. 9)

UJV Group

INSIDER - *Danièle Roudil (CEA, France)*

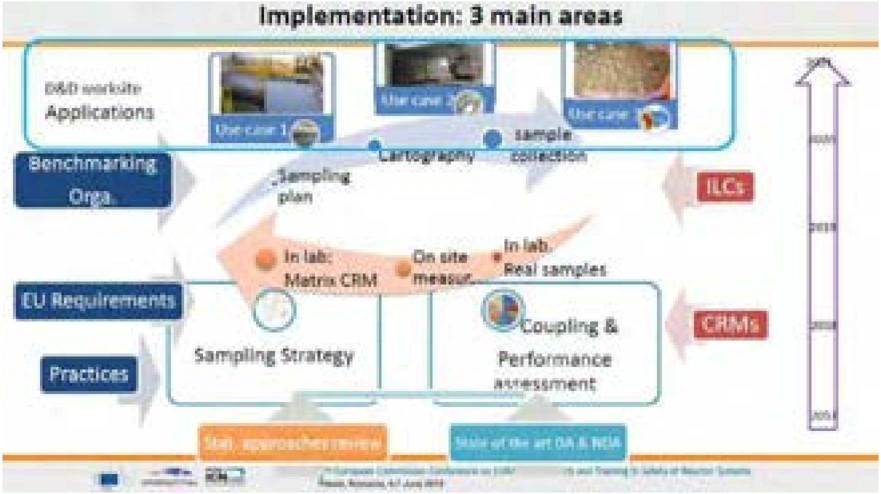


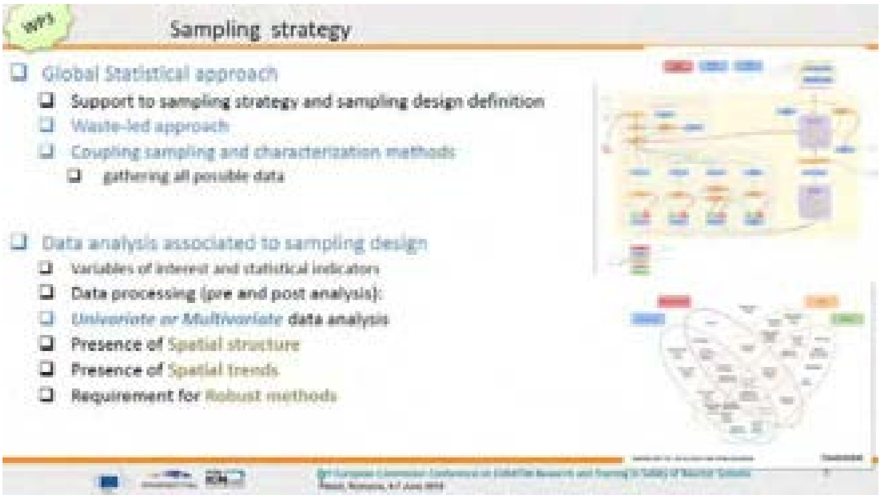


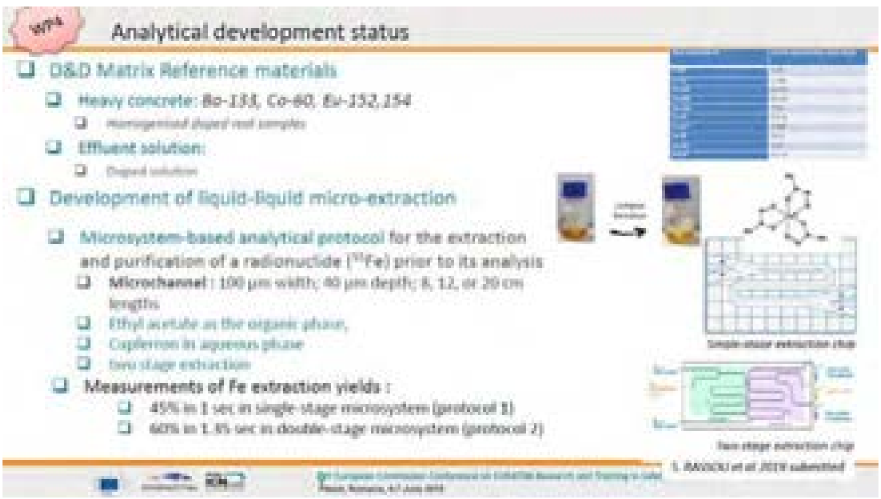

INSIDER project
❑ A EU-funded Horizon 2020 project
❑ "Research and innovation on the overall management of radioactive waste other than geological disposal"
❑ "Management of non-standard waste including D&D waste"
❑ 4-year project: launched in June 2017
❑ What INSIDER will achieve
❑ To develop and validate a new and improved integrated characterisation methodology and strategy during nuclear decommissioning and dismantling operations (D&D) of nuclear power plants, post accidental land remediation or nuclear facilities under constrained environments.
Results will be validated through 3 case studies
IAEA
IRSN
ANDRA
ENRESA
SOGIN
NDF
KAERI
ORANO
IRE

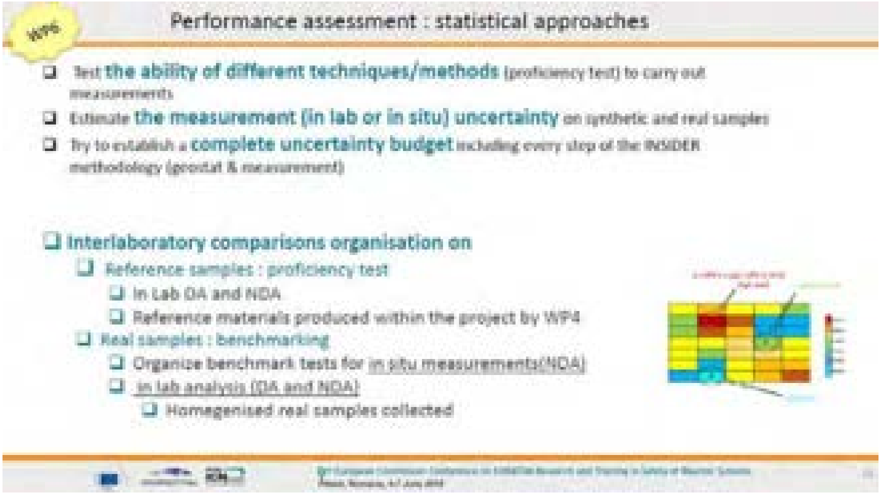

Key objectives- Project organisation
Establish common methodologies to deploy reference guidelines
Optimise the sampling strategy under constrained conditions
Coupling sampling/measurement:
Performance assessement of avalaible measurement techniques

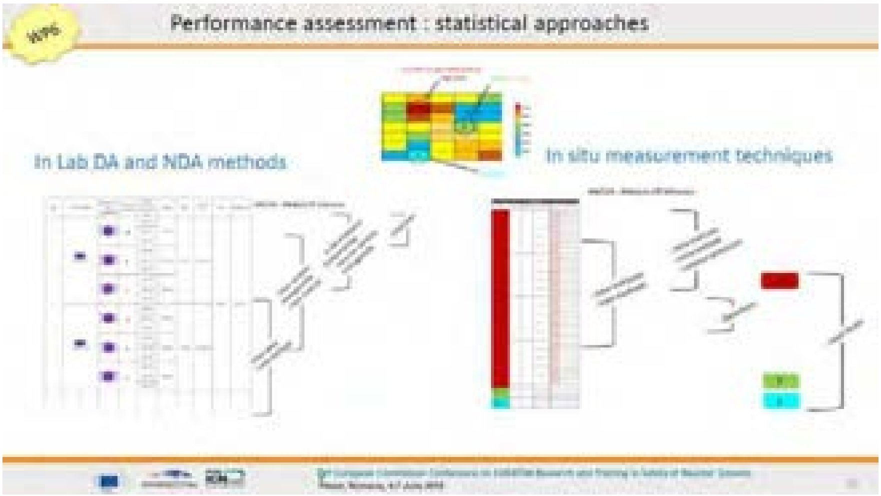

Three case studies
Apply the methodologies to real worksites under decommissioning
1
Decommissioning of a back/end fuel cycle and/or research facility - Ispra (JRC)
2
Decommissioning of a nuclear reactor - Mol (SCK/CEN)
3
Post accidental land remediation - (CEA)

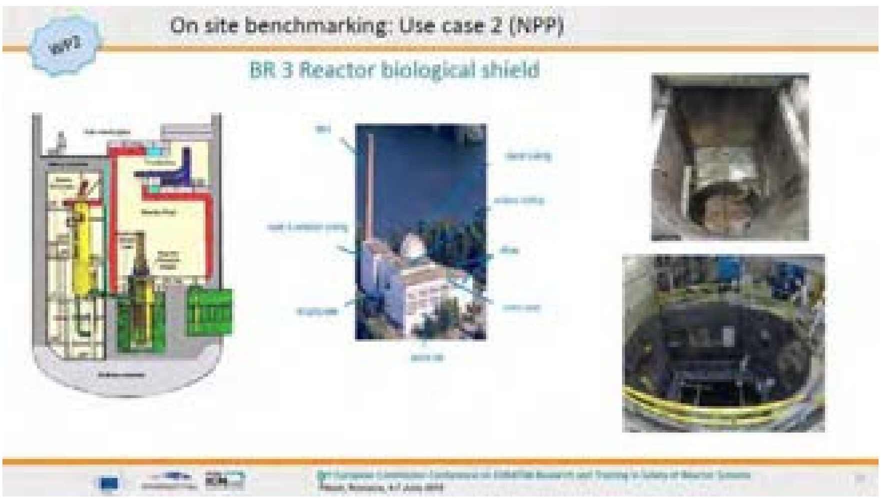

Implementation: 3 main areas
D&D worksite
Applications
Use case 1
Use case 2
Use case 3
Benchmarking
Orga.
Sampling
plan
Cartography
sample
collection
ILCs
In lab:
Matrix CRM
On site
measur.
In lab:
Real samples
EU Requirements
Practices
Sampling Strategy
Coupling &
Performance
assessment
CRMs
Stat. approaches review
State of the art DA & NDA

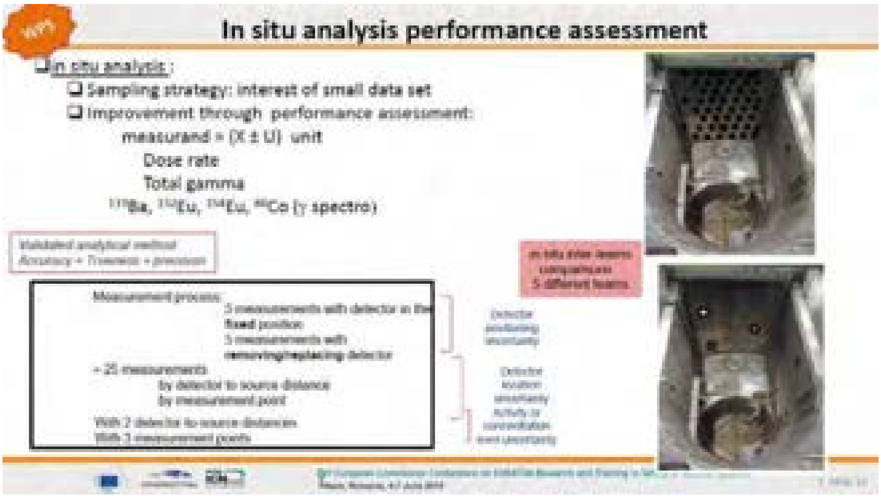

WP3
Sampling strategy
Global Statistical approach
Support to sampling strategy and sampling design definition
Waste-led approach
Coupling sampling and characterization methods
gathering all possible data
Data analysis associated to sampling design
Variables of interest and statistical indicators
Data processing (pre and post analysis):
Univariate or Multivariate data analysis
Presence of Spatial structure
Presence of Spatial trends
Requirement for Robust methods

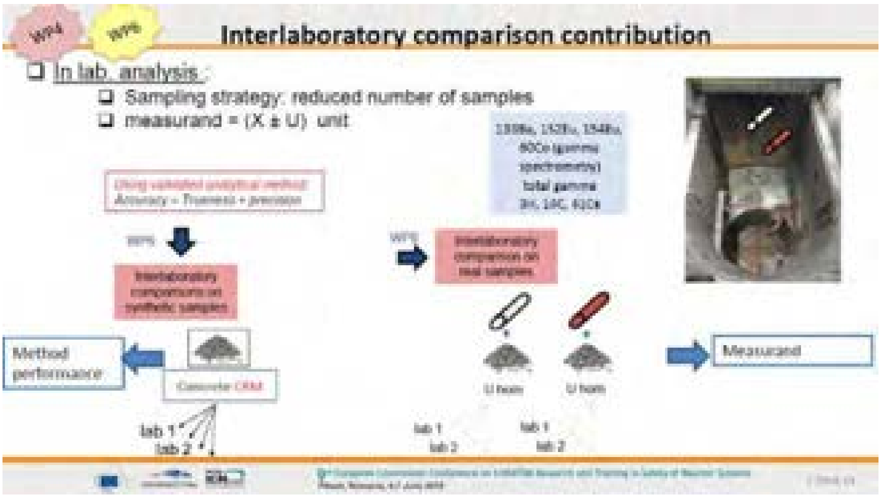

WP4
Analytical development status
D&D Matrix Reference materials
Heavy concrete: Ba-133, Co-60, Eu-152,154
Effluent solution:
Development of liquid-liquid micro-extraction
Microsystem-based analytical protocol for the extraction
and purification of a radionuclide (55Fe) prior to its analysis
Microchannel : 100 µm width; 40 µm depth; 8, 12, or 20 cm
lengths
Ethyl acetate as the organic phase,
Cupferron in aqueous phase
two stage extraction
Measurements of Fe extraction yields :
45% in 1 sec in single-stage microsystem (protocol 1)
60% in 1.85 sec in double-stage microsystem (protocol 2)
Simple-stage extraction chip
Two stage extraction chip
S. RAGOCKI et al 2019 submitted

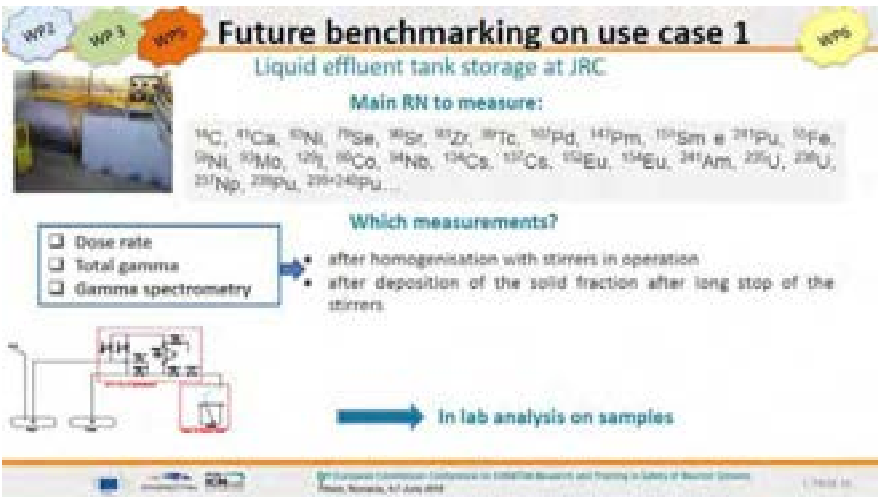

WP6
Performance assessment : statistical approaches
Test the ability of different techniques/methods (proficiency test) to carry out measurements
Estimate the measurement (in lab or in situ) uncertainty on synthetic and real samples
Try to establish a complete uncertainty budget including every step of the INSIDER methodology (geostat & measurement)
Interlaboratory comparisons organisation on
Reference samples : proficiency test
In Lab DA and NDA
Reference materials produced within the project by WP4
Real samples : benchmarking
Organize benchmark tests for in situ measurements(NDA)
in lab analysis (DA and NDA)
Homogenised real samples collected


WP6
Performance assessment : statistical approaches
In Lab DA and NDA methods
In situ measurement techniques


WP2
On site benchmarking: Use case 2 (NPP)
BR 3 Reactor biological shield


WP5
In situ analysis performance assessment
In situ analysis :
Sampling strategy: interest of small data set
Improvement through performance assessment:
measurand = (X ± U) unit
Dose rate
Total gamma
^{133}Ba, ^{152}Eu, ^{154}Eu, ^{60}Co (γ spectro)
Validated analytical method
Accuracy = Trueness + precision
Measurement process:
5 measurements with detector in the fixed position
5 measurements with removing/replacing detector
= 20 measurements
by detector to source distance
by measurement point
With 2 detector to source distances
With 3 measurement points
In situ inter-teams comparisons
5 different teams
Detector positioning uncertainty
Detector location uncertainty
Activity or contamination level uncertainty


WP4
WP6
Interlaboratory comparison contribution
In lab analysis :
Sampling strategy: reduced number of samples
measurand = (X ± U) unit
133Ba, 152Eu, 154Eu, 60Co (gamma spectrometry)
total gamma
3H, 14C, 41Ca
Using validated analytical method
Accuracy = Trueness + precision
WP5
Interlaboratory comparisons on synthetic samples
WP5
Interlaboratory comparison on real samples
Method performance
Concrete CRM
Measurand
lab 1
lab 2


WP2
WP 3
WP5
Future benchmarking on use case 1
WP6
Liquid effluent tank storage at JRC
Main RN to measure:
^{14}C, ^{41}Ca, ^{63}Ni, ^{79}Se, ^{90}Sr, ^{93}Zr, ^{99}Tc, ^{107}Pd, ^{147}Pm, ^{151}Sm e ^{241}Pu, ^{55}Fe, ^{59}Ni, ^{93}Mo, ^{129}I, ^{60}Co, ^{94}Nb, ^{134}Cs, ^{137}Cs, ^{152}Eu, ^{154}Eu, ^{241}Am, ^{235}U, ^{238}U, ^{237}Np, ^{238}Pu, $^{239+240}$Pu...
Which measurements?
Dose rate
Total gamma
Gamma spectrometry
after homogenisation with stirrers in operation
after deposition of the solid fraction after long stop of the stirrers
In lab analysis on samples


INSIDER project perspectives
Innovative metrological study based on a multidisciplinary network and D&D key activities
New D&D matrix reference materials development
Intercomparisons on real samples and inter-team
Analytical innovation needs identification, development and implementation
Correlation and scaling factors: improvement of accuracy estimation of traces (DTM RN)
Advanced integrated approach for site radiological characterisation and automation of characterization process…
Decommissionning operating experience
Methodological guides updated according to benchmarking feedback
Established link with standardisation commissions (ISO) for future international standards
Contribution to European learning (ELINDER)
Interface with other EU initiative (SHARE, METRODECOM projects)
Potential further opening of the project
Extension/application of the methodology and approaches : historic wastes, graphite reactors…
Interface with digital tools: Imaging, virtual and augmented reality


EURADWASTE '19
THANK YOU for your attention
Any questions?

CHANCE - *Denise Ricard (ANDRA, France)*

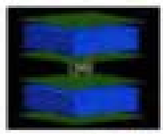
CHANCE objectives

- To establish at the European level **a comprehensive understanding of current conditioned radioactive waste characterization and quality control schemes** across the variety of different national radioactive waste management programmes
  - Based on inputs from end-users such as Waste Management Organisations, regulators, waste producers and repository operators

CHANCE objectives

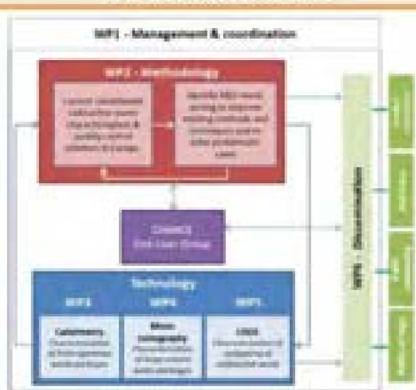
To **further develop, test and validate non-destructive techniques that will improve the characterization of conditioned radioactive waste (CRW)** and complement current methodology while particularly targeting large and heterogeneous waste compounds

- **Calorimetry** as a non-destructive technique to reduce uncertainties on the inventory of radionuclides
- **Muon Tomography** as a non-destructive technique to control the content of large volume nuclear waste
- **Cavity Ring-Down Spectroscopy** (CRDS) to characterize outgassing of radioactive waste



Destructive technologies followed by chemical or radiological analyses are commonly used techniques for radioactive waste characterization but are not addressed in CHANCE, since these techniques are applied to the raw waste itself, this is not in the scope of this project.

CHANCE structure



WP2 METHODOLOGY

WP2 objectives

To identify **current methodologies** and shortcomings of current characterization and metrology of CRW in Europe

- **Key parameters** that need characterization and uncertainties assessment
- **Technologies commonly used** for conditioned waste characterization
- **Specific problematic issues** for the characterization of CRW
- **Knowledge and technology gaps** for radioactive waste package characterization methodologies
  - Driven by the end-user requirements for the characterization of radioactive waste
    - Waste Management Organizations (WMOs), regulators, disposal operators, waste producers...
  - A specific End-Users Group (EUG)

Leader: Andra – Contributors: CEA, ENEA, FZJ, SCK•CEN, RATEN, INCT

WP2 current status

- A questionnaire was prepared to obtain a broad overview of the characterization of conditioned radioactive waste (WAC, methods currently used, needs, special issues, etc)
  - Includes questions pertaining to Work Package 6 (socio-technical and ethical frameworks of radioactive waste characterization practices and policies)

  End-User-Group Questionnaire (available on www.chance-h2020.eu)

- Transmission of the Questionnaire to EUG members
  - 13 questionnaire answers received
  - Synthesis of questionnaire answers under finalization (available soon on www.chance-h2020.eu)

WP2 current status

Identification of Waste Acceptation Criteria (WAC)

Depend on the disposal and country considered

- Radiological: radionuclide activity, dose rate, surface contamination, content of fissile materials, heating power
- Chemical : inventory of toxic species, complexing and chelating agents, accelerators of leaching processes, organic substances, pyrophoric, flammable, corrosive, oxidizing materials
- Mechanical: compression resistance, drop resistance, matrix behavior (swelling, diffusivity and leachability)...
- Other parameters: hydrogen production, homogeneity of the waste, parameter associated to disposal container (physical dimensions and weight)

WP2 current status

Specific problematic issues for the characterization of conditioned RW

- Proper characterization of the conditioned legacy/ historical waste packages
  - Radiologic characterization: interrogators radiation have difficulties to penetrate; the measurable emissions (γ or neutron) are strongly attenuated
  - Type of different materials – often difficult to identify
- Determination of alpha and beta activities in conditioned RW due to signal attenuation by the waste packages and backfill (compacted drums, concrete)
- Little traceability of the chemical content of waste packages
- Accessibility of the waste for sampling (due to the limited access at the waste packages)
- Difficulties in monitoring and periodical control of the waste drums packed deeply in a storage facility

All results will be available soon on www.chance-h2020.eu

WP3 CALORIMETRY

WP3 Objectives

- To test and evaluate the performance of calorimetry for inventory of radionuclides (measure Beta or alpha radiation heat source)
- To identify how calorimetry can complement existing, widely-used techniques (gamma spectrometry and neutron passive measurement)
- To carry out an exhaustive study of uncertainties assessment related to calorimetry and its coupling to other non-destructive techniques

A dedicated calorimeter (200 litres) will be designed and built by KEP Nuclear

A dedicated experimental program will be carried out with mock-up drums, and possibly real drums (CEA and SCK•CEN)

Leader: KEP Nuclear – Contributors: CEA, FZJ, SCK•CEN, WUT

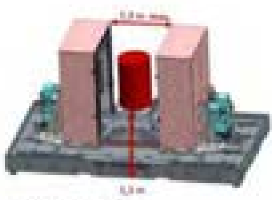
WP3 current status

First deliverable : Report on the Applicability of calorimetry to real waste characterization (available on www.chance-h2020.eu)
- Overview of NDA techniques (Gamma methods; Neutron methods, calorimetric methods)
- MCNP CHANCE calorimeter modelling
- Evaluation of Gamma energy and neutron deposition inside the calorimeter and impact on the measurement

Applicability of calorimetry
- Calorimetry is adapted to alpha and beta emitters (e.g. Pu, Am, ^{3}H) – all the heat emitted by radioactive decay can be measured (less of 1% of uncertainty)
- Calorimetry can not discriminate/ locate the heat source (s)
- Calorimetry is complementary and supplementary, mainly to gamma- and neutron spectrometry

WP3 current status

- Construction of the LVC calorimeter (200L, 10-3000mW range) with optimized lower detection limit (1.5mW)
- Commissioning and experiments to commence in summer 2019
- MCNP / GEANT4 modelling of CHANCE LVC calorimeter



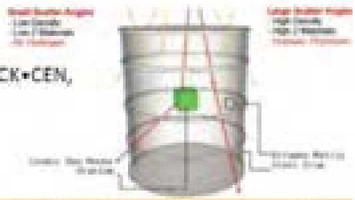
LVC calorimeter (KEP)

WP4 MUON TOMOGRAPHY

WP4 Objectives

To develop mobile muon tomography instrumentation to address imaging of large volume and heterogeneous nuclear waste packages

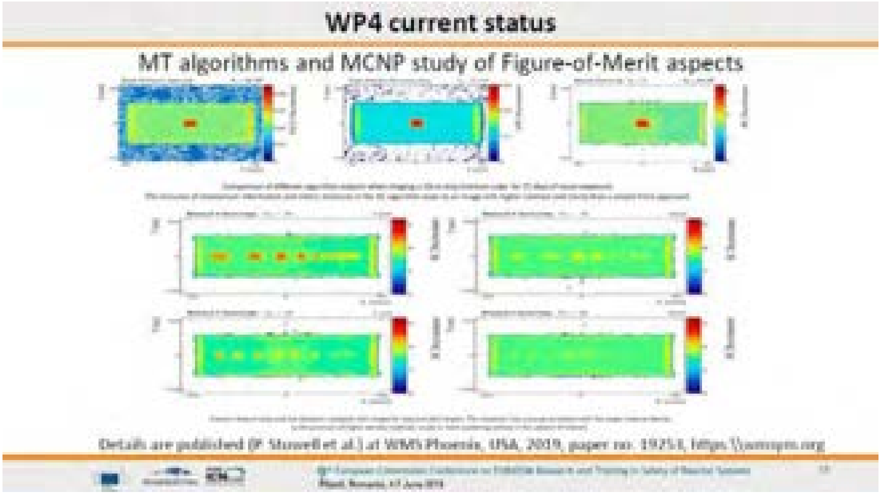
- To build a suitable mobile muon detection system
- To demonstrate real waste drum muon tomography
- To evaluate performances of the technique

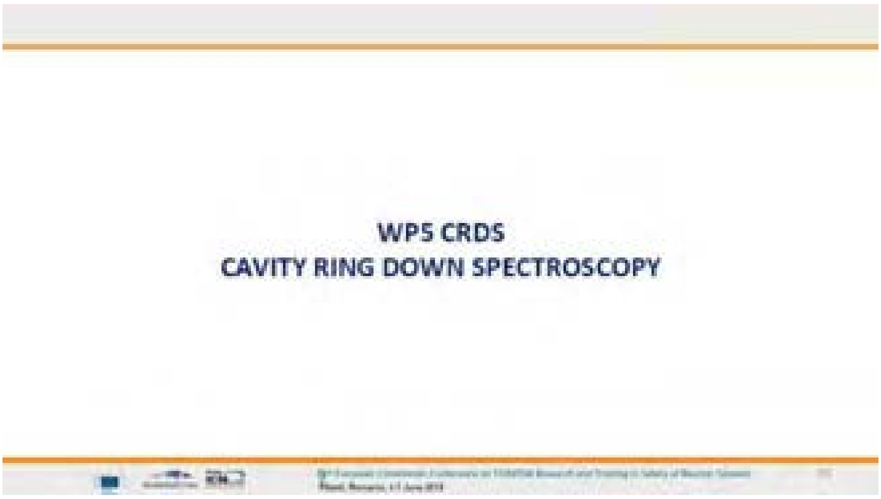


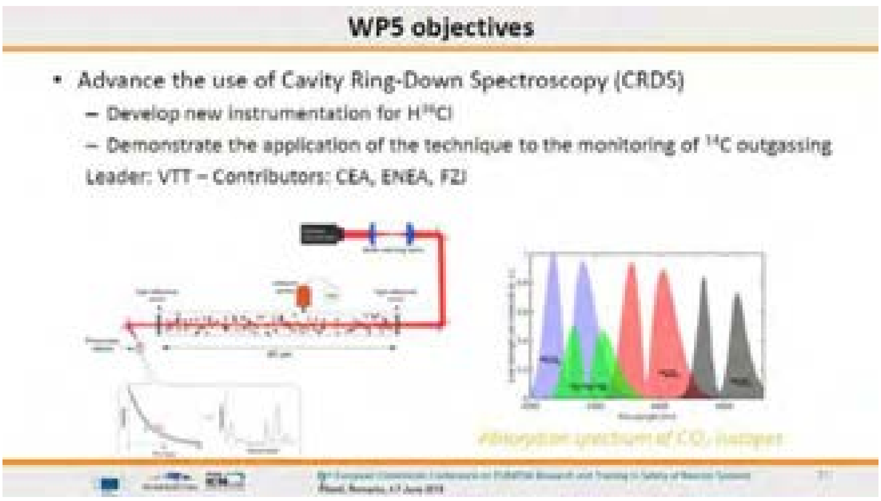
WP4 Leader: University of Bristol – Contributors: FZJ, SCK•CEN, University of Sheffield, WUT

WP4 current status

- The detector system is being commissioned in a non-laboratory environment.
- Topics of interests/goals:
  - detection of U cuboids embedded in concrete with a few mm resolution.
  - distinguishing between cuboids of U, W and Pb.
  - detection of voids (e.g. gas bubbles) in the matrix.
  - Hot drum simulations and estimates for large volume and heterogeneous waste compounds
- Looking for industry partners to guide our activities
- Imaging of large-scale CASTOR drums containing high-Z material

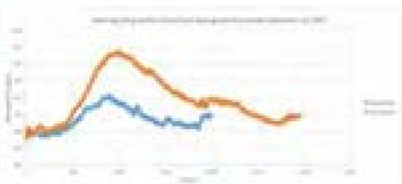

WP4 current status
MT algorithms and MCNP study of Figure-of-Merit aspects
Details are published (P. Stowell et al.) at WMS Phoenix, USA, 2019, paper no. 19254, https:\\wmsym.org


WP5 CRDS
CAVITY RING DOWN SPECTROSCOPY


WP5 objectives
• Advance the use of Cavity Ring-Down Spectroscopy (CRDS)
– Develop new instrumentation for H14Cl
– Demonstrate the application of the technique to the monitoring of 14C outgassing
Leader: VTT – Contributors: CEA, ENEA, FZJ
Absorption spectrum of CO2 isotopes

WP5 current status

- Development of CRDS $H^{36}Cl$ measurement
  - Identification of a suitable $H^{36}Cl$ absorption line
  - Matrix composition – potential impact of water has been studied
- Investigation of the release behaviour of C-14
  - Study of CO_2 outgassing from non irradiated graphite



WP6 DISSEMINATION & TRAINING

Communication tools

To integrate, communicate and disseminate CHANCE results within the European community involved in radioactive waste management

- **Communication** to broader European community involved in radioactive waste disposal
- **Study on the socio-technical concerns** and uncertainties associated with the principles and characterization methodology of radioactive waste
- **Training and education** of young professionals
  - CHANCE Mobility-fund in the field of characterization of conditioned radioactive waste by means of non-destructive analytical techniques and methodologies
  - Open to Master students, PhD students and junior professionals
    - Internships, thesis preparations or scientific visits hosted by a partner of the CHANCE project
    - Participation in conferences and workshops

  Further information available on www.chance-h2020.eu
- **Synthesis** report integrating all CHANCE results

WP6 Leader: SCK•CEN – Contributors: Andra, ENEA, FZJ, INCT

Communication tools

- Public website : www.chance-h2020.eu
  - News about the project, events, Public Deliverables, Publications
- Participation to national and international events (conferences, workshops,...)
- Specific communication through IGD-TP (website, newsletter,...)
- Training course (will be organized towards the end of CHANCE project)

- CHANCE Topical Day (SCK•CEN)
  - 21 - 22 March 2019 in Mechelen, Belgium
  - Objectives were to give an overview of NDA characterization methods and share experiences and future challenges

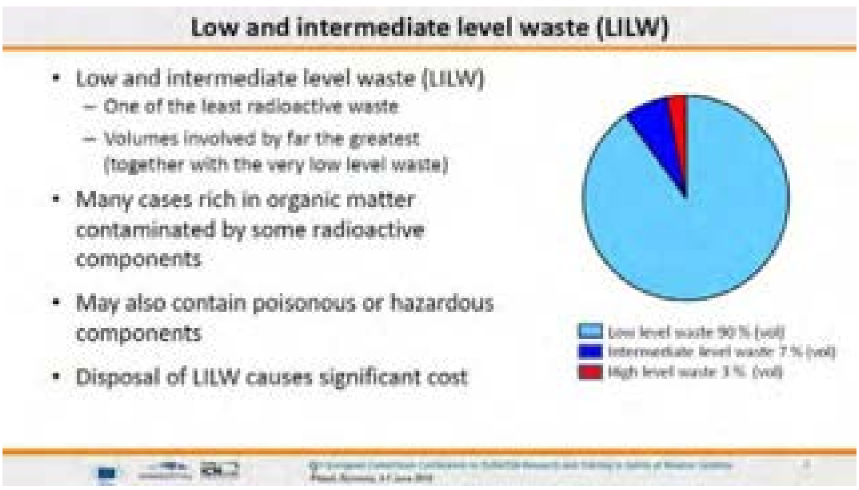
102 persons participated at the Topical Day

141 different devices logged onto the live-stream during the day

THANK YOU FOR YOUR ATTENTION !

CHANCE

THERAMIN - *Matti Nieminen (VTT, Finland)*



Thermal treatment of LILW

- Thermal vitrification is applied for high level waste (HLW) in industrial scale
  - The capacity of western European vitrification plants is about 1000 t/a
- Thermal treatment offers also an alternative way to process LILW before disposal
- Thermal processing will
  - reduce volume
  - enhance safety
  - reduce toxicity

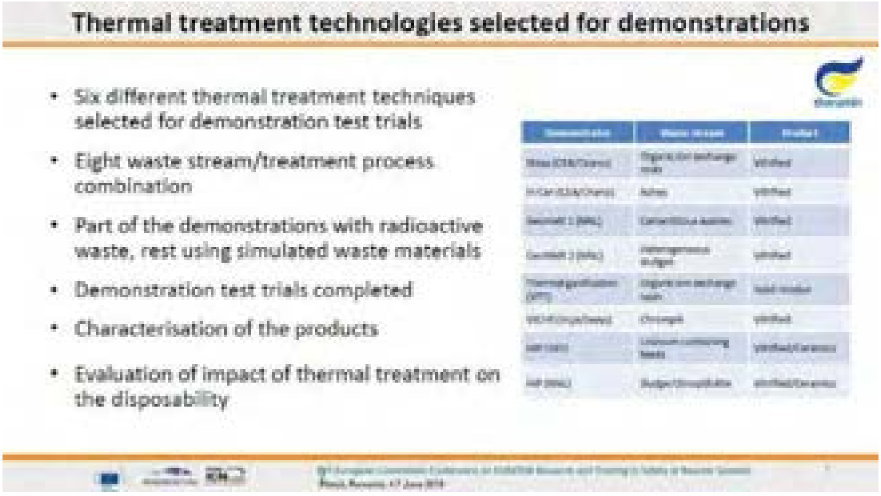
- In many cases enable best possible immobilisation of radioactive components
- Thermal processing is not free of charge and risk but it might save money and improve safety in longer term

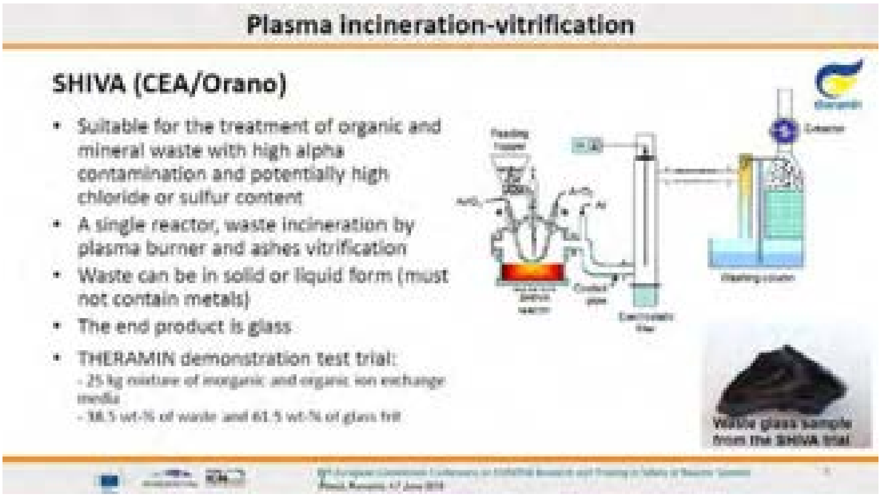
The Horizon 2020 funded THERAMIN project

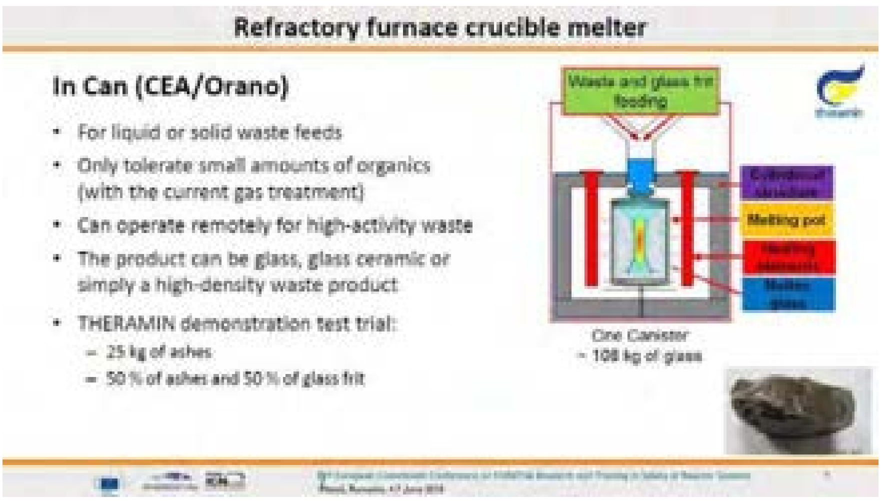
- Thermal treatment for radioactive waste minimisation and hazard reduction
- The main objectives of the project are to
  - promote thermal treatment of LILW by piloting/demonstrating several thermal treatment technologies
  - improve the overall understanding and knowhow on thermal treatment
  - make thermal treatment technologies more well-known technologies

Large number of thermal treatment alternatives

- **Incineration** (with burner and refractory walls): Rotary kiln incineration, pyrolysis, gasification, calcination, underwater plasma incineration, hydrothermal oxidation
- ***Conditioning by immobilisation in glass***: Joule-Heated In-Can Vitrification, Joule-Heated Ceramic Melter (JHCM), Cold crucible induction melter (CCIM), Advanced CCIM (A-CCIM), Indirect induction (metallic wall - hot metal pot), Coupled cold wall direct metal induction melting and plasma burner, Coupled cold wall direct glass induction melting and plasma burner and Refractory wall plasma burning and melting
- ***Conditioning by immobilisation in ceramic, glass or glass-ceramic***: Hot Isostatic Pressing (HIP)


Thermal treatment technologies selected for demonstrations
• Six different thermal treatment techniques selected for demonstration test trials
• Eight waste stream/treatment process combination
• Part of the demonstrations with radioactive waste, rest using simulated waste materials
• Demonstration test trials completed
• Characterisation of the products
• Evaluation of impact of thermal treatment on the disposability

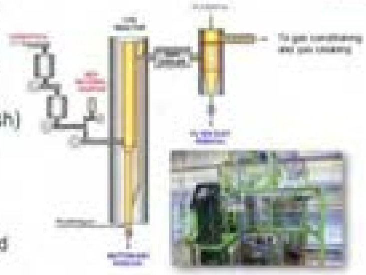

Plasma incineration-vitrification
SHIVA (CEA/Orano)
• Suitable for the treatment of organic and mineral waste with high alpha contamination and potentially high chloride or sulfur content
• A single reactor, waste incineration by plasma burner and ashes vitrification
• Waste can be in solid or liquid form (must not contain metals)
• The end product is glass
• THERAMIN demonstration test trial:
- 25 kg mixture of inorganic and organic ion exchange media
- 38.5 wt-% of waste and 61.5 wt-% of glass frit
Washing column
Waste glass sample from the SHIVA trial


Refractory furnace crucible melter
In Can (CEA/Orano)
• For liquid or solid waste feeds
• Only tolerate small amounts of organics (with the current gas treatment)
• Can operate remotely for high-activity waste
• The product can be glass, glass ceramic or simply a high-density waste product
• THERAMIN demonstration test trial:
– 25 kg of ashes
– 50 % of ashes and 50 % of glass frit
Waste and glass frit feeding
Melting pot
One Canister
~ 108 kg of glass

Thermal gasification

Thermal gasification (VTT)

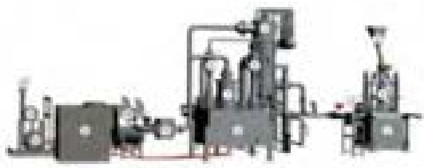
- Designed for processing of high organic matter containing ion exchange resins and organic operational waste (liquid organic waste not yet tested)
- Product: solid residue (filter dust and bottom ash)
- VTT has developed geopolymerisation for immobilisation of the product ash
- THERAMIN demonstration test trial: 325 kg organic ion exchange resin was treated and solid residue was geopolymerised => 40...70 kg geopolymerised final product



Joule melting

GeoMelt (NNL)

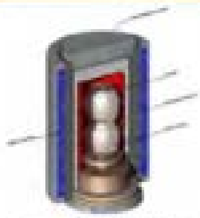
- The GeoMelt melter consists of a steel container lined with refractory materials containing the melt
- Direct electric heating (Joule heating)
- Product of the process is semi-crystalline glass, which immobilises heavy metals and radionuclides
- THERAMIN demonstration test trials:
  - Thermal treatment of 275 kg of representative cementitious waste stream with a pre-treatment waste loading of 40%
  - 239 kg of a sludge stream consisting of clinoptilolite, sand and Magnox sludge with a pre-treatment waste loading of 72%

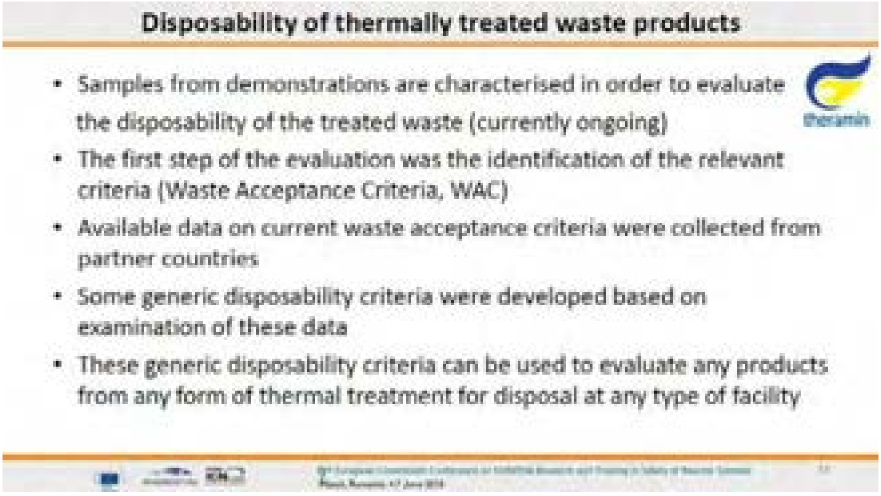


Hot Isostatic Pressing

HIP (NNL and USFD)

- The HIP is used to consolidate a pre-prepared waste feed sealed in a HIP can resulting in a monolithic waste form
- The can is placed inside the furnace and the vessel closed before applying pressure and temperature furnace
- THERAMIN test trials:
  - USFD: magnesium hydroxide sludges with triuranium octoxide (U_3O_8)
  - NNL: sludge feeds




Disposability of thermally treated waste products
• Samples from demonstrations are characterised in order to evaluate the disposability of the treated waste (currently ongoing)
• The first step of the evaluation was the identification of the relevant criteria (Waste Acceptance Criteria, WAC)
• Available data on current waste acceptance criteria were collected from partner countries
• Some generic disposability criteria were developed based on examination of these data
• These generic disposability criteria can be used to evaluate any products from any form of thermal treatment for disposal at any type of facility
theramin


theramin
The EC project THERAMIN will host a conference to share the results of the project and other recent developments in the field of thermal treatment of radioactive waste
theramin 2020 conference
thermal treatment of radioactive waste
MECHANICS INSTITUTE, MANCHESTER
TUESDAY 4TH TO WEDNESDAY 5TH FEBRUARY 2020
Plus optional visit to University of Sheffield on Thursday 6th February 2020
More information available:
http://www.theramin-h2020.eu/

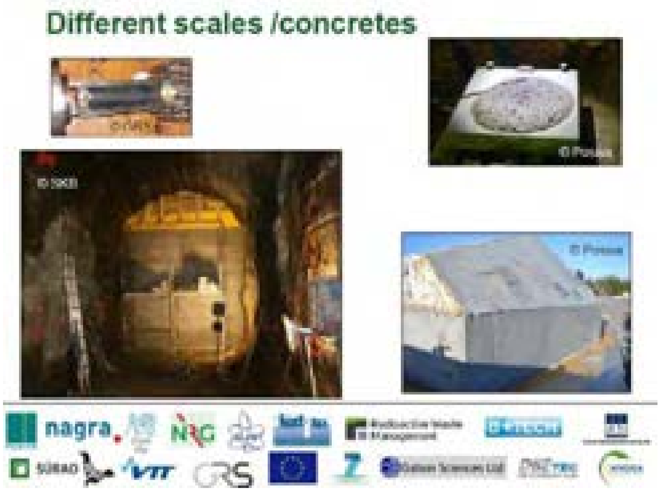
DOPAS - *Johanna Hansen (POSIVA, Finland)*


Plugs and seals in repository
nagra
SÚRAO
VTT
GRS


nagra
SÚRAO
VTT
GRS


DOPAS Experiments and work packages
nagra
SÚRAO
VTT
GRS


DOPAS Experiments
nagra


Different scales /concretes
nagra


Different scales /bentonite
nagra

Underground or above ground

Assessing the experiments

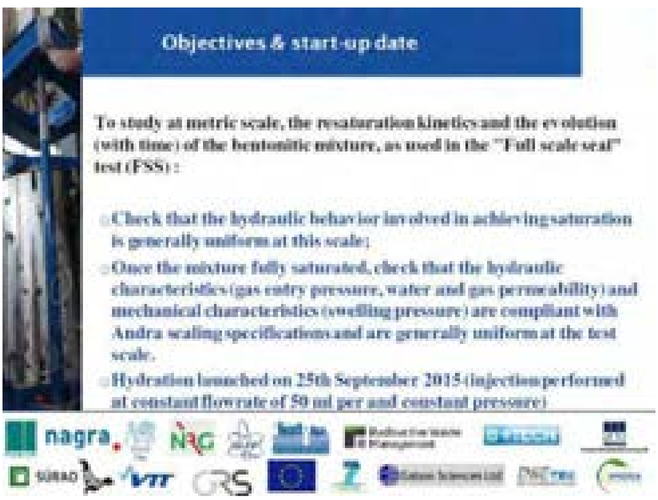
- Description of site constraints and future evolution
- Setting performance requirements
- Theoretical calculations to support the design and implementation phase
  - Model development
  - PA-methodology.
- Processes and phenomena
- Integration of results to the overall safety

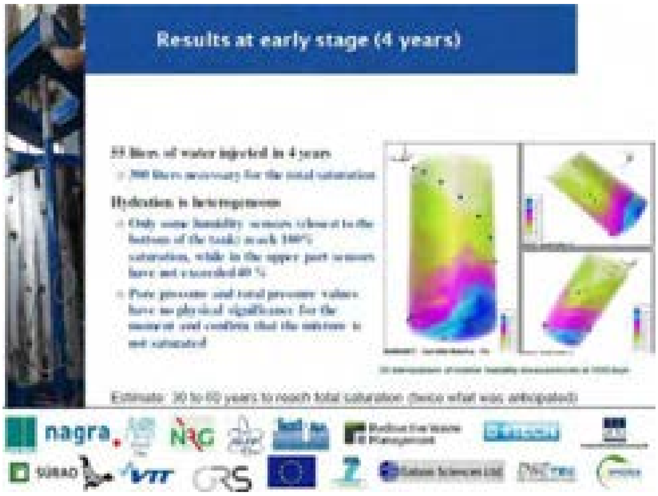
Joint aspects and benefits for co-operation with plugs and seals

- Preparation for demonstrations before operation phase
- Similar type of materials and methods
- Improved quality and risk management including occupational and long-term safety
- Theoretical calculations to support the design and implementation phase
- Similar work phases is good way of benchmarking how other organisations are working
- The success and challenges are good to discuss and analyse with people having similar experience

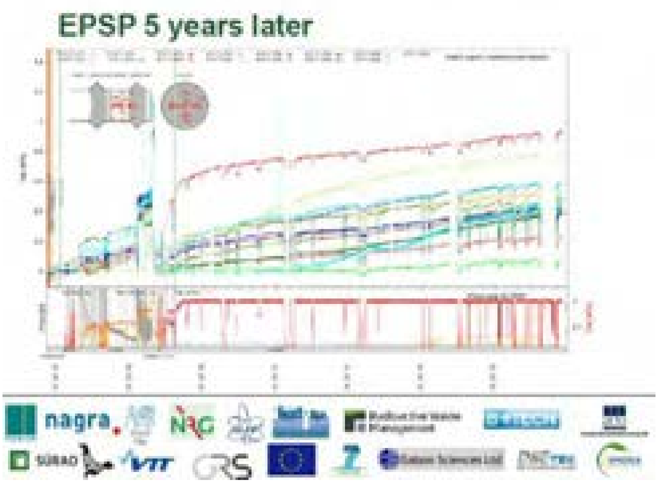

DOPAS provides further
Developed and described design basis, reference designs and strategies and examples
Detailed design and implementation chain for different type of demonstrations
Experiences on materials to be used in repositories and their interactions
Improved quality and risk management procedures, which has been used in practice
Experiences on plug performance in different conditions
Experience on performance assessment tool for plugs and seals
Role on plugs and seals in Safety case
nagra
SÚRAO
VTT
GRS


FSS, ANDRA, St. Dizier, FR
nagra
SÚRAO
VTT
GRS

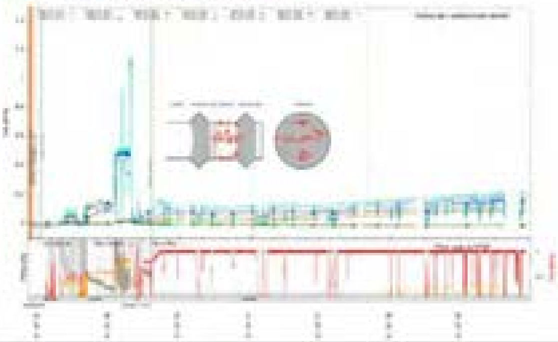

Objectives & start-up date
To study at metric scale, the resaturation kinetics and the evolution (with time) of the bentonitic mixture, as used in the "Full scale seal" test (FSS) :
Check that the hydraulic behavior involved in achieving saturation is generally uniform at this scale;
Once the mixture fully saturated, check that the hydraulic characteristics (gas entry pressure, water and gas permeability) and mechanical characteristics (swelling pressure) are compliant with Andra sealing specifications and are generally uniform at the test scale.
Hydration launched on 25th September 2015 (injection performed at constant flowrate of 50 ml per and constant pressure)
nagra
SÚRAO
VTT
GRS


Results at early stage (4 years)

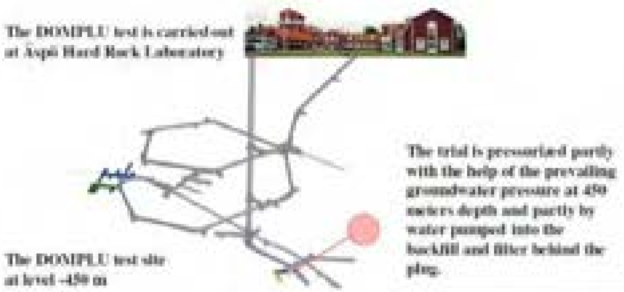

EPSP, CTU, Josef gallery, CZ


EPSP 5 years later

EPSP 5 years later



DOMPLU, SKB, ÄSPÖ, SE



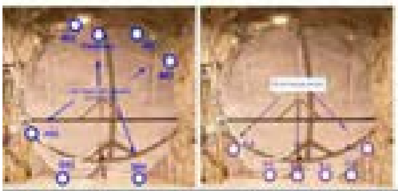
DOMPLU – Leakage measurements

- DOMPLU was monitored 3 years (2013-2016) at a constant water pressure of 4MPa. During this period the leakage past the plug varied between one and two litres per hour (17-33 ml/min). This can be considered as an upper limit of the expected leakage of the DOMPLU plug design (artificial pressure was higher than groundwater pressure)

DOMPLU – Gas tightness test

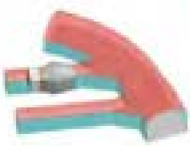
- Swedish/Finnish requirement states that plugs must be reasonably gas tight during the operation phase of the Spent Fuel Repository
- In 2017, the DOMPLU plug was drained and a gas tightness test was performed by injecting helium to a pressure of 40 kPa in the filter section. The plug proved to be completely gas tight at this pressure!

DOMPLU – Strength test and dismantling



- In the final strength test, water was injected to a total pressure of 10 MPa. The concrete dome behaved as expected at this load and deformations did not result in significant cracking or damages within the concrete dome.
- During demolition, great experience was obtained from material test sampling of concrete and bentonite.

POPLU, POSIVA, ONKALO, FI



- Construct a full-scale deposition tunnel end plug (workmanship and quality control)
- Develop the detailed structural design, including development of the concrete mix
- Develop tunnel plug location excavation
- Produce a quality manual for quality control practices and risk mitigation measures
- Develop instrumentation and performance monitoring techniques (mechanical load transfer, concrete shrinkage, water tightness), including models
- Observe and solve practical challenges prior to construction and implementation, related to occupational safety, documentation, quality assurance, practical work procedures etc.

POPLU and FISST Plug

- After the pressurisation of the POPLU in spring 2016 Posiva started to prepare for the further development of the end plug design
- The aim was to construct Posiva's next plug for the FISST-test (Full-Scale In-Situ System Test) in 2019
- Before the further development of the plug design, Posiva performed a comparison of the results and experiences of the POPLU and DOMPLU tests
- Based on the comparison Posiva wanted to test the DOMPLU type dome plug design in full scale test, since wedge plug was already tested
- The main reasons for this were the smaller amount of concrete and construction feasibility of the dome plug design (casting in one piece vs. in two)

POPLU followed by FISST plug

DOPAS foreground and dissemination

- Each experiment produced a public summary report
- Integration of experiments presented in Work Package summary reports and DOPAS Technical summary
- Staff exchange programme
- Main DOPAS events:
  - Training workshop September 2015
  - DOPAS 2016 seminar May 2016
    - focusing on plugs and seals and the lessons learned around DOPAS demonstrations

DOPAS project experiences

- Integration between Experiments and Work Packages:
  - requires regular discussion between Exp. leaders and WP leaders (Work Package and management team meetings)
- Full scale demonstrations requires more resources (cost & personnel) than expected, but demonstrations are essential from learning and training point of view
- The DOPAS staff exchange programme has been useful
- Expert Elicitation process for summary reports has been found very useful
- Main reports D6.4; D5.10; D4.4; D3.30; D2.4

MODERN2020 - *Johan Bertrand (ANDRA, France)*

content

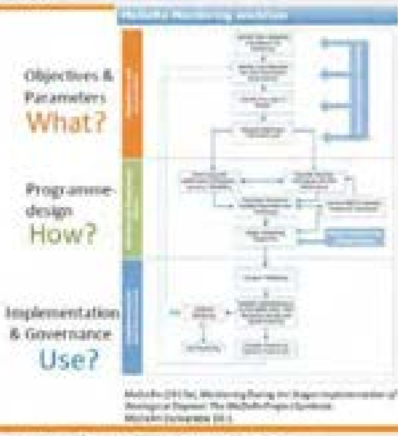
1. Introduction
2. WP2 : monitoring strategies
3. WP3: Monitoring technlogies
4. WP4: in situ demonstration
5. WP5: Public stakeholders
6. WP6: dissemination
7. Conclusion
8. Futher works

INTRODUCTION

Background

Extensive « literature » on monitoring (20 years)

- National legislation and regulatory demands
  - **STUK YVL Guide D.5**
  - **French ASN-2008 Geological Disposal Safety Guide,**
- Guiding principles from international organizations (IAEA, NEA, EU)
  - **IAEA TECDOC 1208 (2001)**
  - **IAEA Safety Requirements WS-R-4 (2006)**
  - (....see paper)
- Generic process for scoping, designing and implementing a repository monitoring programme - the MoDeRn-FP7 project (2010-2014)



Approach

- All programmes agree that it is impractical to monitor all of the repository
- High-level strategies will be used to monitor specific parts of the repository during the operational period
- In Modern2020 a strategy consists of the following elements:
  - **What:** waste packages and near field; dummy packages and near field; specific EBS elements; the geological barrier; the biosphere
  - **Where:** preparation main repository, pilot repository, underground rock characterisation facility
  - **When:** during construction (baseline for operations); during emplacement; after emplacement; during closure; after closure
  - **How:** the types of technologies used, including *in situ* sensors; borehole-based sensors; surface –based technologies; air-based technologies
  - **"Whom":** operator, regulators, lay stakeholders...

Why to monitor?

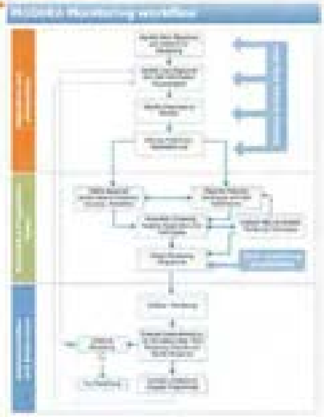
- Definition of **monitoring** (IAEA Safety Standards): "continuous or periodic observations and measurements to help evaluate the behaviour of the components of a waste disposal system and the impact of the waste disposal system on the public and the environment"

- The emphasis placed on different reasons for monitoring the near field during the operational period differ from programme one to another
  - Monitoring may provide an opportunity to demonstrate understanding of the thermal, hydraulic, mechanical and chemical processes occurring, thereby demonstrating WMO **understanding and building further confidence**
  - Monitoring programmes might focus on the short-term evolution of the repository system to show that this **evolution is consistent with the safety case**
  - Monitoring may also provide the means for **continuing to engage with stakeholders** and check the evolution of the disposal system following waste emplacement

WP2 MONITORING STRATEGIES

What to monitor?

- The MoDeRn Project formulated a reference framework and a generic workflow for developing and conducting a monitoring programme
- Further work was required to consider explicitly **how monitoring parameters could be identified**



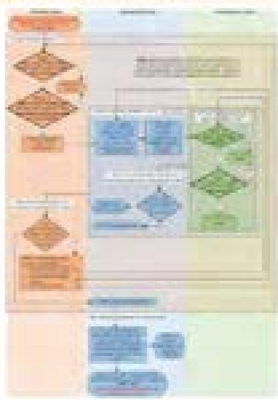
Recommendation from the Nuclear Energy Agency

Monitoring of Geological Disposal Facilities: Technical and Societal Aspects" (NEA, 2014)

- *The current, and justifiable, tendency is to measure as many parameters as possible*
- *With the transition from the repository development stage to implementation, it becomes necessary to optimise the selection of the parameters*
- *The identification of those parameters which would sufficiently demonstrate the attainment or approach to the passive safety status of the disposal system would be of substantial benefit*
- The recommendations of the NEA have been addressed in Modern2020 through the development of a generic structured approach to the selection of parameters
  - The Modern2020 Screening Methodology

The Modern2020 Screening Methodology

- The Methodology is presented as three strands: processes, parameters and technologies
- Starting point is list of processes or parameters that have been proposed for monitoring
- Basis for decisions are judgements based on existing knowledge
- The Methodology is a stepwise process to allow for **traceability and transparency**
- Judgements used as a basis for decisions may change, so processes and parameters are parked and not rejected



Decision making process (use of monitoring Data?)

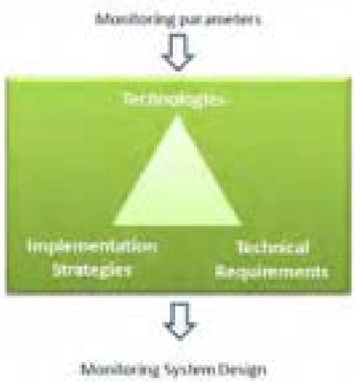
- Consider how a waste management organisation might plan for responding to monitoring results
- Develop recommendations and observations on responding to monitoring results
  - General guidance and principals, rather than specific plans
- Develop a generic process for responding to monitoring results
- Terminology on performance measures and response plans
- Decision making is a complex process where monitoring is only one input

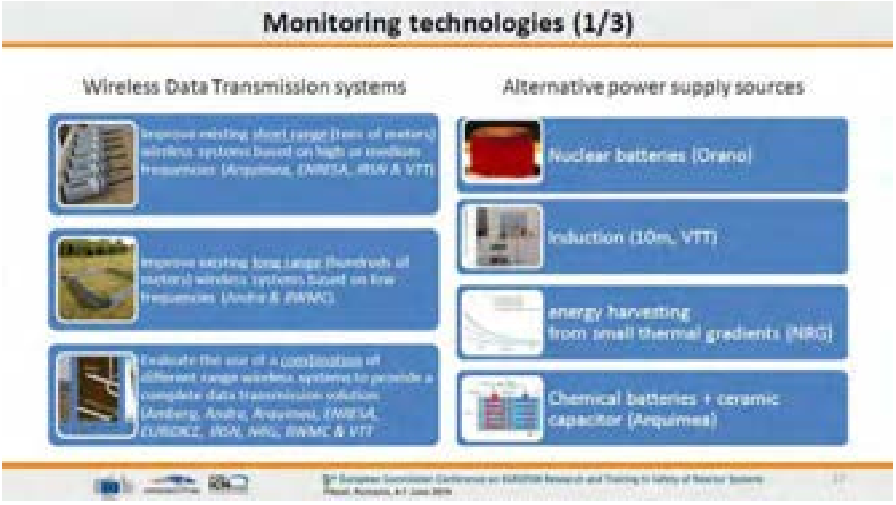
WP3 : MONITORING TECHNOLOGIES

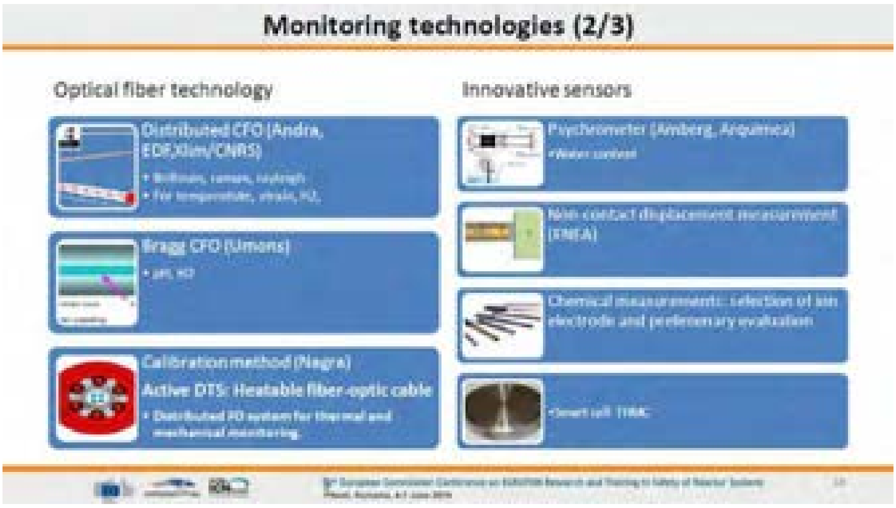
How to monitor?

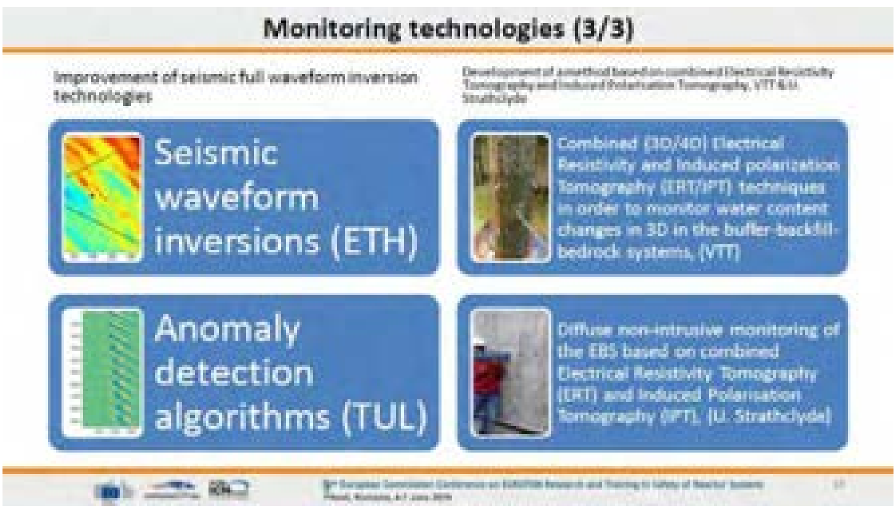
Monitoring technlogies

- Technologies exist but with evident limitation
- Actions to carry out before repository monitoring starts
  - **Adaptation** of the technologies to specific monitoring objectives, host rocks and repository concepts
  - **Innovate** of technologies for monitoring specific parameters
  - **Improvement** of the long-term performance.
- Objectives
  - Accelerate the development of suitable monitoring technologies VS needs
  - Guidance for the monitoring system qualification

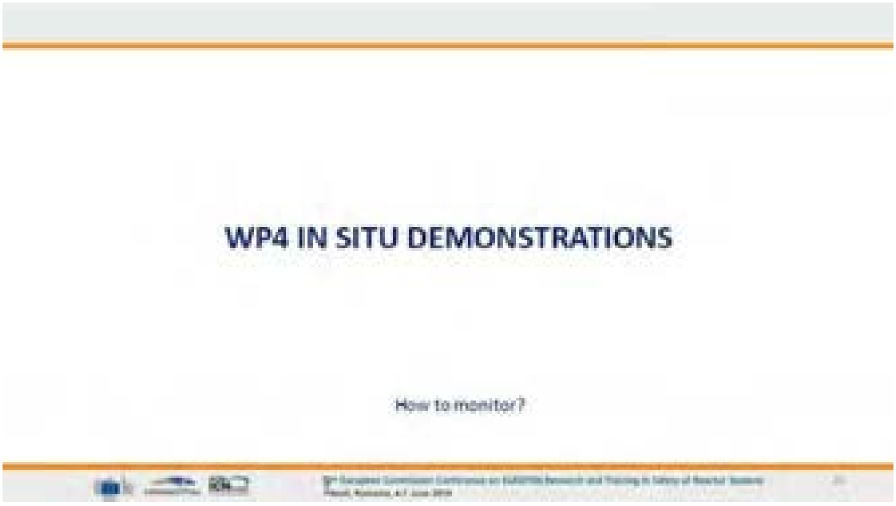


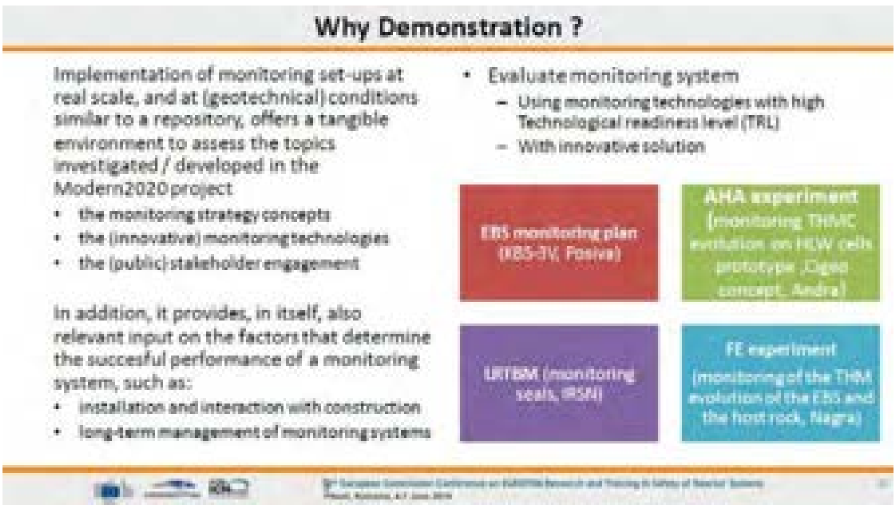

Monitoring technologies (1/3)
Wireless Data Transmission systems
Alternative power supply sources
Improve existing short range (tens of meters) wireless systems based on high or medium frequencies (Arquimea, ENRESA, IRSN & VTT)
Improve existing long range (hundreds of meters) wireless systems based on low frequencies (Andra & RWMC)
Evaluate the use of a combination of different range wireless systems to provide a complete data transmission solution (Amberg, Andra, Arquimea, ENRESA, EURIDICE, IRSN, NRG, RWMC & VTT)
Nuclear batteries (Orano)
Induction (10m, VTT)
energy harvesting
from small thermal gradients (NRG)
Chemical batteries + ceramic capacitor (Arquimea)


Monitoring technologies (2/3)
Optical fiber technology
Innovative sensors
Distributed CFO (Andra, EDF,Xlim/CNRS)
• Brillouin, raman, rayleigh
• For temperature, strain, H2,
Bragg CFO (Umons)
Calibration method (Nagra)
Active DTS: Heatable fiber-optic cable
• Distributed FO system for thermal and mechanical monitoring
Psychrometer (Amberg, Arquimea)
Non-contact displacement measurement (FNEA)
Chemical measurements: selection of ion electrode and preliminary evaluation


Monitoring technologies (3/3)
Improvement of seismic full waveform inversion technologies
Development of a method based on combined Electrical Resistivity Tomography and Induced Polarisation Tomography, VTT & U. Strathclyde
Seismic waveform inversions (ETH)
Anomaly detection algorithms (TUL)
Combined (3D/4D) Electrical Resistivity and Induced polarization Tomography (ERT/IPT) techniques in order to monitor water content changes in 3D in the buffer-backfill-bedrock systems. (VTT)
Diffuse non-intrusive monitoring of the EBS based on combined Electrical Resistivity Tomography (ERT) and Induced Polarisation Tomography (IPT). (U. Strathclyde)

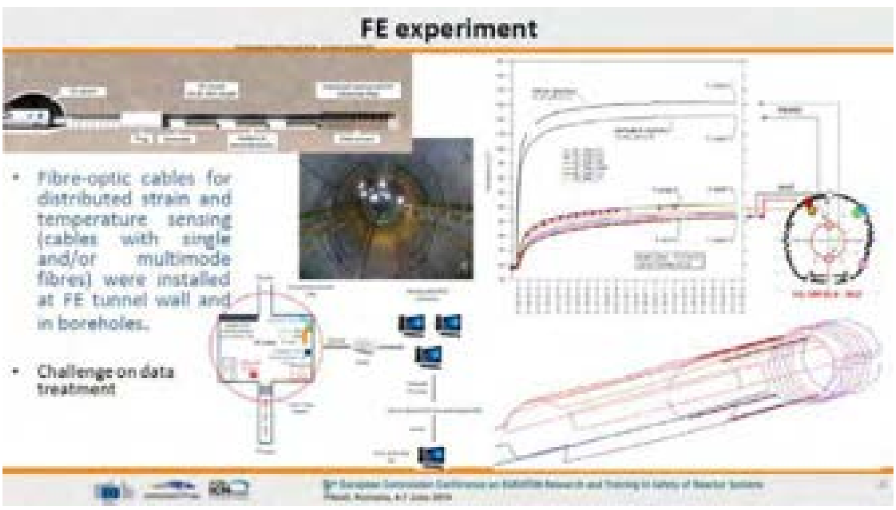

Guidance for the monitoring system qualification
a common multi-stage qualification methodology
• Strong synergy between Energy, Space fields and DGR needs with a qualification process in 3 stages: i) Selection of components, ii) The laboratory qualification and iii) On-site qualification
Global sketch for the qualification of monitoring components in DGRs
Proposal of an Approval DOCument (ADOC) for a monitoring component qualification


WP4 IN SITU DEMONSTRATIONS
How to monitor?


Why Demonstration ?
Implementation of monitoring set-ups at real scale, and at (geotechnical) conditions similar to a repository, offers a tangible environment to assess the topics investigated / developed in the Modern2020 project
• the monitoring strategy concepts
• the (innovative) monitoring technologies
• the (public) stakeholder engagement
In addition, it provides, in itself, also relevant input on the factors that determine the succesful performance of a monitoring system, such as:
• installation and interaction with construction
• long-term management of monitoring systems
• Evaluate monitoring system
– Using monitoring technologies with high Technological readiness level (TRL)
– With innovative solution
EBS monitoring plan (KBS-3V, Posiva)
AHA experiment (monitoring THMC evolution on HLW cells prototype, Cigeo concept, Andra)
URTBM (monitoring seals, IRSN)
FE experiment (monitoring of the THM evolution of the EBS and the host rock, Nagra)


Evaluate possible monitoring design
Evaluate possible monitoring design
Implement monitoring design using monitoring technologies with high Technological readiness level (TRL)
• Evaluate practical aspect (duration, implementation methods)
• Evaluate cost
• Evaluate of the monitoring on the safety
Full scale in situ system test, Onkalo Posiva


Evaluation of innovative solution
Long-Term Rock Buffer Monitoring experiment (LTRBM)
New measuring instruments from partners
•Chemical sensor
•Thermocouple Psychrometers
•THMC smart sensor
•Total pressure
•Pore water sensors


FE experiment
• Fibre-optic cables for distributed strain and temperature sensing (cables with single and/or multimode fibres) were installed at FE tunnel wall and in boreholes.
• Challenge on data treatment

WP5: public Stakeholders

- To **actively engage** local public stakeholders (people in concerned communities) in repository monitoring RD&D within the Modern2020 project, and to **analyse the impact** this has on both the participating stakeholders' and the project partners' understanding of, and expectations regarding, repository monitoring
- To **define** more specific **ways for integrating public stakeholder concerns and expectations** into specific repository monitoring programs
- To **develop ideas on how to ensure accessibility and transparency of monitoring data** (of the type gathered through in-situ monitoring) to public stakeholders
- To **learn lessons** on how local stakeholder groups could be engaged effectively with RD&D programs and projects **at EU level**.

Responsible research and innovation (RRI)

Responsible research and innovation (RRI)

- RRI pushed by the EU
- RRI: "societal actors work together during the whole research and innovation process in order to better align both the process and its outcomes with the values, needs and expectations of society" (Horizon 2020 website)
- RD&D should be anticipatory, inclusive, responsive, reflective, and sustainable
- Modern2020 has tried to adapt to RR

- 'Home engagement activity' (making use of existing configurations; in collaboration with respective NWMO)
  - Municipality of Eurajoki (Finland), Municipality of Östhammar (Sweden), Local partnerships in Mol and Dessel (Belgium), Clis de Bure (France)
  - Belgium and Sweden from the start; Finland and France to follow later
  - 'Activity level' influenced by national programme (cf. environmental court process in Sweden)

STORA MONA ÖSTHAMMARS KOMMUN Clis EURAJOKI

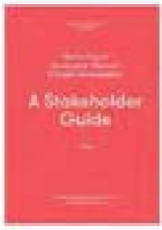
Specific outputs

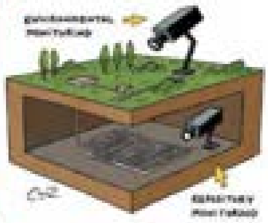
More reflective and analytical

- Monitoring the Underground: Specific Challenges for Engaging Concerned Stakeholders (D5.1)
- Lessons learned from engaging with local citizens in an international R&D project (D5.3)

More practical

The Stakeholder Guide to Repository Monitoring (D5.2)





Dissemination

2nd International Conference on Monitoring in geological disposal of radioactive waste

Strategies, technologies, decision making and public involvement

150 participants 15 countries
90 organizations 43 speakers

All presentation is available on Modern2020 website

Training school about monitoring

Learning unit 1 : Nuclear fuel cycle and geological disposal concept
Learning unit 2 : Monitoring : objectives, process and parameters
Learning unit 3 : Monitoring program design
Learning unit 4 : Implementation and governance

Conclusion

- The Modern2020 Project has enhanced our ability to implement, both strategically and technically, repository monitoring during the operational phase to build further confidence in the post-closure safety case
  - international consensus on strategies, parameter-selection methodologies and plans for responding to monitoring result
  - Identify and accelerate the R&D on monitoring technologies
  - Real test cases
  - the work on stakeholder engagement in the Modern2020 Project has been successful and has identified innovative methods for early engagement of stakeholders in the development of monitoring programmes
    - Both groups benefitted from the interaction, especially as it was a long-term interaction over the course of the four-year Project

Further Work

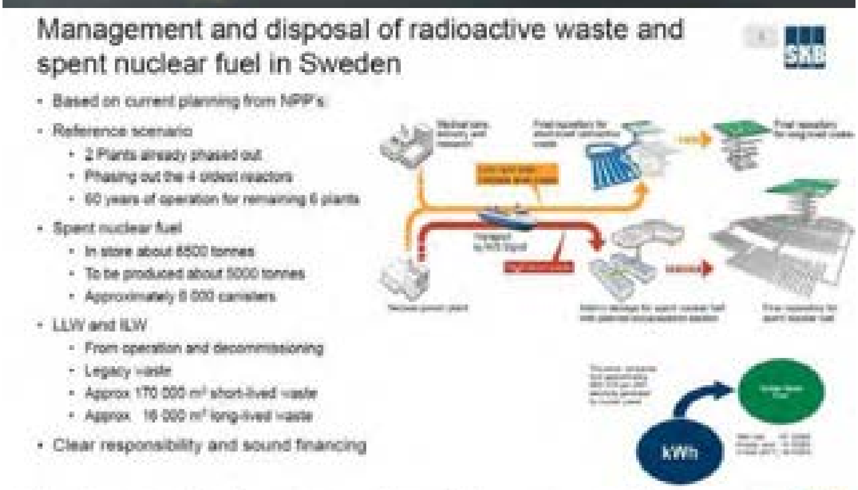
- The key requirement now, is for the guidance to be applied in specific programmes, and for detailed operational phase monitoring programmes to be developed.
  - Common strategy : Pilot phase, industrial pilot phase, first emplacement field, Full-Scale *in Situ* System Test….always heavy monitoring system
- the new monitoring techniques provide much more information (huge amounts of digital or analog data) that the standard data acquisition systems can not properly handle. Furthermore, the fast spreading of the BIM (Building Information Modelling) technologies to all kind of civil works will demand to integrate the monitoring data as part of the digital model of the future repository.

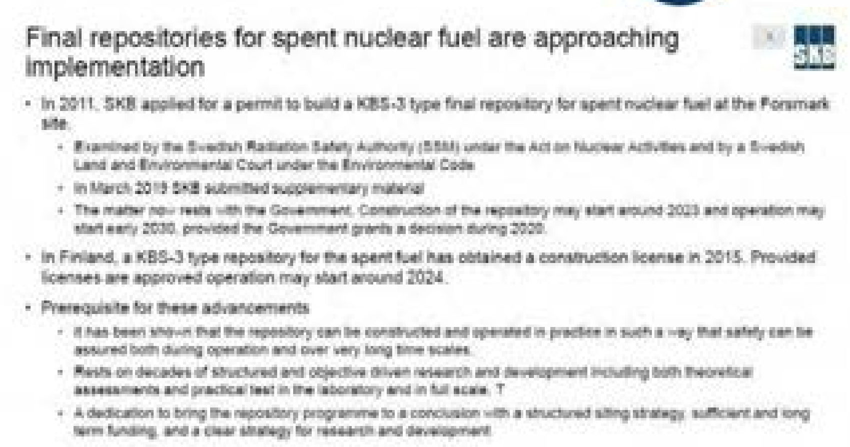
Acknowledgement

MODERN 2020

WWW.MODERN2020.EU

KEYNOTE - *Johan Andersson (SKB, Sweden)*





Research strategy - objectives

- Research is one of the pillars in SKB's programme since its start in the 1970s.
  - Secure safe management and final disposal of nuclear waste by ensuring access to the knowledge that is needed in order to assess a site, design, licence, construct and operate existing and planned facilities.
- Research should:
  - provide sufficient knowledge of post-closure safety and make sure that safety can be assessed for SKB's existing and planned facilities also in the future,
  - provide sufficient information for the continued technology development and planning that is needed in order to obtain efficient and optimised solutions that at the same time provide safety both during operation and after closure of SKB's final repository.

Strategy - Iterative development

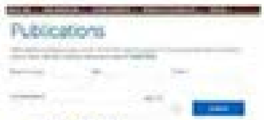
- Designs are evaluated in safety assessments that provide feedback to (siting factors) technology development, design and requirements
  - Each decision step requires an assessment of post-closure safety to judge whether the knowledge base concerning post-closure safety is sufficient to proceed to the next step.
- Steps in the past
  - KBS-3 in 1983 – design concept established
  - SR-97 (1997) – siting factors
  - SR-Can (2006) – detailed design requirements
  - SR-Site (2011) – basis for license application
- Coming steps
  - PSAR - supported by updated requirements and more detailed designs, to be submitted to SSM as a basis for obtaining a license to start underground excavation.
  - Updated to a safety analysis report (SAR) that will form the basis for the construction and operation of the repository.

Research strategy – in house competence

- Need sufficient in-house competence to
  - assimilate the knowledge that is present in the community of importance for management and final disposal of nuclear waste, and
  - be a skilled research client.
- Core of the in house competence has been to maintain a coherent group of professionals
  - with knowledge of the methodology for the assessment of post-closure safety
  - with both wide and deep interdisciplinary insight on how the different processes that affect repository safety interact.
- By conducting its own research, SKB has ensured this maintenance of competence
  - Need also input from a very wide range of scientific and technical disciplines

Research strategy – openness

- All research should be publicly available
- A strive to publish results in open peer reviewed journals.
- In communicating with the public through media, open seminars or other events
  - let the internal experts be the main spokespersons
  - foster a frank and open discussion
- Openness and an strive to demonstrate that there is nothing to hide
  - judged a basis for developing confidence with the public, the research community and authorities



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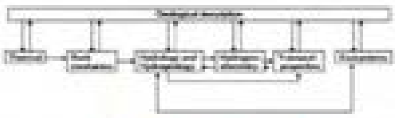
Research strategy – international cooperation

- In building up and maintaining competence international cooperation has been essential
  - Direct cooperation with sister organisations
  - using experts trained in other programmes
  - Participation in the work of International organisations like the IAEA, OECD/NEA and the European Commission.
- Direct cooperation with sister organisations
  - E.g between SKB in Sweden and Posiva in Finland or NWMO in Canada.
  - Allows for sharing resources and ensuring that the expertise involved reaches critical mass.
- IAEA , NEA and EU
  - provide platforms for interaction with peers from sister organisations and
  - also allowed interaction with regulators from other countries.
  - Over the years these interactions have strongly advanced the understanding on how to conduct a repository development programme and how to carry out safety assessments.
  - Direct funding of research projects by the European Commission not primarily important in relation to other funding but, *it has allowed networking on a detailed level directly with a broad range of researchers and other experts.*

Knowledge management tools – site descriptive modelling

- Introduced in 2001 when surface based investigation started
  - to be used both as input to the safety assessment and to the engineering design work
  - Entails transfer of the information from quality-assured databases produced by the site investigations to discipline-specific descriptions applicable to various subdivisions of the system made up of surfaces and volumes.
- Included in the SDM work is
  - Control of primary data
  - Disciplinary and interdisciplinary integrated modelling providing basic geometrical descriptions and parameterisations of the bedrock and the surface system.
  - Evaluation of uncertainties in values of parameters describing the material properties and states of the studied system and the variation in the subdivision of the studied system
- Development and updating an SDM forces interaction
  - between experts from different geoscientific disciplines
  - between experts and designing engineers and safety assessment teams.



Knowledge management tools – data qualification

- Safety assessment and design work involves several different teams using data on e.g. fundamental processes, site characteristics and design solution
  - These data originate from various sources of different quality
  - Different teams may need data on the same aspects and phenomena
- When SKB updated the safety assessment methodologies was realised that
  - it is necessary to ensure that different teams use the same data for describing the same things and
  - that the quality of the data are assessed as well as their uncertainties
  - Strict procedures for data and uncertainty qualification were introduced by the concept of data reports

Knowledge management tools – peer review

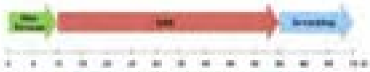
- Both internal and external peer review are essential quality assurance tools.
- SKB has developed and applies strict protocols for these reviews.
  - Review plans are established defining the review criteria and the qualification of the reviewer.
  - A review is conducted using standardized protocols where the reviewer both makes an overall assessment against the review criteria stated in the review plan and provides detailed comments.
  - In completing the reviewed document the reviewee needs to respond to every such comment in writing.
- May have been regarded as tedious in the beginning- now seen as essential and a safeguard against the many mistakes that otherwise would have been made

Knowledge management tools – Requirements and quality control of production and installation

- Confidence in the post-closure safety assessment rests upon
  - understanding of the THMC processes determining the evolution of the repository
  - a demonstration that the installed engineered barriers and the underground construction work conforms to stated technical design requirements
- For the latter a Quality Control programme is being developed
  - Implies possibilities to find potential manufacturing or installation errors or other deviations in material, equipment and handling
  - Before and during waste emplacement, quality control provides the main source for ensuring that the as-built stage complies with stated design requirements
- Well-defined technical design requirements needed
  - Formulation of design requirements is not trivial
  - From the Safety Assessment perspective they should be sufficient to yield a safe repository
  - From the designers perspective they need to be possible to implement and verify
- Step-wise development
  - An initial set of design requirements were specified in SKB's license application
  - Together with Posiva, SKB has presented revised technical design requirements

Future challenges - Safety case needs to be up to date during the entire operational time

- Need to be able to make safety assessments does not disappear with the construction license.
    - Need to assess how the engineered barriers and the natural processes in the rock and on the ground surface interact and evolve in time.
- Research and new findings regarding the long term properties will continue,
    - driven by SKB,
    - within other implementing organisations
    - the scientific community at large.
- There has to be a readiness to assess the safety implications of such new findings.
- According to the regulations, the SAR should be constantly kept up-to-date and with a periodic overall evaluation.

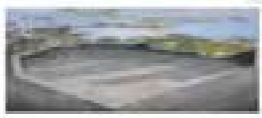


Developing the Safety Case for the KBS-3 repository when approaching construction and operation

- While licensing process proceeds
    - Assessments and analyses to prepare the Preliminary Safety Assessment Report (PSAR) needed in an application for a permit to start the construction of the repository are underway.
    - Initial planning on the updated Safety Assessment Report (SAR) needed in an application for a permit to start emplacement.
- New aspects to consider in these safety cases

Access to detailed data from the underground

- Volumes of the host rock that are hard to characterize from the surface will be accessible to mapping and (short) borehole investigation from the underground galleries being excavated.
- Provides input both for
    - confirmation that the host rock has the expected (and suitable) properties
    - high resolution data allowing for local adaptation of the repository like specifying the exact location of deposition tunnels and deposition holes
- Parts of the repository will already have been constructed, and characterized, other parts are yet to be excavated.
    - "As-built" will be revealed gradually

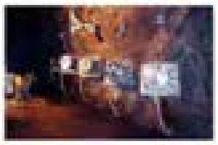


Relation between operational safety and post-closure safety

- Conflicts between operational safety, workers' protection and post-closure safety could be a reason to update designs such that these conflicts are resolved.
- Actions during operation should not only consider impacts on operational safety, but also how these actions might affect post-closure safety.

Monitoring

- Monitoring changes due to disturbances from excavation and operation both
  - characterization aspects and
  - provides additional input to the confidence in the safety case.
- Monitoring results can essentially never relate to direct safety impacts,
  - But a management structure should be in place to handle situations when monitoring results deviate from expectations
- A monitoring program to be implemented at the start of construction is now being developed
  - Measurements in most of the boreholes drilled during site investigations as well as in boreholes drilled from the underground
  - Long term tests at different scales building on experiences gained at Äspö HRL and from other URL:s



Future challenges - Proven quality control as an essential part of the safety case

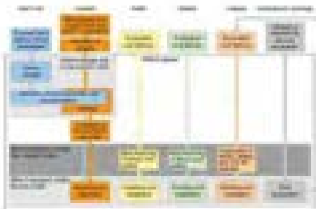
- Ensure TDRs technically achievable and possible to verify at the latest at the time of final installation, deposition or backfilling.
  - Ongoing and future technology developments focus on these aspects.
- Concern
  - processes, methods, equipment and personnel for fabrication and installation, testing and inspection.
- Important to establish:
  - principles for safety and quality classification,
  - what is to be quality-managed and quality-controlled, and
  - when quality management and control are to be performed and by whom in terms of first, second and third parties.

Future challenges - Implementation

- Technology development and need for detailed investigations
  - SKB has established a technically feasible reference design and layout
  - Detailed designs adapted to an industrialized process designed to fulfilling specific requirements on quality, cost and efficiency need still be developed
  - Layout needs to be adapted to the local conditions found when constructing the repository at depth
- Should result in at least the same level of safety as the current reference design
- To be implemented in production system
  - Encapsulation facility, Clink
  - Final repository
  - External production facilities

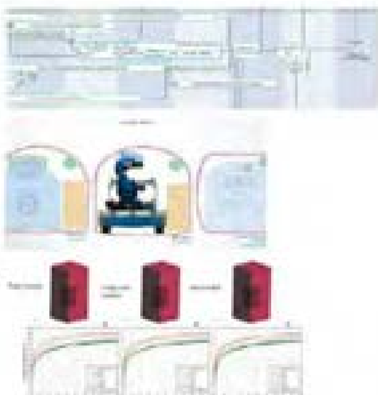
e.g. Logistics studies

- Map the different flows of material etc
  - Spent fuel flow
  - EBS material flow
    - Focus on storage levels, flow and AGV amounts
  - Deposition sequence
    - Modelled for both dry and wet deposition hole scenarios
    - Both general planning tunnel lengths and detail level planning tunnel lengths can be applied to the model
  - Rock work together with detailed investigations
- Among issues studied
  - Identification of plausible bottlenecks
  - Need of storage in KTB logistics and operations
  - Utilization levels of machinery, buffer production, resources and Sigrid
  - Impact of uncertainties



Future challenges - Optimisation

- Systematic and organized approach to provide the necessary functions in a project at the lowest cost without sacrificing functionality
- Examples
  - Ventilation solution
  - Faster time to operation Excavation logistics of the first deposit area needs to be rearranged
  - Decrease deposition tunnel area
  - Shorter distance between deposition holes (thermal optimization)
  - Bentonite handling
  - Canister manufacturing and procurement process
- Need
  - an overall system understanding
  - focus on where the great costs are both in investment and operation



Future challenges - Knowledge management and in-house competence needed

- Research and development will need to continue also after a license to construct a repository is granted.
  - A need to apply, maintain and develop the knowledge management tools already established.
  - Workable procedures for information handling and QA already developed and successfully applied but wealth of information and pressure to act quickly will increase when construction and operation starts.
  - Practical application of tools for requirements management and quality control of production and installation.
  - Will also be used by even larger groups of experts.
- A core competence on post closure safety assessment including at least on overall understanding on how the repository components evolve over time needed for each WMO
  - Evaluation of the knowledge base both with regard to processes and input data in the assessment.
- Safety assessments are thus fundamental for the prioritisations of the research programme.
  - *It may be more difficult to attract a new generation of researchers and to justify funding the R&D when the fundamental issues are less acute.*

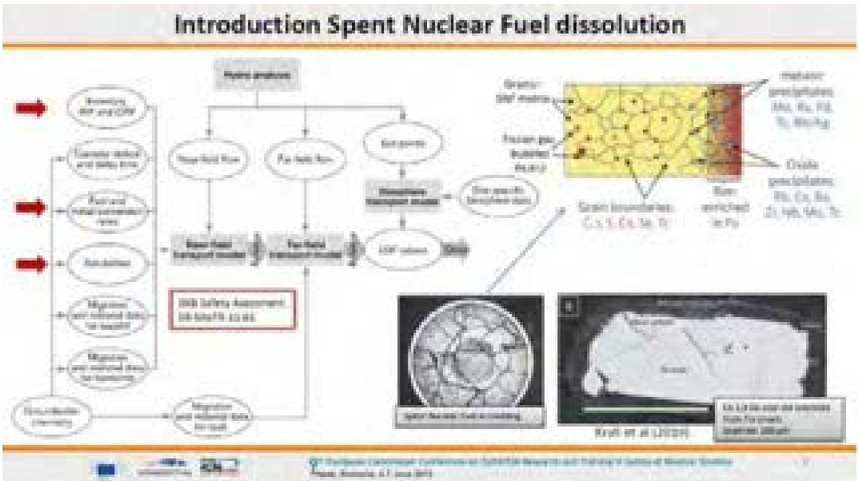
Role of international cooperation to meet future challenges

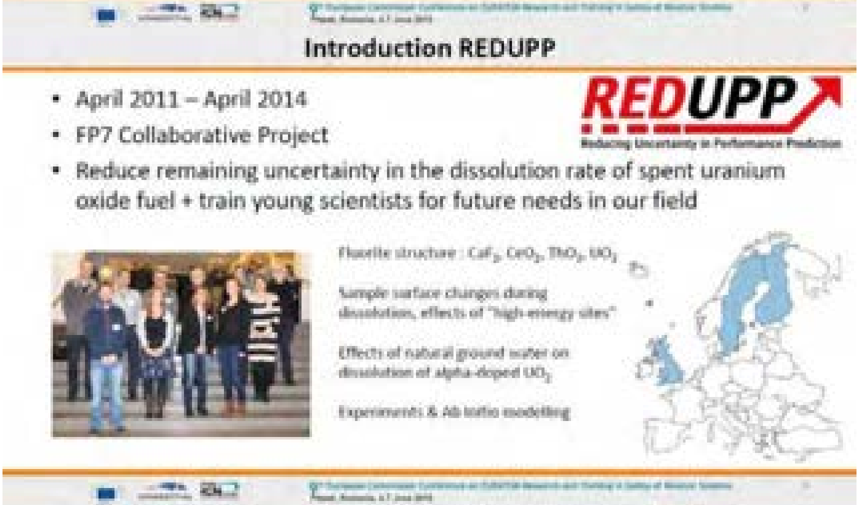
- Even more important on developing, sharing and managing the knowledge needed.
- Guidelines and other recommendations issued by the international agencies
  - not only important for developing programmes
  - also serve as a fundamental memory in more developed programmes when the experts ones being authoring such guides now have retired or soon will retire.
- Essential for sharing competences where the national contexts is too small, especially on issues essentially only of interest to the nuclear waste community
- Training
- Participation in international work may also be an inspiration and reason to carry on for internal staff, as well as researches at universities, to consider the work sufficiently interesting

Conclusions

- SKB is closing the back end of the fuel cycle
  - Research and development would need to continue, although with a new focus.
  - Need to apply, maintain and develop the knowledge management tools already established.
- International cooperation will be even more important on developing, sharing and managing the knowledge needed

REDUPP and DISCO - *Lena Zetterstrom Evins(SKB, Sweden)*





Introduction DisCo

- June 2017 – May 2021
- Horizon 2020 Collaborative Project
- Improve understanding of spent fuel matrix dissolution in repository conditions
- Test modern nuclear fuel types (doped & MOX) for comparison with conventional fuels:
  - *Both real spent fuel and synthesized model materials*
- Disseminate the new knowledge : reach a wider community through training and mobility measures
- Associated Group: CV Rez (CH), LEI (LT), MTA EK (HU), ICHTJ (PL), EIMV (SI), Subatech(FR)

DisCo
Modern Spent Fuel Dissolution and Chemistry in Failed Container Conditions

Methods REDUPP

Experimental

- Synthesis of spent nuclear fuel analogues: fluorite structure, grain size, porosity, defects ...
- Dissolution in various conditions & aqueous phases analyses
- Post-dissolution analyses of the solid phases

Back-Scattered Electron (BSE) image of ThO_2 fragment, 4 weeks leaching

Modelling

- Density Functional Theory in first-principles (Ab Initio) modelling (L(S)DA & DFT+U)
- Modelling a surface: 6-8 layers
- Stepped surfaces on fluorite materials: terraces and steps
- Ab initio molecular dynamics (AIMD) and atomistic thermodynamics simulations for different temperatures & water reactions on UO_2 surfaces

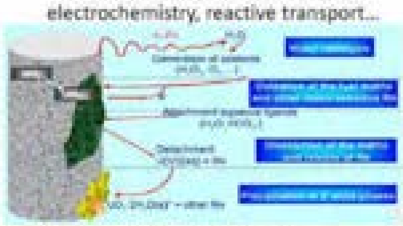
Methods DisCo

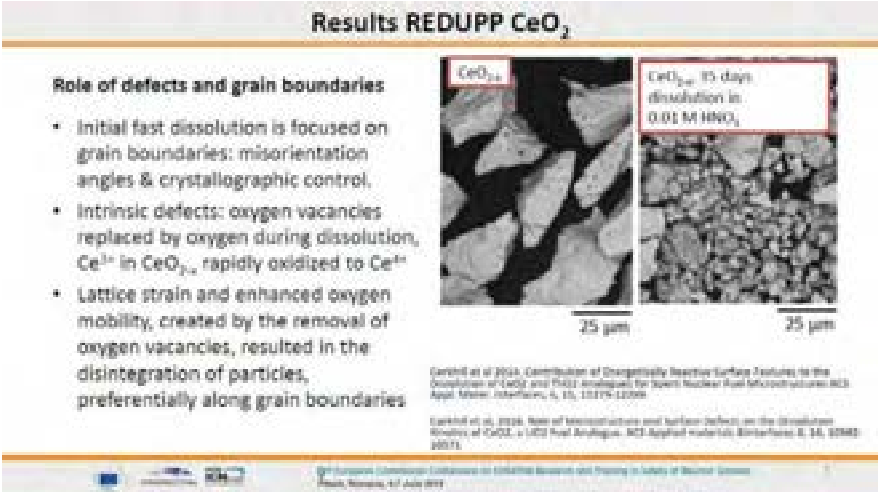
Experimental

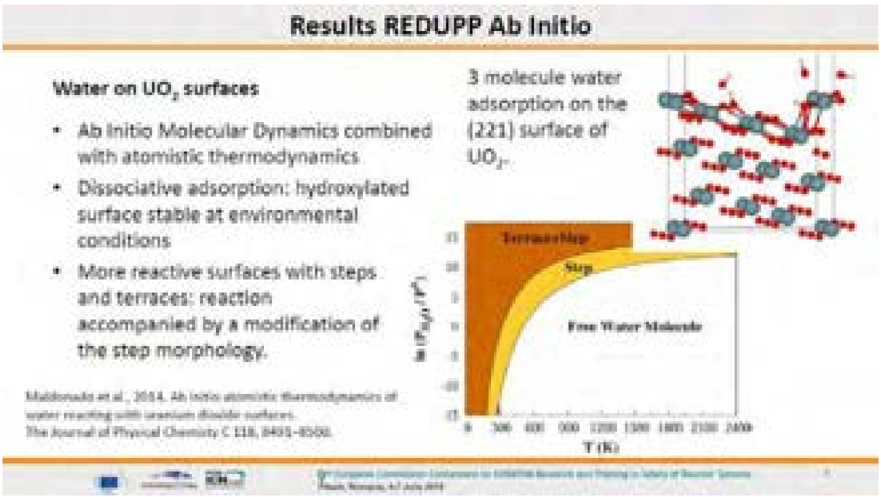
- Real Spent Fuel dissolution experiments: used MOX, Cr-doped, Cr/Al-doped, and standard fuel.
- Model materials: UO_2 with and without dopants (Cr, Al, Gd), with and without alpha-emitter (^{233}U, ^{238}Pu)
- Dissolution experiments
  - 1) oxidizing, SNF & air (as reference, SNF & Ar, Model materials & H_2O_2
  - 2) inert atmosphere & Fe (reducing)
  - 3) under Hydrogen (reducing)
- Post-dissolution analyses

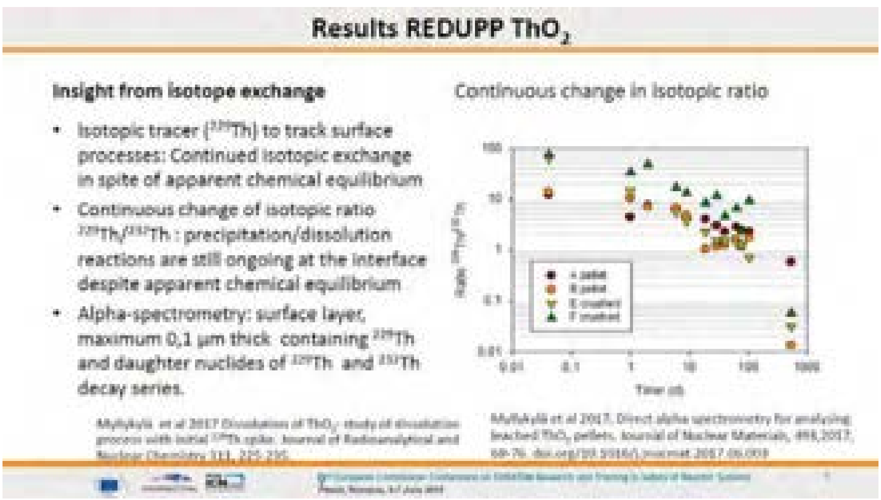
Modelling

- Improve existing models through inclusion of Fe corrosion, hydrogen effect & metallic particles
- Thermodynamics, chemical kinetics, electrochemistry, reactive transport...




Results REDUPP CeO_2
Role of defects and grain boundaries
• Initial fast dissolution is focused on grain boundaries: misorientation angles & crystallographic control.
• Intrinsic defects: oxygen vacancies replaced by oxygen during dissolution, Ce^{3+} in CeO_{2-x} rapidly oxidized to Ce^{4+}
• Lattice strain and enhanced oxygen mobility, created by the removal of oxygen vacancies, resulted in the disintegration of particles, preferentially along grain boundaries
CeO_{2-x}
CeO_{2-x} 35 days dissolution in 0.01 M HNO_3
25 µm
25 µm


Results REDUPP Ab Initio
Water on UO_2 surfaces
• Ab Initio Molecular Dynamics combined with atomistic thermodynamics
• Dissociative adsorption: hydroxylated surface stable at environmental conditions
• More reactive surfaces with steps and terraces: reaction accompanied by a modification of the step morphology.
3 molecule water adsorption on the (221) surface of UO_2.
Terrace+Step
Step
Free Water Molecule
T (K)
Maldonado et al., 2014. Ab initio atomistic thermodynamics of water reacting with uranium dioxide surfaces. The Journal of Physical Chemistry C 118, 8491–8500.


Results REDUPP ThO_2
Insight from isotope exchange
• Isotopic tracer (^{229}Th) to track surface processes: Continued isotopic exchange in spite of apparent chemical equilibrium
• Continuous change of isotopic ratio $^{229}Th/^{232}Th$: precipitation/dissolution reactions are still ongoing at the interface despite apparent chemical equilibrium
• Alpha-spectrometry: surface layer, maximum 0,1 µm thick containing ^{229}Th and daughter nuclides of ^{229}Th and ^{232}Th decay series.
Continuous change in isotopic ratio
100
10
1
0.1
0.01
0.01
0.1
1
10
100
1000
Time (d)

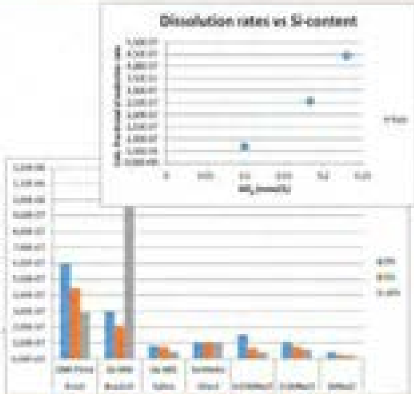
Results REDUPP UO_2 in natural groundwater

Effects of natural groundwater

- 3 ground waters with different salinity
- Experiments used isotopic exchange: Rates are calculated using change in isotopic ratio
- Calculated dissolution rates highest in fresh groundwater
- This has highest silica and carbonate content
- Precipitates were found with U and Si

Ollila et al 2013. Dissolution rate of alpha-doped UO_2 in natural groundwater. Journal of Nuclear Materials 442 (2013) 320-325

Evins L Z, Juhola P, Vähänen M, 2014. REDUPP. Final report. Posiva Working Report 2014-12, Posiva Oy, Finland.



Results DisCo WP2: Sample preparation

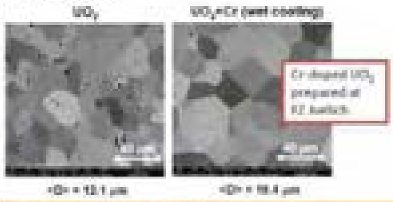
Spent nuclear fuel samples

- SNF samples prepared in Hot Cells at Studsvik, KIT INE, JRC & NNL
- Samples for dissolution prepared either as segments of a fuel rod, or as fragments with the cladding removed

Model materials

- UO_2 (as reference), UO_2+Gd, UO_2+Cr, UO_2+Cr+Al, $(U,Th)O_2$.
- Sample synthesis procedures have been optimized and samples characterized

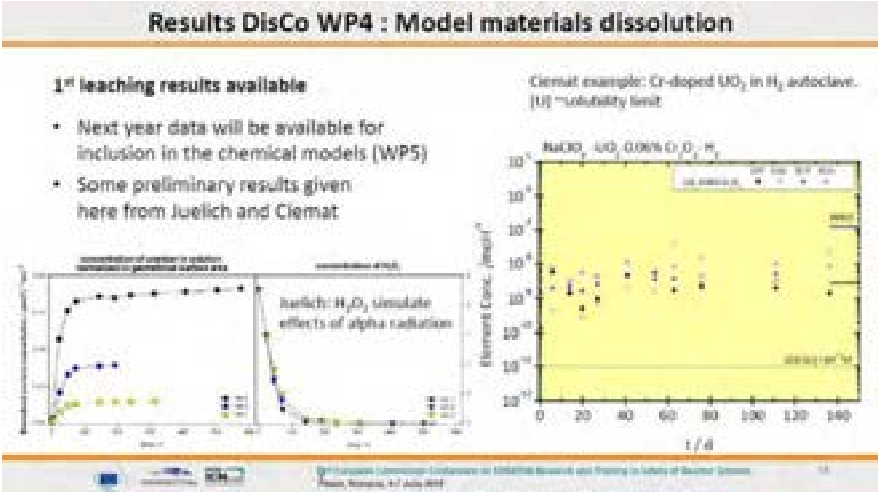
Spent nuclear fuel (MOX) prepared at KIT INE

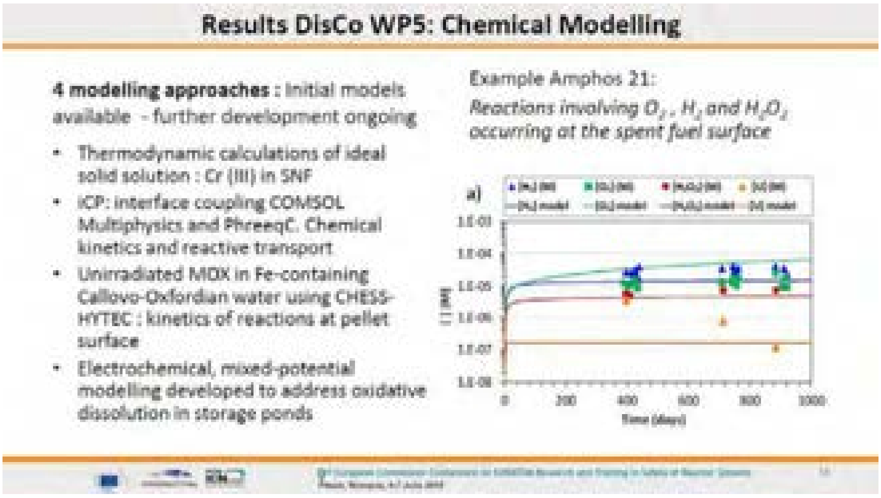


Results DisCo WP3: Spent fuel dissolution

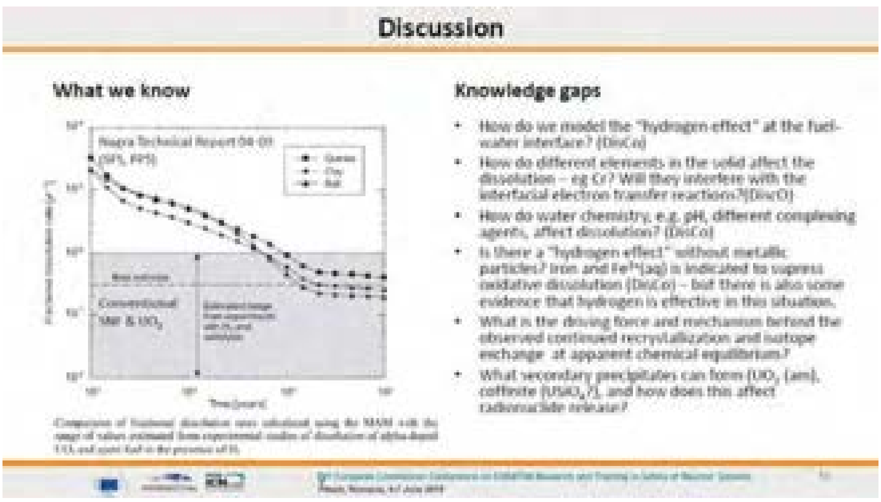
1st leaching results available

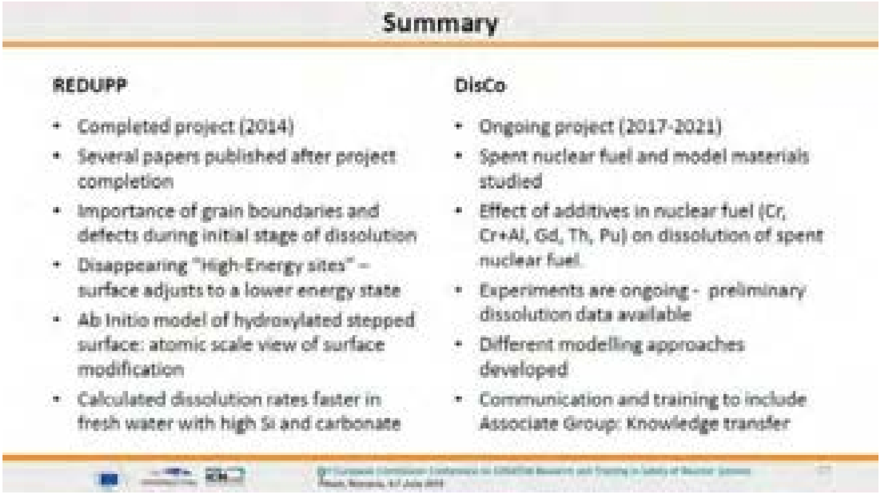
- Next year data will be available for inclusion in the chemical models (WP5)
- Tests run in reducing conditions: H_2 or Mix of Ar/H_2, plus reference test in air
- Studsvik Example given here


Results DisCo WP4 : Model materials dissolution
1st leaching results available
• Next year data will be available for inclusion in the chemical models (WP5)
• Some preliminary results given here from Juelich and Ciemat
Juelich: H_2O_2 simulate effects of alpha radiation
Ciemat example: Cr-doped UO_2 in H_2 autoclave. [U] ~solubility limit
Element Conc. /mol·l⁻¹
t / d


Results DisCo WP5: Chemical Modelling
4 modelling approaches : Initial models available - further development ongoing
• Thermodynamic calculations of ideal solid solution : Cr (III) in SNF
• ICP: interface coupling COMSOL Multiphysics and PhreeqC. Chemical kinetics and reactive transport
• Unirradiated MOX in Fe-containing Callovo-Oxfordian water using CHESS-HYTEC : kinetics of reactions at pellet surface
• Electrochemical, mixed-potential modelling developed to address oxidative dissolution in storage ponds
Example Amphos 21:
Reactions involving O_2 , H_2 and H_2O_2 occurring at the spent fuel surface
a)
Time (days)

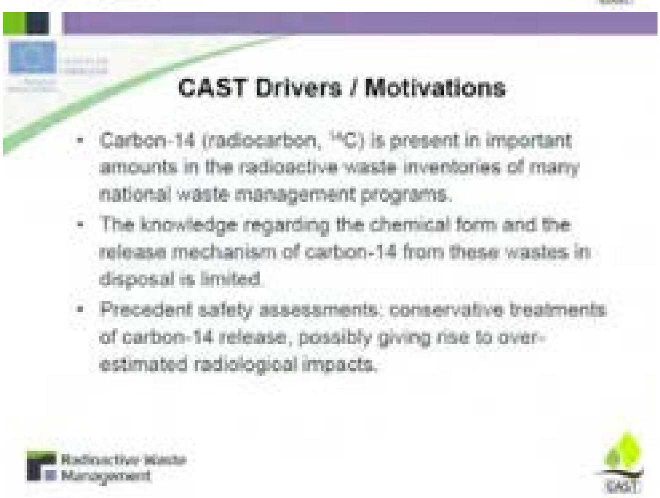
V


Discussion
What we know
Nagra Technical Report 08-07
Time [years]
Knowledge gaps
• How do we model the "hydrogen effect" at the fuel-water interface? (DisCo)
• How do different elements in the solid affect the dissolution – eg Cr? Will they interfere with the interfacial electron transfer reactions?(DisCO)
• How do water chemistry, e.g. pH, different complexing agents, affect dissolution? (DisCo)
• Is there a "hydrogen effect" without metallic particles? Iron and Fe^{2+}(aq) is indicated to supress oxidative dissolution (DisCo) – but there is also some evidence that hydrogen is effective in this situation.
• What is the driving force and mechanism behind the observed continued recrystallization and isotope exchange at apparent chemical equilibrium?
• What secondary precipitates can form (UO_2 (am), coffinite ($USiO_4$)), and how does this affect radionuclide release?


Summary
REDUPP
• Completed project (2014)
• Several papers published after project completion
• Importance of grain boundaries and defects during initial stage of dissolution
• Disappearing "High-Energy sites" – surface adjusts to a lower energy state
• Ab Initio model of hydroxylated stepped surface: atomic scale view of surface modification
• Calculated dissolution rates faster in fresh water with high Si and carbonate
DisCo
• Ongoing project (2017-2021)
• Spent nuclear fuel and model materials studied
• Effect of additives in nuclear fuel (Cr, Cr+Al, Gd, Th, Pu) on dissolution of spent nuclear fuel
• Experiments are ongoing - preliminary dissolution data available
• Different modelling approaches developed
• Communication and training to include Associate Group: Knowledge transfer


Thank you for listening!
Acknowledgements: all project contributors
Petra Christensen, Olga Riba, Theo Cordara, Hannah Smith, Kaija Ollila, Tiina Lavonen, Ernesto Gonzales-Robles, Michel Herm, Joaquin Cobos, Nieves Rodriguez, Philip Kegler, Evgeny Alekseev, Aleksej Popel, Olivia Roth, Alexandre Barreiro Fidalgo, Anders Puranen, Karel Lemmens, Thierry Mennecart, Christelle Cachoir, Luis Iglesias, Frederic Clarens, Joan de Pablo, Ignasi Casas, Christophe Jegou, Valentin Kerleguer, David Hambley, Chris Maher, Enzo Curti, Dmitrii Kulik, Laurent de Windt, Paul Carbol, Daniel Serrano-Purroy, Detlef Wegen, Peter Oppeneer (in REDUPP) ...and more!
REDUPP:
The research leading to these results has received funding from the European Atomic Energy Community's Seventh Framework Programme (FP7/2007-2011) under grant agreement No. 269903
DisCo:
This project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 755443

CAST - *Simon Norris (RWM, UK)*



CAST Objectives

- The EC CAST project (CArbon-14 Source Term) aimed to improve understanding of the potential release mechanisms of carbon-14 from radioactive waste materials under conditions relevant to waste packaging and disposal to underground geological disposal facilities.
- The project focused on the release of carbon-14 as dissolved and gaseous species from irradiated metals (**WP2** steels, **WP3** Zircaloys), from ion-exchange materials (**WP4**) and from irradiated graphite (**WP5**).
- Results from CAST evaluated in the context of national safety assessments (**WP6**) and disseminated to interested stakeholders (**WP7**).

Radioactive Waste Management

CAST Participants

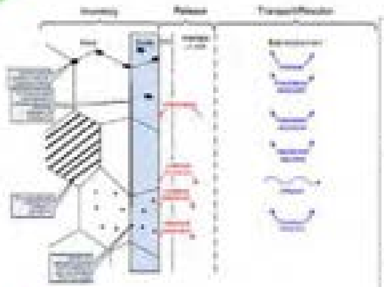
- The CAST consortium has brought together 33 partners with a range of skills and competencies in the management of radioactive wastes containing carbon-14, geological disposal research, safety case development and experimental work on gas generation.
- The consortium consists of national waste management organisations, research institutes, universities and commercial organisations.

Radioactive Waste Management

Key generation and migration processes affecting the fate of C-14 in the disposal system

Radioactive Waste Management

CAST Experimental Work Packages



- Inventory
  - How much?
  - In what (chemical) form?
  - How is it distributed?
- Release
  - Rate
  - Mechanism
  - Speciation
- Transport/reaction
  - After release
  - Possibility of change of speciation

Radioactive Waste Management

CAST

Work Package 2 Steels

- Aims
  - State-of-the-art review
  - Advance understanding of C-14 speciation
  - Develop analytical techniques
  - Measure release rates
  - Confirm/measure inventory
- Challenges
  - Obtaining and working with irradiated samples
  - Extremely low C-14 release rates in test environments
  - Measuring corrosion rates of irradiated materials under alkaline conditions
  - Demonstrating congruent release of C-14
  - Distinguishing surface contamination from IRF from long-term release
  - Uncertainty in inventory, in part because of lack of archive material (actual N content)
  - Effect of dose rate on release and speciation of C-14
  - Duration of experiments
  - Characterisation of inventory – how much, in what form, and distribution within samples

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Summary release of ^{12}C and ^{14}C

Organisation	Conditions	Material	Liquid phase		Gas phase	
			Species	%	Species	%
PSI inactive	alkaline anoxic	SS	AA, FA, OA	95	Methane, Ethane	5
PSI active	alkaline anoxic	SS	FA, AA, LA	n.d.	n.d.	n.d.
NRG / Wood	alkaline anoxic	SS	CO_3	90	Methane, (CO)	10
KIT	acidic digestion	SS	organic	70	organic	30
SCK-CEN	alkaline anoxic	CS	AA, FA	n.d.	Methane	n.d.
Ciemat	alkaline oxic	SS	n.d.	n.d.	CO	n.d.
	acidic oxic	SS	OA	n.d.	CO	n.d.

Radioactive Waste Management

SS – Stainless steel, CS – Carbon steel, OA - Oxalic acid, FA - Formic acid, AA - Acetic acid, n.d. - Not Detected

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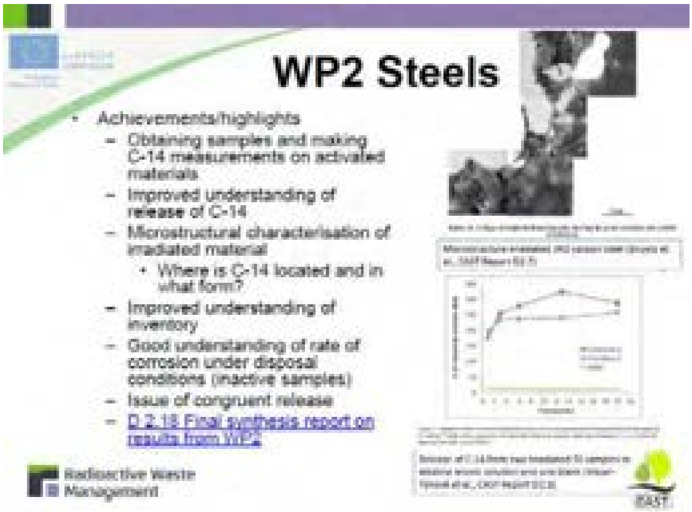
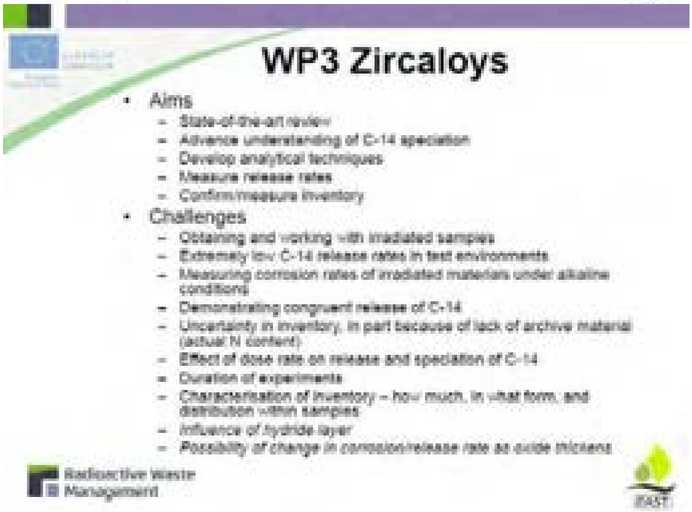
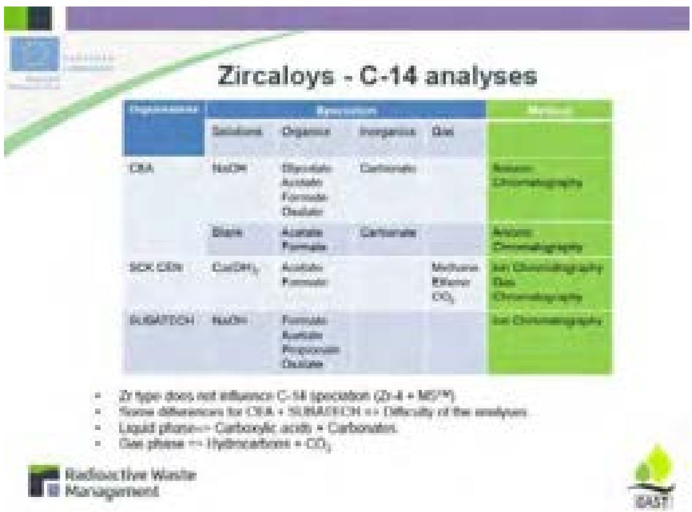
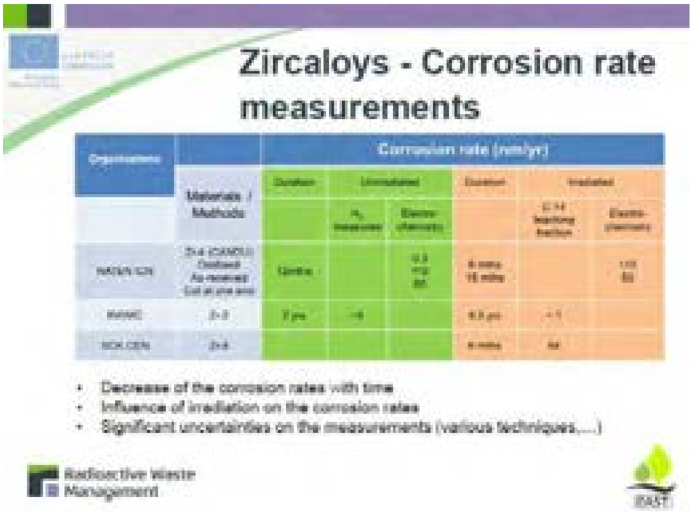

WP2 Steels
Achievements/highlights
Obtaining samples and making C-14 measurements on activated materials
Improved understanding of release of C-14
Microstructural characterisation of irradiated material
Where is C-14 located and in what form?
Improved understanding of inventory
Good understanding of rate of corrosion under disposal conditions (inactive samples)
Issue of congruent release
D 2.18 Final synthesis report on results from WP2
Radioactive Waste Management
EAST


WP3 Zircaloys
Aims
State-of-the-art review
Advance understanding of C-14 speciation
Develop analytical techniques
Measure release rates
Confirm/measure inventory
Challenges
Obtaining and working with irradiated samples
Extremely low C-14 release rates in test environments
Measuring corrosion rates of irradiated materials under alkaline conditions
Demonstrating congruent release of C-14
Uncertainty in inventory, in part because of lack of archive material (actual N content)
Effect of dose rate on release and speciation of C-14
Duration of experiments
Characterisation of inventory – how much, in what form, and distribution within samples
Influence of hydride layer
Possibility of change in corrosion/release rate as oxide thickens
Radioactive Waste Management
EAST


Zircaloys - C-14 analyses
Solutions
Organics
Inorganics
Gas
CEA
NaOH
Carbonate
Carbonate
Ion Chromatography
Ion Chromatography
Radioactive Waste Management
EAST


Zircaloys - Corrosion rate measurements
Corrosion rate (nm/yr)
Materials / Methods
Decrease of the corrosion rates with time
Influence of irradiation on the corrosion rates
Significant uncertainties on the measurements (various techniques,...)
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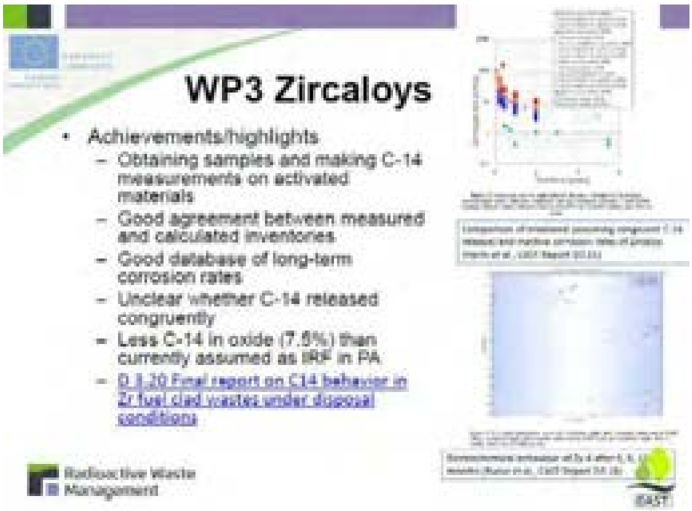
WP3 Zircaloys
Achievements/highlights
Obtaining samples and making C-14 measurements on activated materials
Good agreement between measured and calculated inventories
Good database of long-term corrosion rates
Unclear whether C-14 released congruently
Less C-14 in oxide (7.5%) than currently assumed as IRF in PA
D 3.20 Final report on C14 behavior in Zr fuel clad wastes under disposal conditions
Radioactive Waste Management
CAST


WP4 Spent Ion Exchange Resins
Aims
State-of-the-art review
Understanding inventory and speciation
Determining release rate and mechanism
Challenges
Wide range of SIER characteristics due to different types of operating plants and different IX locations within a given plant
Relating release to geological disposal conditions for cemented and immobilised SIERs
Effects of porosity, groundwater flow, etc.
Uncertainty over long-term (radiation) stability of resins
Rizzo et al., CAST Report D4.5, Appendix V
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WP4 Spent Ion Exchange Resins

- Achievements/highlights
  - Because of the wide variability of SIERs, country-specific inventories and speciation are required
  - Good understanding of speciation
    - In general, majority present as inorganic C-14 but fraction depends on reactor type
      - PWR: 1-70% organic
      - BWR: 1-8% organic
      - CANDU: 7% organic (single sample)
  - Gas-phase inorganic C-14 is released when SIERs are contacted with alkaline pH **solutions** (precipitation of $CaCO_3$ under storage and long-term disposal conditions (cement)
  - Effect of immobilization in cement, epoxy, bitumen matrix
    - At least for cement, significantly reduces release of C-14
- D 4.8 Final synthesis report

Radioactive Waste Management

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WP5 Irradiated Graphite

- Aims
  - Built on earlier EC CARBOWASTE project and took input from other relevant international projects
  - Determine inventory and distribution of C-14 and factors that may control these
  - Measure rate and speciation of gaseous and dissolved C-14 released
  - Assess impacts of selected waste treatment options
- Challenges
  - Diversity of national interests
    - Amount of irradiated graphite waste
    - Surface vs. deep geological disposal

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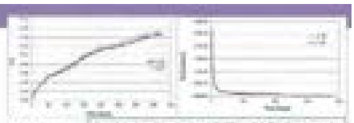
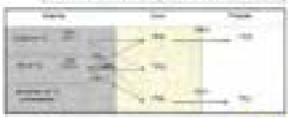
WP5 Irradiated Graphite



Graphite leaching tests at NRPIN KN, Toulhoat et al, CAST Report D5.19

Impact of in-reactor irradiation and temperature, Toulhoat et al, CAST Report D5.19



C-14 release mechanism proposed by Toulhoat et al, CAST Report D5.19

- Achievements/highlights
  - Detailed understanding of distribution of C-14 within the waste
  - Improved mechanistic understanding
    - Small releasable fraction
    - Initial fast release, slow long-term
    - Speciation
    - Inventory and especially distribution
    - Consequences of in-reactor behaviour
- D 5.19 Final report on results from WP5

Radioactive Waste Management

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WP6 Relevance to the Safety Case

- Aims
  - Improve treatment of C-14 in safety analysis/ assessment
    - Speciation, IRF, release rate, etc.
  - Improve treatment of C-14 in safety case
    - Scientific understanding
- Challenges
  - Working with experimental groups to ensure the study of processes that are safety-relevant
  - Diversity of national disposal programmes
  - Abstraction of data (and uncertainties) from experimental programmes

Radioactive Waste Management

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WP6 Relevance to the Safety Case

- Achievements/highlights
  - Understanding of relative importance of C-14 for different host rock types
    - Clay vs. crystalline vs. salt
  - Understanding of relative importance of C-14 for different waste types
    - e.g., for spent fuel, C-14 will likely decay in long-lived canister
  - Understanding of relative importance of C-14 depending on repository location
    - Surface vs. deep disposal
  - CAST has produced a lot of useful information for the safety case as well as for underlying safety analyses
  - D.6.4 Final WP6 report

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WP7 Dissemination

- The objectives of WP7 Dissemination were to disseminate information about CAST activities and results (provided they are suitable for public circulation) as widely as possible to various target groups having an interest in the project and its results.

Radioactive Waste Management

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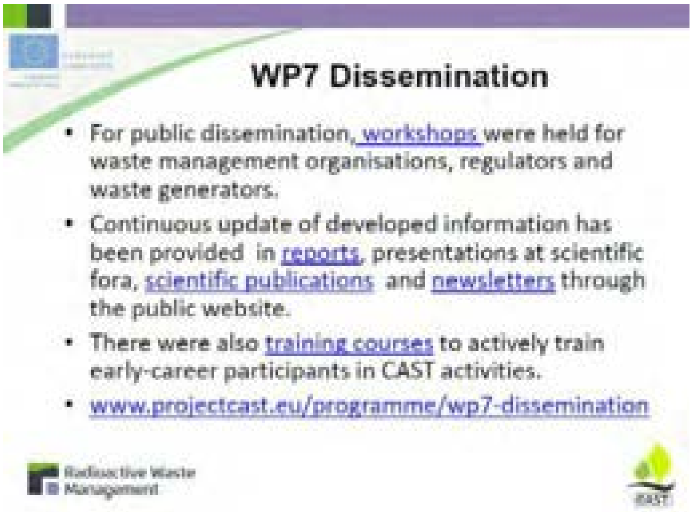
WP7 Dissemination
• For public dissemination, workshops were held for waste management organisations, regulators and waste generators.
• Continuous update of developed information has been provided in reports, presentations at scientific fora, scientific publications and newsletters through the public website.
• There were also training courses to actively train early-career participants in CAST activities.
• www.projectcast.eu/programme/wp7-dissemination
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Interaction, Collaboration, Enhancement of Knowledge Base
Whole-project meetings London (2013), Brussels (2014), Bucharest (2015) & Lucerne (2016); many work-package meetings; Symposium in Lyon (2018)
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Outreach
• CAST website available www.projectcast.eu
• CAST Radiocarbon journal special issue (https://www.cambridge.org/core/journals/radiocarbon/issue/B16E687954999C131670CC8705D8A2B0)
• 20+ papers
– Irradiated steels
– Irradiated Zircaloys
– SIERs
– Irradiated graphite
– Safety assessments
Radiocarbon
CAST
Radioactive Waste Management


Conclusions
"... to gain new scientific understanding ...."
– Clearly achieved
".... of relevance to safety assessment ..."
– Useful data generated for safety analyses and especially underlying information to support the safety case
"... disseminated to stakeholders ...."
– Workshops, impressive number of reports / deliverables (>100), open symposium, Radiocarbon special issue ...
"... opportunity for early career researchers ..."
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Thank you for your help!
Christophe Davies (EC)
Steve Williams (RWM – original coordinator)
Jens Mibus (Nagra – CAST WP2 Leader)
Sophia Necib (Andra – CAST WP3 Leader)
Pascal Reiller (CEA – CAST WP4 Leader)
Manuel Capouet (Ondraf/Niras – CAST WP6 Leader)
Erika Neeft (Covra – CAST WP7 Leader)
Fraser King (Integrity Corrosion Consulting, CAST Expert Review Group)
Irka Hajdas (ETH, Switzerland, CAST Expert Review Group)
Radioactive Waste Management
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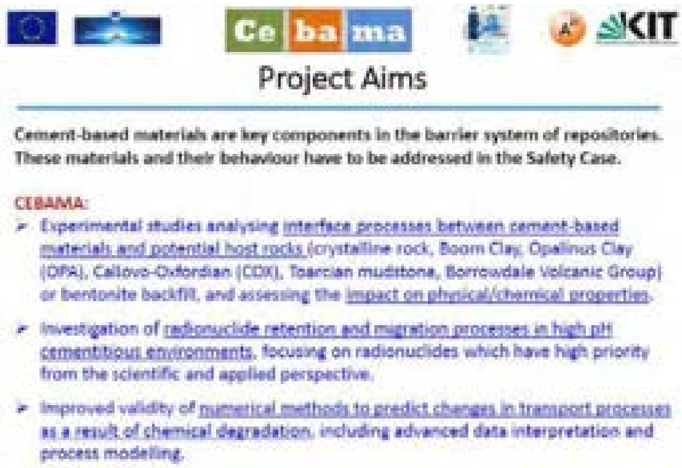
CEBAMA - *Marcus Altmaier (KIT/INE, Germany)*


Ce ba ma
KIT
Project Aims
Cement-based materials are key components in the barrier system of repositories. These materials and their behaviour have to be addressed in the Safety Case.
CEBAMA:
➢ Experimental studies analysing interface processes between cement-based materials and potential host rocks (crystalline rock, Boom Clay, Opalinus Clay (OPA), Callovo-Oxfordian (COX), Toarcian mudstone, Borrowdale Volcanic Group) or bentonite backfill, and assessing the impact on physical/chemical properties.
➢ Investigation of radionuclide retention and migration processes in high pH cementitious environments, focusing on radionuclides which have high priority from the scientific and applied perspective.
➢ Improved validity of numerical methods to predict changes in transport processes as a result of chemical degradation, including advanced data interpretation and process modelling.


Ce ba ma
KIT
Consortium and bodies
CEBAMA: consortium of 27 partners consisting of large
Research Institutions, Universities, one TSO, one SME,
from 9 EURATOM Signatory States, Switzerland and Japan.
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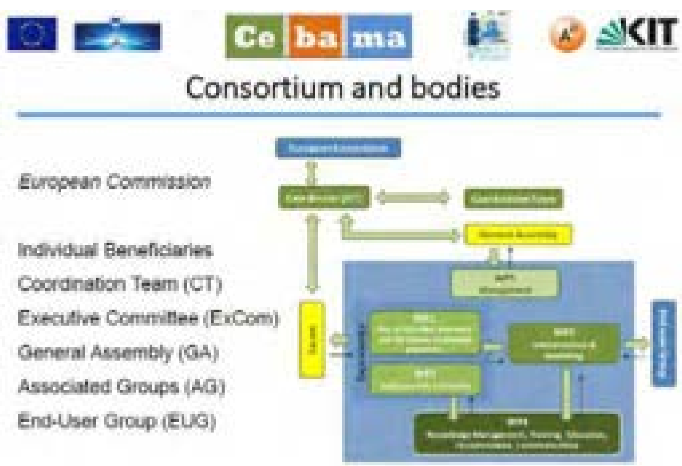
Ce ba ma
KIT
Consortium and bodies
European Commission
Individual Beneficiaries
Coordination Team (CT)
Executive Committee (ExCom)
General Assembly (GA)
Associated Groups (AG)
End-User Group (EUG)


Ce ba ma
KIT
Executive Committee
End User Group
WP 1 - Experiments on interface processes and the impact on physical properties
Erika Holt (VTT) "spokesperson", Francis Claret (BRGM), Urs Mäder (UNIBERN)
WP 2 - Radionuclide retention
Bernd Grambow (ARMINES)
WP 3 - Interpretation & Modelling
Andrés Idiart (AMPHOS21)
WP 4 Documentation, Knowledge Management, Dissemination and Training
Alba Valls (AMPHOS21)
WP 5 Management
Marcus Altmaier, Vanessa Montoya (KIT)
ANDRA - Pierre Henocq
COVRA - Erika Neeft
ENRESA - Miguel Angel Cuñado
NAGRA - Nikitas Diomidis
ONDRAF/NIRAS - Seif Ben Hadj Hassine (EUG chairperson)
POSIVA - Marja Vuorio
RWM - Amy Shelton
SKB - Per Martensson
SURAO - Lucie Hausmannova (and Antonin Vokal)


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Project Overview
Start: 01-06-2015
End: 31-05-2019
Project months
0
12
24
36
48
WP 1
WP 2
WP 3
WP 4
WP 5


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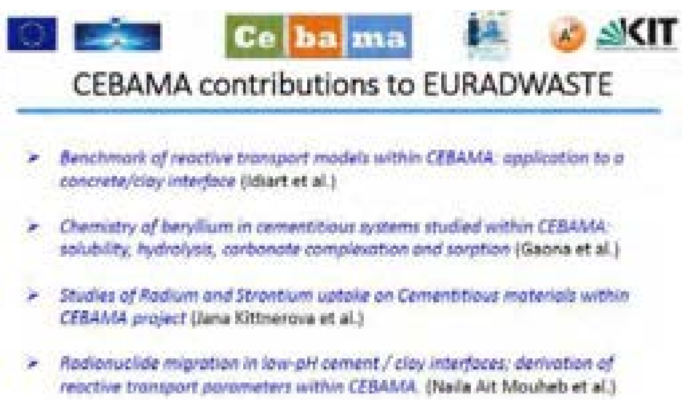
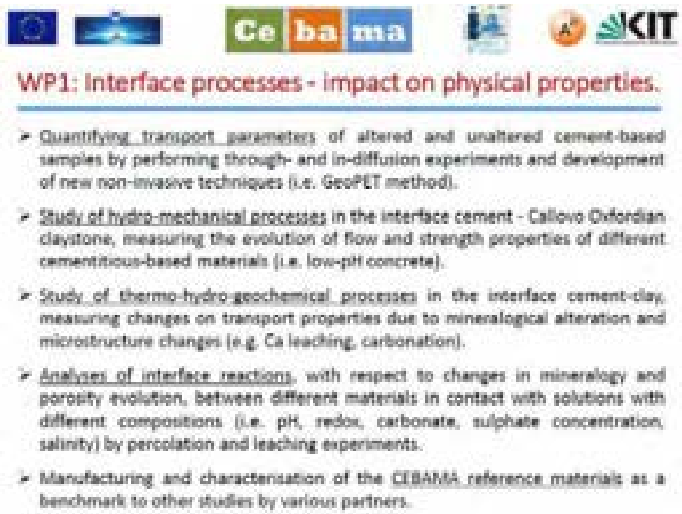
KIT
Dissemination, training, education, KM
Webpage
Workshops
Newsletters
Publications
PhD/Master Thesis
Mobility measures
PhD sessions
Deliverables
Proceedings
Dissemination and Comunication
Training and Education
Knowledge Management


Dissemination, training, education, KM
Project outcome summary
Papers
Conference presentations
Deliverables
PhD


Where to find CEBAMA results
CEBAMA Newsletter, Website...
S&T contributions to Annual CEBAMA Workshop Proceedings
Individual peer-reviewed scientific publications
Individual publications by beneficiaries in scientific journals
Contributions to Special Issue in Applied Geochemistry
Integrated Reports
Three peer-reviewed publications on WP level
Application to the Safety Case
Final report (EURADWASTE paper)


CEBAMA contributions to EURADWASTE
Benchmark of reactive transport models within CEBAMA: application to a concrete/clay interface (Idiart et al.)
Chemistry of beryllium in cementitious systems studied within CEBAMA: solubility, hydrolysis, carbonate complexation and sorption (Gaona et al.)
Studies of Radium and Strontium uptake on Cementitious materials within CEBAMA project (Jana Kittnerova et al.)
Radionuclide migration in low-pH cement / clay interfaces: derivation of reactive transport parameters within CEBAMA. (Naila Ait Mouheb et al.)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WP1: Interface processes - impact on physical properties.
➢ Quantifying transport parameters of altered and unaltered cement-based samples by performing through- and in-diffusion experiments and development of new non-invasive techniques (i.e. GeoPET method).
➢ Study of hydro-mechanical processes in the interface cement - Callovo Oxfordian claystone, measuring the evolution of flow and strength properties of different cementitious-based materials (i.e. low-pH concrete).
➢ Study of thermo-hydro-geochemical processes in the interface cement-clay, measuring changes on transport properties due to mineralogical alteration and microstructure changes (e.g. Ca leaching, carbonation).
➢ Analyses of interface reactions, with respect to changes in mineralogy and porosity evolution, between different materials in contact with solutions with different compositions (i.e. pH, redox, carbonate, sulphate concentration, salinity) by percolation and leaching experiments.
➢ Manufacturing and characterisation of the CEBAMA reference materials as a benchmark to other studies by various partners.


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WP1 – work performed
Preparation of samples


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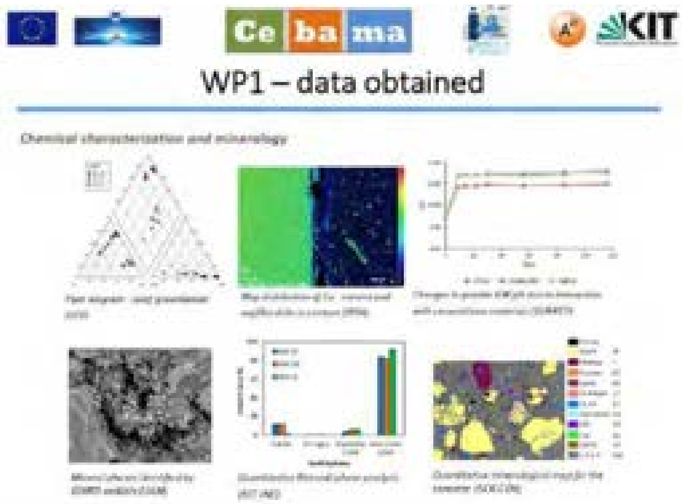
WP1 – work performed
Experimental set-up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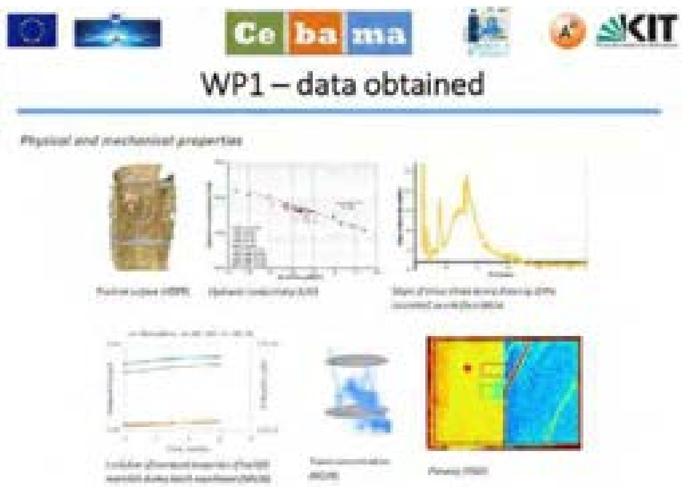
WP1 – data obtained
Chemical characterization and mineralogy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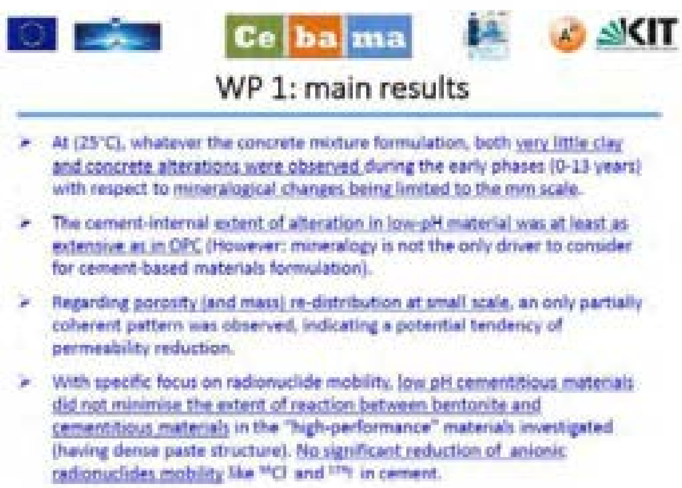
WP1 – data obtained
Physical and mechanical properties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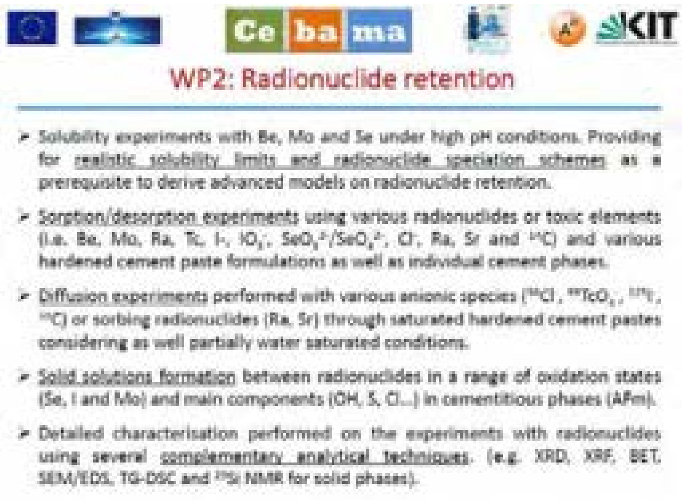
WP 1: main results
At (25°C), whatever the concrete mixture formulation, both very little clay and concrete alterations were observed during the early phases (0-13 years) with respect to mineralogical changes being limited to the mm scale.
The cement-internal extent of alteration in low-pH material was at least as extensive as in OPC (However: mineralogy is not the only driver to consider for cement-based materials formulation).
Regarding porosity (and mass) re-distribution at small scale, an only partially coherent pattern was observed, indicating a potential tendency of permeability reduction.
With specific focus on radionuclide mobility, low pH cementitious materials did not minimise the extent of reaction between bentonite and cementitious materials in the "high-performance" materials investigated (having dense paste structure). No significant reduction of anionic radionuclides mobility like ^{36}Cl and ^{129}I in cement.


Ce ba ma
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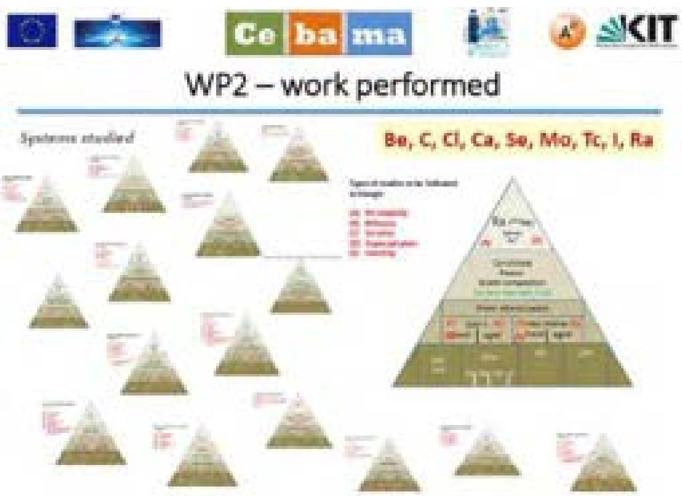
WP2: Radionuclide retention
➢ Solubility experiments with Be, Mo and Se under high pH conditions. Providing for realistic solubility limits and radionuclide speciation schemes as a prerequisite to derive advanced models on radionuclide retention.
➢ Sorption/desorption experiments using various radionuclides or toxic elements (i.e. Be, Mo, Ra, Tc, I-, IO3-, SeO3 2-/SeO4 2-, Cl-, Ra, Sr and 14C) and various hardened cement paste formulations as well as individual cement phases.
➢ Diffusion experiments performed with various anionic species (36Cl, 99TcO4-, 125I-, 14C) or sorbing radionuclides (Ra, Sr) through saturated hardened cement pastes considering as well partially water saturated conditions.
➢ Solid solutions formation between radionuclides in a range of oxidation states (Se, I and Mo) and main components (OH, S, Cl...) in cementitious phases (AFm).
➢ Detailed characterisation performed on the experiments with radionuclides using several complementary analytical techniques. (e.g. XRD, XRF, BET, SEM/EDS, TG-DSC and 29Si NMR for solid phases).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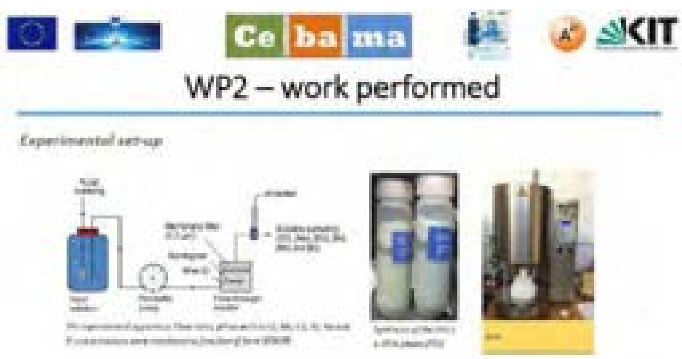
WP2 – work performed
Systems studied
Be, C, Cl, Ca, Se, Mo, Tc, I, Ra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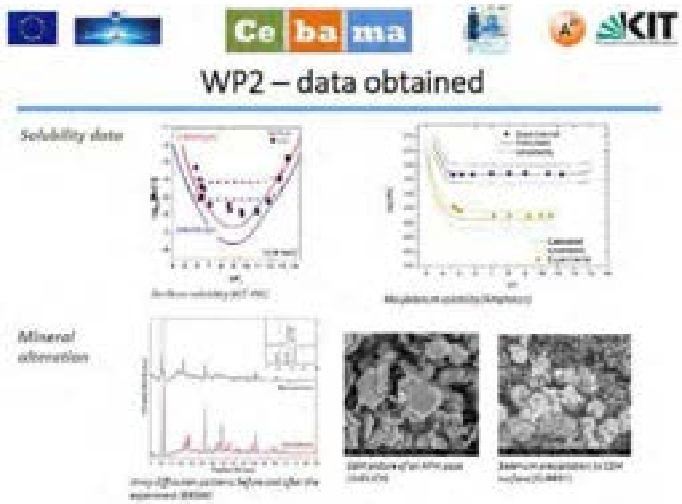
WP2 – work performed
Experimental set-up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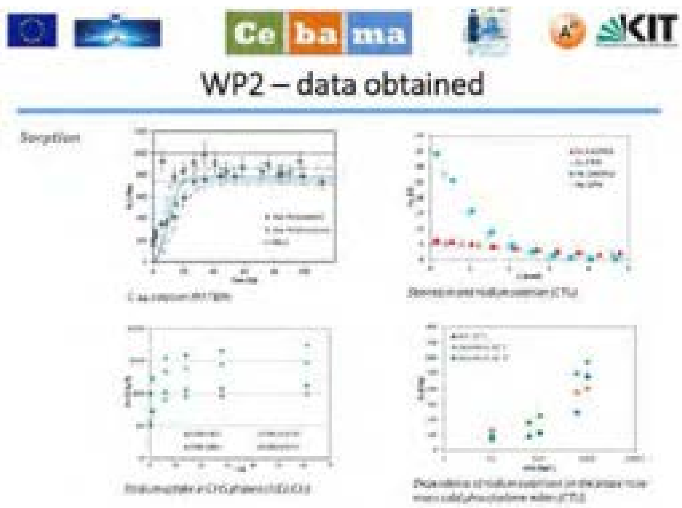
WP2 – data obtained
Solubility data
Mineral alteration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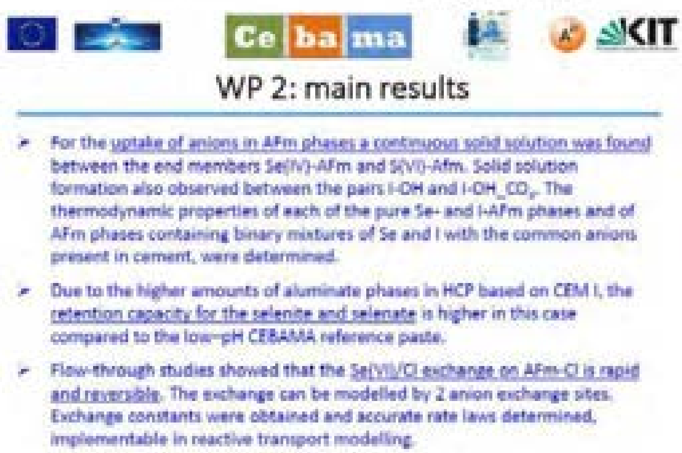
WP2 – data obtained
Sorption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WP 2: main results
For the uptake of anions in AFm phases a continuous solid solution was found between the end members Se(IV)-AFm and S(VI)-AFm. Solid solution formation also observed between the pairs I-OH and I-OH_CO3. The thermodynamic properties of each of the pure Se- and I-AFm phases and of AFm phases containing binary mixtures of Se and I with the common anions present in cement, were determined.
Due to the higher amounts of aluminate phases in HCP based on CEM I, the retention capacity for the selenite and selenate is higher in this case compared to the low-pH CEBAMA reference paste.
Flow-through studies showed that the Se(VI)/Cl exchange on AFm-Cl is rapid and reversible. The exchange can be modelled by 2 anion exchange sites. Exchange constants were obtained and accurate rate laws determined, implementable in reactive transport modelling.

WP 2: main results

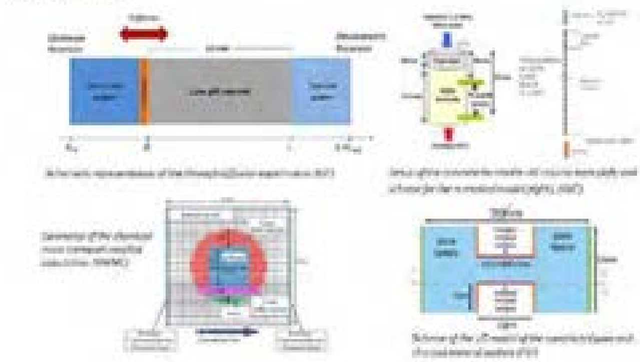
- CEBAMA has provided a first set of sorption parameters of Beryllium onto cementitious phases. In contrast to the traditional hypothesis of very weak Be sorption, assumed on the basis of the negative charge of the Be(II) species at high pH values, a strong uptake has been confirmed in the investigations.
- Sorption of molybdenum is not associated with ettringite in cementitious environments, in contrast to what has been traditionally assumed. This has important implications on sorption analogies - the project recommends not to use selenium as analogue for molybdenum in sorption estimations.
- Significantly higher retention of Ra than that of Sr onto cementitious materials. This again, decreases uncertainty and conservativism.
- Strong reduction of sorption of ^{14}C has been observed with the increased degradation of cement pastes in contrast to Ra sorption.

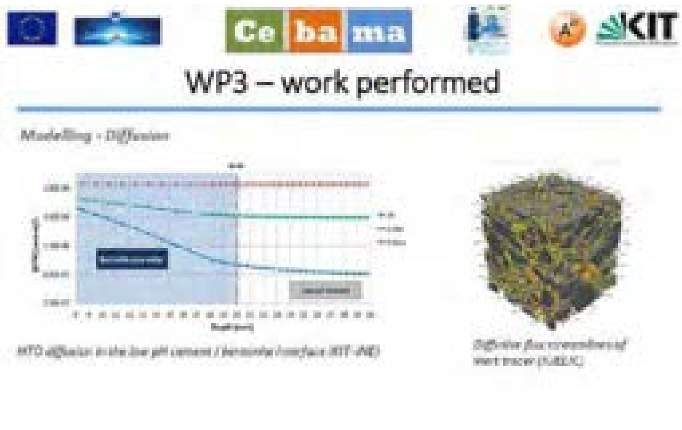
WP3: Modelling

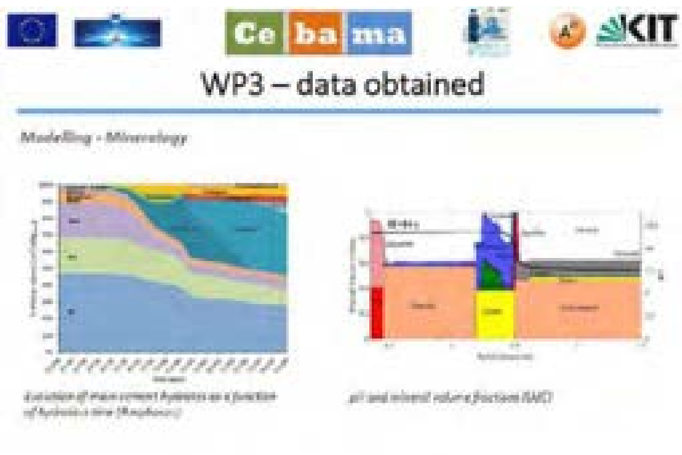
- Development of modelling tools with pore- and continuum-scale applications including new capabilities (i.e. Poisson-Nernst-Planck equations, Poisson-Boltzmann equations, coupling with geochemical solvers, coupling between chemistry and mechanics, etc.) in already existing or new codes (i.e. iCP, ORCHESTRA, MATLAB, iPP, Yantra, etc.).
- Modelling work with application to WP1 and WP2 experiments (i.e. through-diffusion tests, leaching tests, cement-clay interaction, etc.), including reactive and mass transport simulations, cement hydration models, solubility calculations and hydromechanical simulations.
- Long-term modelling of concrete-clay interactions including reactive transport and hydro-mechanical-chemical coupled analyses.

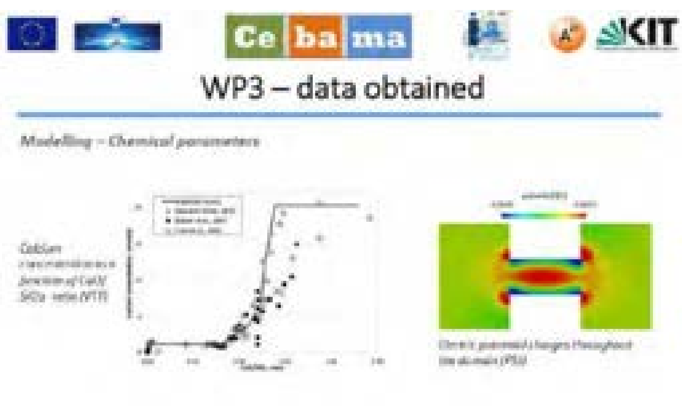
WP3 – work performed

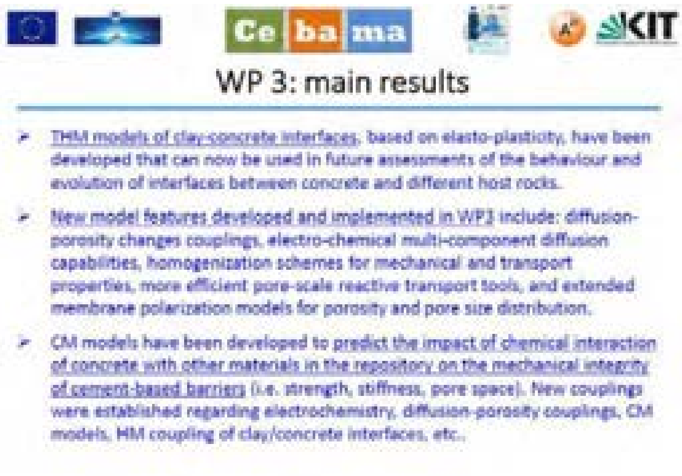
Modelled systems




Ce ba ma
WP3 – work performed
Modelling - Diffusion


Ce ba ma
WP3 – data obtained
Modelling - Mineralogy


Ce ba ma
WP3 – data obtained
Modelling – Chemical parameters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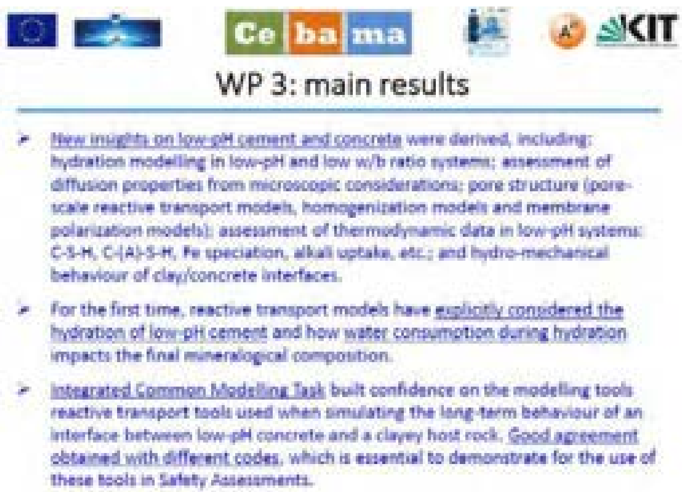
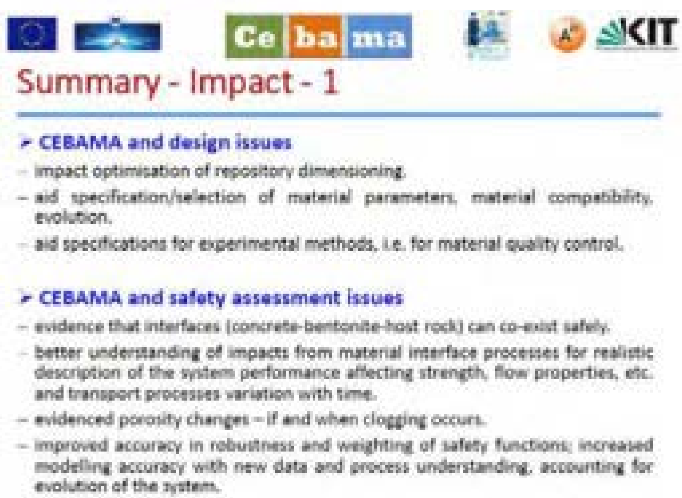
WP 3: main results
➢ THM models of clay-concrete interfaces, based on elasto-plasticity, have been developed that can now be used in future assessments of the behaviour and evolution of interfaces between concrete and different host rocks.
➢ New model features developed and implemented in WP3 include: diffusion-porosity changes couplings, electro-chemical multi-component diffusion capabilities, homogenization schemes for mechanical and transport properties, more efficient pore-scale reactive transport tools, and extended membrane polarization models for porosity and pore size distribution.
➢ CM models have been developed to predict the impact of chemical interaction of concrete with other materials in the repository on the mechanical integrity of cement-based barriers (i.e. strength, stiffness, pore space). New couplings were established regarding electrochemistry, diffusion-porosity couplings, CM models, HM coupling of clay/concrete interfaces, etc..


Ce ba ma
KIT
WP 3: main results
➢ New insights on low-pH cement and concrete were derived, including: hydration modelling in low-pH and low w/b ratio systems; assessment of diffusion properties from microscopic considerations; pore structure (pore-scale reactive transport models, homogenization models and membrane polarization models); assessment of thermodynamic data in low-pH systems: C-S-H, C-(A)-S-H, Fe speciation, alkali uptake, etc.; and hydro-mechanical behaviour of clay/concrete interfaces.
➢ For the first time, reactive transport models have explicitly considered the hydration of low-pH cement and how water consumption during hydration impacts the final mineralogical composition.
➢ Integrated Common Modelling Task built confidence on the modelling tools reactive transport tools used when simulating the long-term behaviour of an interface between low-pH concrete and a clayey host rock. Good agreement obtained with different codes, which is essential to demonstrate for the use of these tools in Safety Assessments.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Summary - Impact - 1
➢ CEBAMA and design issues
– impact optimisation of repository dimensioning.
– aid specification/selection of material parameters, material compatibility, evolution.
– aid specifications for experimental methods, i.e. for material quality control.
➢ CEBAMA and safety assessment issues
– evidence that interfaces (concrete-bentonite-host rock) can co-exist safely.
– better understanding of impacts from material interface processes for realistic description of the system performance affecting strength, flow properties, etc. and transport processes variation with time.
– evidenced porosity changes – if and when clogging occurs.
– improved accuracy in robustness and weighting of safety functions; increased modelling accuracy with new data and process understanding, accounting for evolution of the system.

Cebama

Summary - Impact - 2

- **CEBAMA and radionuclide retention in cementitious repository near fields**
  - decreased uncertainties and increased safety margins with respect to relevant radionuclide retention processes.
  - substantiated and justified assumptions with respect to radionuclide migration behaviour in Safety Assessments.
  - improved sorption databases for cementitious environments for so far less studied systems and different stages of system evolution .
  - direct input to case studies like for the LLW-ILW repository Bratrstvi (Czech Republic) and the licensing process for the near surface repository in the proximity of Cernavoda NPP (Romania).

Cebama

Summary - Impact - 3

- **CEBAMA and modelling**
  - increased level of confidence in reactive transport models for further use in Safety Cases for near-field applications.
  - improved reactive transport modelling tools to quantify how bentonite barrier or clayey host rocks could affect the integrity of normal and low-pH cementitious materials (tools available as open source or upon request).
  - developed models can be used by to study the impact of reactive transport processes, but also other THMC coupled processes on the long-term performance of the near-field, including low-pH cement-based materials.
  - Pore-scale reactive transport models can be used as process models to enhance understanding of the impact of alteration of cement-based materials on their transport properties.

Cebama

Summary - Impact - 4

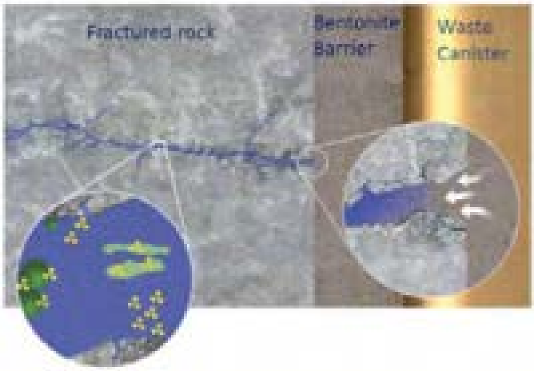
- **Overarching aspects in CEBAMA**
- Enhanced cooperation, exchange and knowledge transfer between different institutions and between different research fields (i.e. Geosciences, Environmental Engineering, Radiochemistry and Computational Sciences).
- Involvement from experts coming from countries at very different stages of implementation. Impact in view of sharing of expertise and resources.
- Cooperation and complementary competences as basis to tackle future challenges in a focused, cost-saving, collaborative approach.
- Experimental and modelling work to a significant extent performed by young researchers and within PhD theses - supporting and developing young talent.
- Ensure availability of highly trained specialists for implementers and regulators.

- **CEBAMA has contributed to European integration !!!**

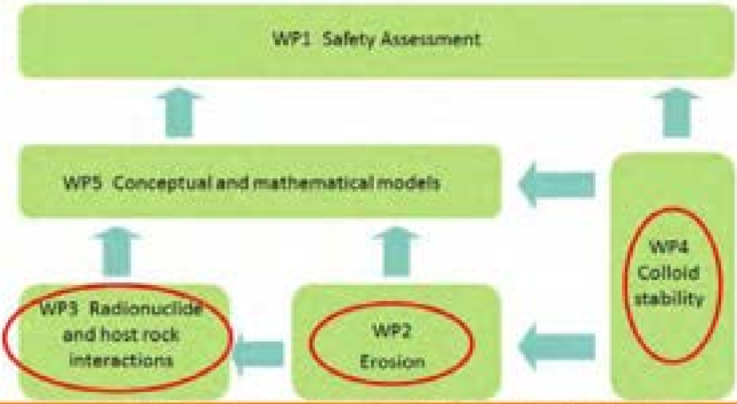

Ce ba ma
KIT
Thank You !!!
"The research leading to these results has received funding from the European Union's European Atomic Energy Community's (Euratom) Horizon 2020 Programme (NFRP-2014/2015) under grant agreement, 662147 - Cebama"
Disclaimer:
This presentation reflects the author's view. The Commission is not responsible for any use that may be made of the information it contains

BELBAR - *Patrick Sellin (SKB, Sweden)*

The problem to study



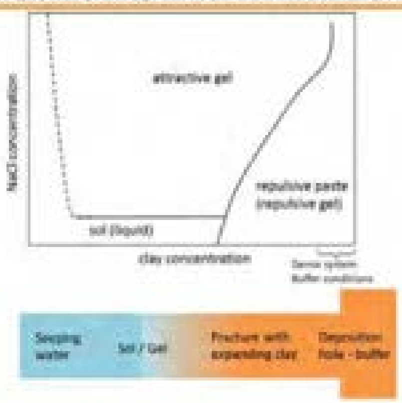
BELBaR Project WP Linkages:

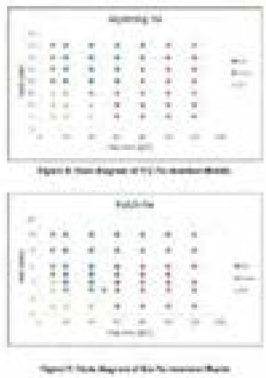


WP4: Clay colloid stability

- Clay colloid stability studies under different geochemical conditions with respect to ionic strength and pH
  - Reason for different behaviour of different clays - trend or correlation between the bentonites characteristics and its stability
- Critical coagulation concentration, coagulation kinetics, (ir)reversibility of coagulation process
  - At the boundary, close to conditions which are favourable for clay colloids coagulation, the aggregation process can be very slow.
  - If the hysteresis of coagulation process take a place, the aggregation or disaggregation of clay colloid will not occur at the same conditions
- Role of complexing agents (organic / humic substances) on clay colloid stability
  - Interaction between the clay colloids and organic molecules greatly influences its stability

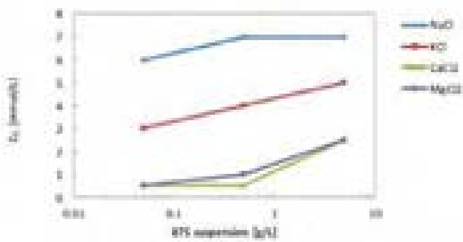
Phase (state) diagram of Na-montmorillonite





In general, it seems like clays having more charge located in the tetrahedral layer form larger colloids: these particles sediment easier being less stable even in DW

Role of cations



Importance of divalent cations. The effect of increasing CCC with the solid content (concentration of bentonite in suspension).

Sodium and potassium, and magnesium and calcium act in similar way during the coagulation process and in real systems (e.g. natural groundwater) their effect can be simplified to the effect of M^{+} (Na+K) or M^{2+} (Ca+Mg) cations.

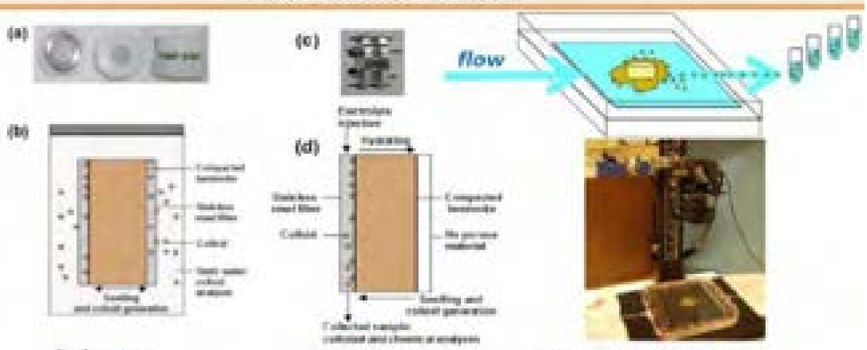
Stability - conclusions

- Above CCC a gel will form
- CCC varies among Na-montmorillonites with different origins
- Ca-montmorillonite does not form colloids
  - However 20 % Na is sufficient for colloid formation
- Anions have minor effect
  - Unless clay particle charge is influenced
- Organics can stabilize colloids
- Attractive forces in the gels increase with aging

WP2: Erosion

- Characteristics of the bentonite clay: role of divalent cations; other clay characteristics
- Groundwater chemistry: role of divalent cations; ionic strength, mixed electrolytes
- Groundwater/clay interactions: modelling inclusion in Safety Case
- Groundwater velocity: dependence of erosion on water velocity
- Clay extrusion paths: dependence of fracture geometry

Experimental setups



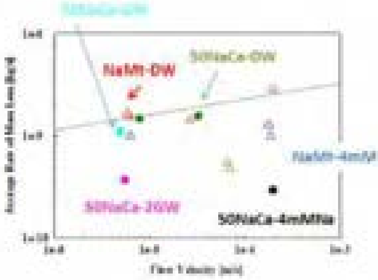
Static system
Chemistry

Dynamic system
Chemistry + flow

Flow – trough artificial fracture
Chemistry + flow + geometry

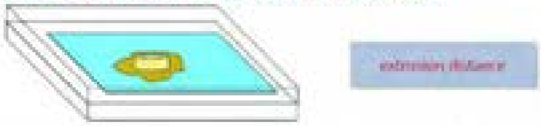
Erosion – results - Flow

- In largely erosive systems (ion concentration well below the CCC, or erosion threshold),
  - the average mass loss rates seems to be (slightly) correlated with the flow velocity
  - The observed variability is generally within the same order of magnitude as changes in flow rate
- In other cases, the water flow velocity did not seem a relevant parameter
  - or, at least, no clear trend between water velocity and erosion could be observed



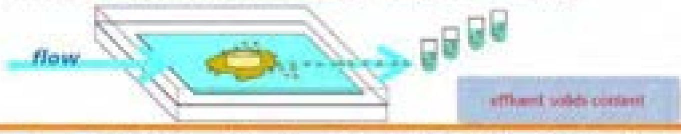
BELBaR Benchmark Test Protocol

Phase 1: stagnant conditions (30 days)

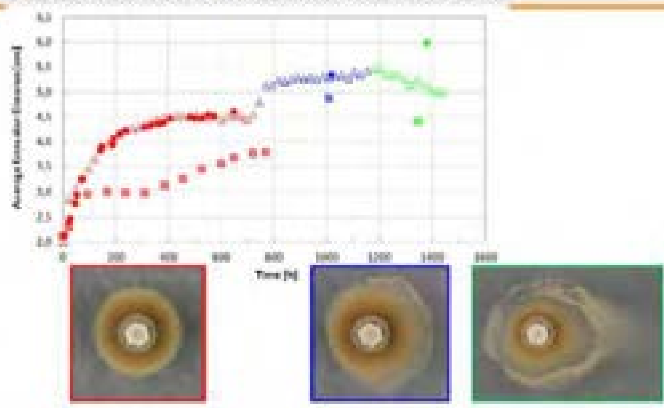


Phase 2: <u>low flow conditions</u> (14 days at 10^{-6} m/s)

Phase 3: <u>high flow conditions</u> (14 days at 10^{-4} m/s)



BELBaR Benchmark Extrusion Distances

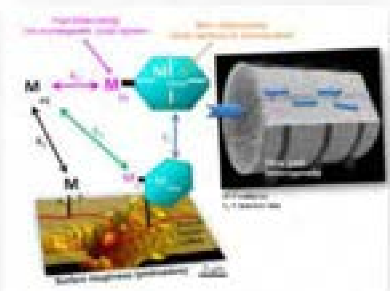


BELBaR Benchmark Summary

			
Emplaced mass	3.8554	7.7023	4.3000
Extruded mass	0.3640	0.3090	0.3137
Remaining mass	3.4040	6.4977	3.2479
Eroded mass	0.0874 (2.3%)	0.8956 (11.6%)	0.7384 (17.2%)
Eluted mass	0.1180	0.5622	0.5576

Radionuclide and host rock interactions

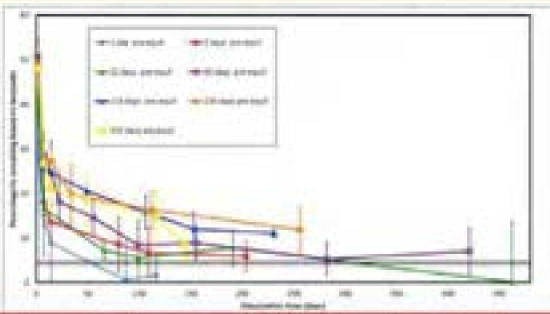
- What are the colloid mobility controlling processes and can we describe them appropriate?
- Is the sorption of strongly sorbing radionuclides fully reversible, why do we observe kinetics?
- Have we indications for additional retention processes occurring?



Eu(III) reversibility vs. irreversibility

Bulk Ligand competition experiments (EDTA)

Na-Montmorillonite (Wyoming) SWy-1



- Evidence for slow release of Eu(III) from the bentonite;
- Amount of 'non-exchangeable' Eu(III) increases with pre-equilibration time;
- All systems still heading towards equilibrium.

Conclusions - Overall

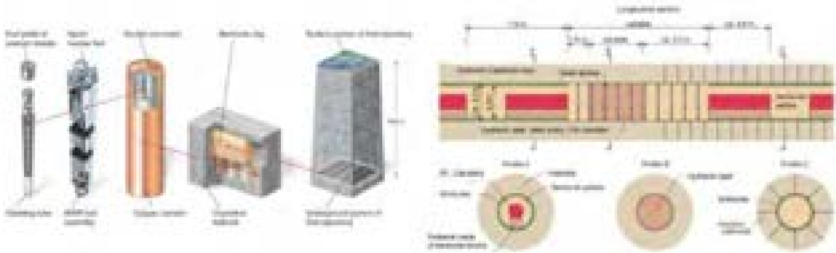
- The understanding of bentonite colloid stability was largely confirmed
  - Colloids may form under unfavorable conditions
- The erosion process is difficult to describe, both conceptually and mathematically
  - The strong effect of gravity was a surprise
- Reversibility of radionuclide sorption unto colloids was largely confirmed
  - However, kinetics needs to be considered

The research leading to these results has received funding from the European Atomic Energy Community's Seventh Framework Programme (FP7/2007- 2011) under grant agreement no 295487.

www.belbar.eu

BEACON - *Patrick Sellin (SKB, Sweden)*

Disposal concepts

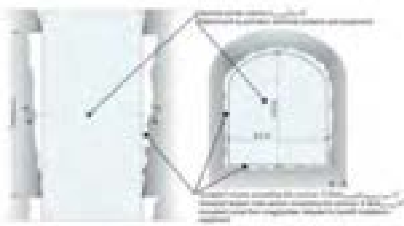


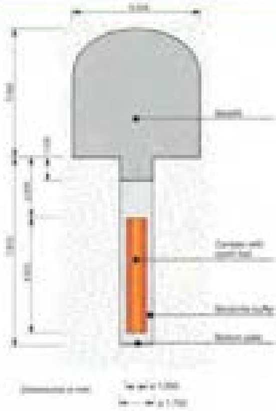
Why Mechanics?

Background

- Gaps, holes or inhomogeneous density distributions may prevail in the buffer or backfill material by several causes:
  - Very heterogeneous initial conditions caused by installation technique
    - Blocks with gaps between them
    - Gaps filled with pellets
    - Mechanical interaction
      - buffer/backfill
      - Backfill/plug
      - etc
  - Bentonite in a deposition hole or a backfilled tunnel may be lost
    - by piping and erosion during the installation and saturation phases
    - by colloid erosion during glacial groundwater conditions
- How well can the bentonite self-seal and homogenise these anomalies?
- Development, calibration and verification of material models and modelling techniques!

Optimistic approach!





Key issues

- Can we justify the "average dry density" approach?
  - Pellets, voids and blocks
  - Complex geometry
- Expansion of bentonite out of the deposition hole
- Mass loss
  - Erosion
  - Installation failures

BEACON

- Part of HORIZON2020
- Running 2017-2021
- Objectives:
  - To develop and test the tools necessary for the assessment of the mechanical evolution of an installed bentonite barrier
    - and the resulting performance of the barrier
  - To verify the performance of current designs for buffers, backfills, seals and plugs.
  - Beacon is focused on the direct application to real assessment cases in actual repository systems
    - cases from relevant repository systems have been selected as test examples

25 partners – 10 countries

SURAO	Czech Republic	ULg	Belgium
Posiva	Finland	BGR	Germany
Andra	France	KIT INE	Germany
Nagra	Switzerland	LEI	Lithuania
ENRESA	Spain	CIEMAT	Spain
RWM	United Kingdom	Clay	Sweden
MKG	Sweden	EPFL	Switzerland
UPC	Spain	ICL	United Kingdom
GRS	Germany	Quintessa	United Kingdom
CTU	Czech Republic	NERC/BGS	United Kingdom
CUNI	Czech Republic	JYU	Finland
CEA	France		
VTT	Finland	SKB (Coordinator)	Sweden

Aim of Work Package 1

- In the framework of WP1, the needs of safety assessment regarding the evaluation of nonhomogeneous backfill properties are addressed, in particular to what extent non-homogeneous material property distributions comply with safety requirements.
- The WP1 report was compiled with the answers to a questionnaire that was distributed to the different WMOs or their representatives.
- The questionnaire aimed at reflecting the state-of-the-art regarding the treatment of heterogeneous bentonite density distribution and properties in the safety case.
- Based on the outcome of the assessment cases and the evaluation method and uncertainties, the end-user may formulate design-specific requirements that can be used for the safety case in a final workshop

WP1 Report:

- The questionnaire consisted of three different parts:
  1. Application of bentonite in the specific design
  2. The required performance of bentonite
  3. Detailed characterization of the required properties of the bentonite

Work Package 2:

- Three tasks:
  - **Task 2.1 Workshop** to present and discuss relevant national and international extant information relating to bentonite mechanical evolution. (M1)
  - **Task 2.2 Identification of relevant data/models**, improvement of understanding of main processes associated to bentonite component evolution taking into account possible heterogeneities. This acts as a source of information on which to base subsequent project WP3 and WP5 activities. The task generated a report, D2.1. (M1-M6)
  - **Task 2.3 Identification of captured knowledge** (M6-M46)

WP2 Database

- Designed a data form to collect appropriate information;
- Requested that Beacon partners fill out the data form for any studies they feel could be relevant to Beacon;
- Collated the completed data forms into a preliminary database;
- Discussed the database at a workshop and defined additional fields that would aid future selection of experiments for study within Beacon;
- Requested additional information to complete additional fields in database;
- Finalised the database.
- Information was received in different formats:
  - Almost 70 completed data forms;
  - abstracts to the Beacon kick-off meeting in Lithuania, June 2017;
  - a list of experiments on bentonite previously compiled by Andra;
  - a brief literature review covering a number of experimental studies.
- Where sufficient information was available, new data forms were created from this additional information.
- For some experiments, however, little information other than the name of the experiment was found to be readily available.

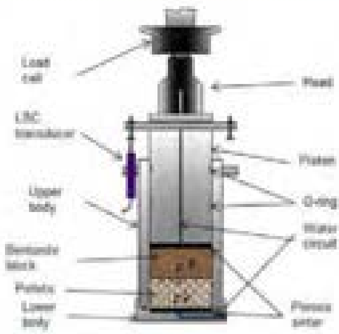
Features of WP3

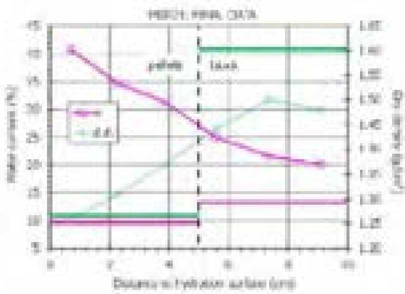
- Focus on the mechanical constitutive model because the state of the barrier at the end of the transient period is dependent on the mechanical evolution of the bentonite
  - Issues of irreversibility stress path dependency and long term deformation are critical
  - This focus on mechanical behavior is in contrast with previous projects where thermal and hydraulic behavior were the primary focus
- The following cases should in principle be considered:
  - Saturated and unsaturated material (wide range of densities)
  - Compacted (blocks) bentonite and pellet-based materials
  - Isothermal and non-isothermal conditions
- Implementation into computer codes capable of performing coupled HM and THM analyses.
  - Additional developments (gaps, large displacements) may be required

Objectives of WP4 – Laboratory Testing

- Provide input data and parameters for development and validation of models
- Reduce uncertainties about conditions and phenomena influencing bentonite homogenisation

WP4 Examples





Strategy for verification and validation of models/Structure of WP5

- Tests cases with different objectives and degrees of complexity
  - Verification/validations cases
    - Tests with simple physic
    - Tests with coupled processes
  - Large scale experiments
    - complex geometry
    - coupled processes
    - Uncertainties on boundary and initial conditions
  - Predictive simulations
    - Lab tests
    - Ongoing field scale experiments
  - Assessment cases
    - Andra tunnel plug
    - Nagra disposal cell
    - KBS-3 deposition tunnel backfill

Task 5.1 - Very well instrumented lab tests

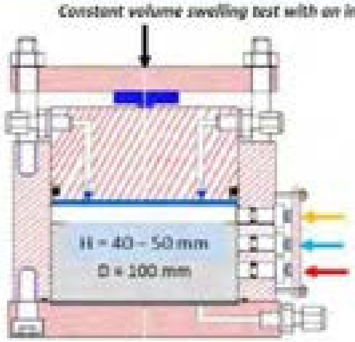
Task 5.2 - Experiments well described, dismantled and showing heterogeneities effects

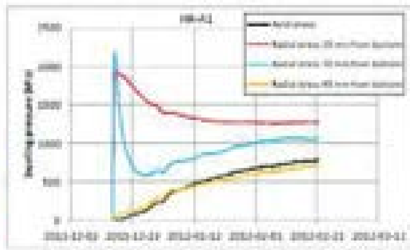
Task 5.3 – Ongoing Experiments

Task 5.4 – cases based on real bentonite component design

Task 5.1 - Very well instrumented lab tests

Constant volume swelling test with an initial gap on the top of the bentonite plug

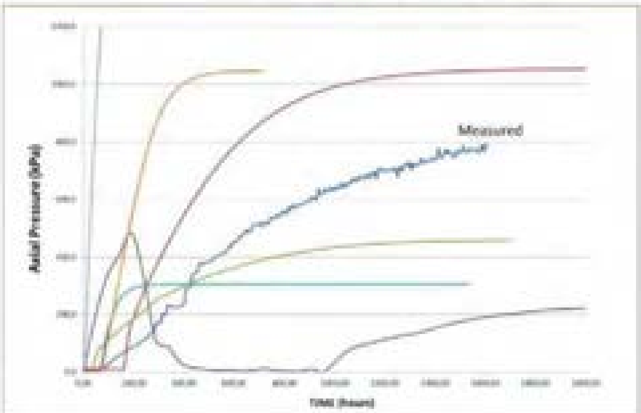


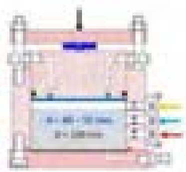


Participants for task5.1

Team	Model/code	Parameters used	Boundary conditions	Results test 1a01	Results test 1a02
ICL	ICFEP	yes	yes	yes	yes
BGR	OpenGeoSys 5	yes	yes	yes	no
Claytech	Comsol/HBM	Yes	yes	yes	yes
EPFL	Lagamine/ACMEG	yes	yes	yes	yes
LEI	Comsol	yes	yes	yes	no
Quintessa	QPAC/ILM	yes	yes	yes	yes
SKB	DACSAR	yes	yes	no	yes
ULG	Lagamine	yes	yes	yes	yes
CU-CTU	Sifel	yes	yes	yes	no
VTT					
UPC					

Analysis of Test 1a02 Axial pressure





Main comments for test1a

- General trend for water ratio and dry density is well reproduced in most cases
- Voids introduces new difficulties →difficult in these zone to obtain simultaneously pressure evolution, void ratio and water content
- Transient phase are difficult to catch
- Collapse during saturation over or under estimated in most cases
- Hysteresis needs to be taken into account?
- Selection of main parameters → comparison needs to be done
- Role of friction in small tests?
- Uncertainties on measurements are sometimes difficult to identify and should be considered
  - Initial gaps
  - Sensor surfaces
  - …

→Needs some exchanges between modelers and experimentalists

WP6

- To give civil society the opportunity to follow, discuss and give feedback on the research conducted in the project by the development of a relevant interaction framework.
- To facilitate the translation of scientific results and other output from WP1-5 to the public and creating the conditions for civil society local and national representatives to interpret, discuss and give feedback on the research result and other information made available by the project.
- To enhance the possibilities of civil society participation in future situations where there are consultation processes as a part of safety case review.

This project receives funding from the Euratom research and training programme 2014-2018 under grant agreement No 745942

MIND - *Birgitta Kalinowski (SKB, Sweden)*

MIND objectives

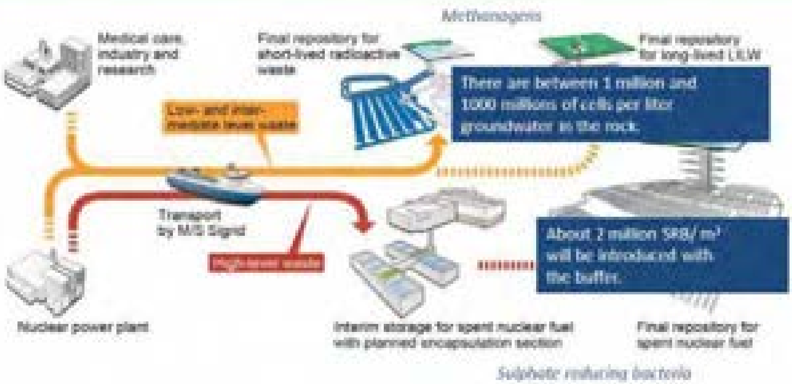
The objectives of the project

- are to target key technical issues, involving microbial processes, which must be addressed to facilitate safe implementation of planned geological disposal projects in the EU.
- will increase the understanding of how life processes will influence the safety and performance of future repositories, by focusing on key topics as defined in the most recent version of the IGD-TP strategic research agenda (SRA) (version July 14, 2011).

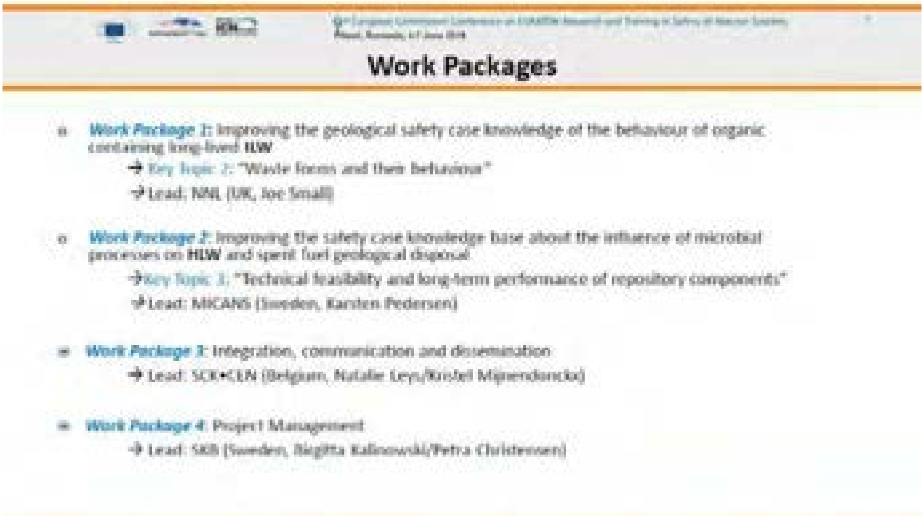
Main microbial processes

- Microbially induced degradation
  - Corrosion of metal canisters
  - Degradation of buffer, backfill and cement
- Gases
  - Production –
  - Consumption +
- Migration
  - Mobilisation –
  - Immobilisation +

Where are the microbes?



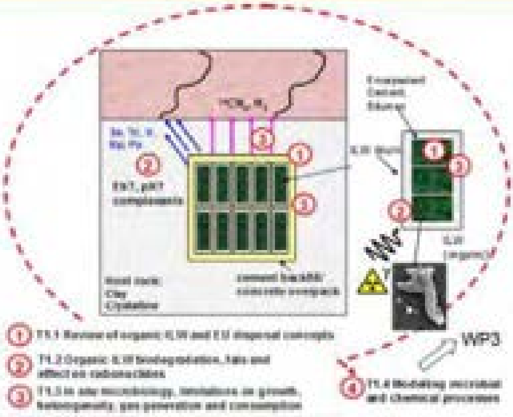

MIND organization
Coordination team
Implementers' Review Board
WP4
Project Executive Committee
WP1
WP2
WP3


Work Packages
Work Package 1: Improving the geological safety case knowledge of the behaviour of organic containing long-lived ILW
→ Key Topic 2: "Waste forms and their behaviour"
→ Lead: NNL (UK, Joe Small)
Work Package 2: Improving the safety case knowledge base about the influence of microbial processes on HLW and spent fuel geological disposal
→ Key Topic 3: "Technical feasibility and long-term performance of repository components"
→ Lead: MICANS (Sweden, Karsten Pedersen)
Work Package 3: Integration, communication and dissemination
→ Lead: SCK•CEN (Belgium, Natalie Leys/Kristel Mijnendonckx)
Work Package 4: Project Management
→ Lead: SKB (Sweden, Birgitta Kalinowski/Petra Christensen)


EURADWASTE '19
WP1: Improving the geological safety case knowledge of the behaviour of organic containing long-lived

ILW disposal concepts

Reduce uncertainty of safety-relevant microbial processes controlling radionuclide, chemical and gas release from long-lived intermediate level wastes (ILW) containing organics



Key findings and outlook

- Key findings
  - First radiolysis + biodegradation studies of organic polymers;
    - Cellulose, Bitumen, PVC, IEX resins
  - Novel RN interactions
  - H_2 consumption
    - Sulfate, nitrate reduction
  - CH_4 generation
    - From cellulose/steel, pH threshold, HS- toxicity
    - Absence from H_2 injection ?
  - pH limits of specific processes
- Further areas of study
  - In situ URL and waste simulant experiments
    - Fate of organics
    - Waste simulant studies (e.g. SRB pH markers)
  - Scale of heterogeneity (pH)
  - Methanogens vs SRB
    - Competition for energy, trace elements
    - Sulfide toxicity

Limits on microbial life in an ILW repository

- Several studies relevant to upper pH limit
  - Nitrate reduction; PVC & Bitumen studies D1.2, D1.3, P7
  - Cellulose studies D1.2, P1, P5
- Controls on Methanogenesis
  - pH, competition with SRBs, sulfide toxicity, thermodynamics, trace elements?
  - TVO experiment D1.6, D1.8, P4, P10
  - Mont Terri H_2 injection D1.7
- Other toxicity effects
  - Cs P9 (Shrestha et al, 2018)
  - Se D1.5, P2, P2, P8

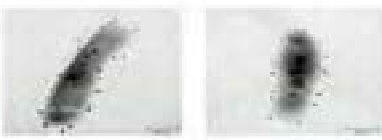
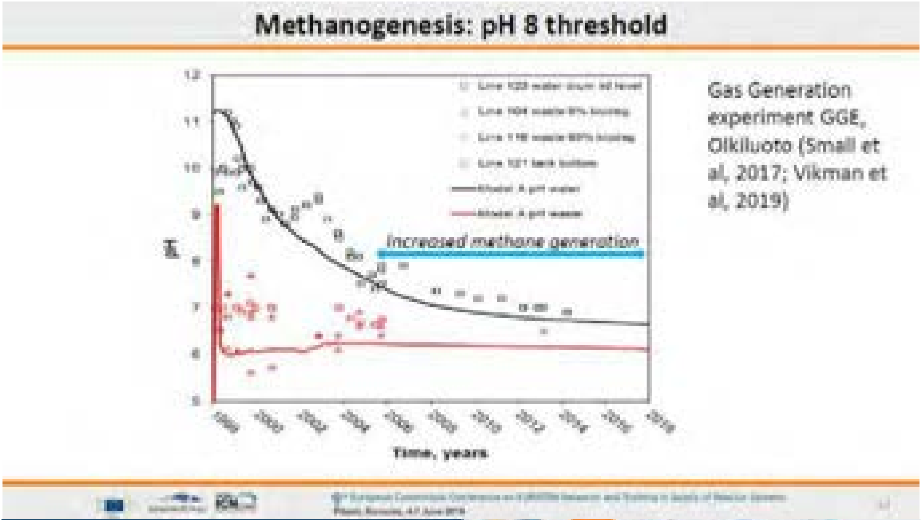
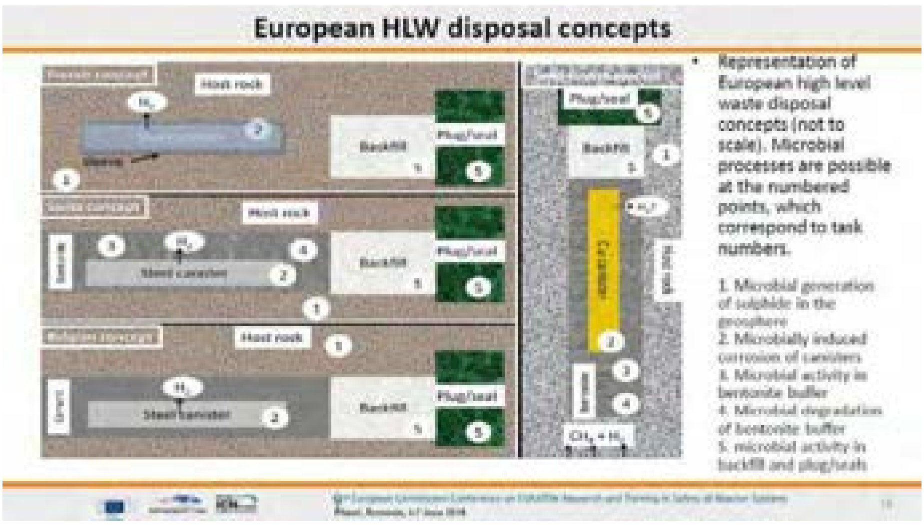


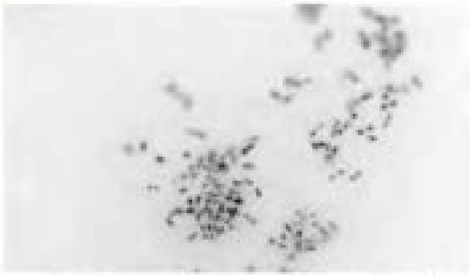
Figure 3: TEM image showing the presence of bacteria in 0.1 mM Cs^+ after 8 days.


Methanogenesis: pH 8 threshold
Increased methane generation
Time, years
Gas Generation experiment GGE, Olkiluoto (Small et al, 2017; Vikman et al, 2019)


EURADWASTE '19
WP2: Improving the safety case knowledge base about the influence of microbial processes on and spent fuel geological disposal


European HLW disposal concepts
Host rock
Backfill
Plug/seal
Steel canister
Canister
$CH_4 + H_2$
Representation of European high level waste disposal concepts (not to scale). Microbial processes are possible at the numbered points, which correspond to task numbers.
1. Microbial generation of sulphide in the geosphere
2. Microbially induced corrosion of canisters
3. Microbial activity in bentonite buffer
4. Microbial degradation of bentonite buffer
5. microbial activity in backfill and plug/seals

Visualization of microbes in clay



Images of extracted bacterial cells from non-spiked FEBEX clay sample B-C-60-18 after hydration

Viable (green fluorescence) and dead (red fluorescence) cells detected in the sample 10 (ring 2, layer 3) of 1400 kg/m3 bentonite

Key findings and outlook

- Key findings
  - The MIND project has identified factors of importance for sulfide production in the geosphere
    - Energy sources, groundwater mixing, electron acceptors etc
  - Swelling pressure is an important limiting factor for microbial activity, but not for presence and survival.
  - The MIND project thoroughly confirms previously published and reported data that have shown microbes to be present in commercial clays as well as in compacted clay in laboratory and in field scale experiments.
  - Microbial activity may decrease pH in high alkaline repository barriers
  - Clay may act as a sink for sulfide
- Further areas of study
  - *In situ* URL and waste simulant experiments

Some research findings

Microbial activity is correlated with bentonite density, swelling pressure and its resulting water activity. Individual commercial bentonites have been shown to display varying effectiveness in mitigating microbial activity at similar densities.

Bentonite clays have a significant capacity for adsorption of sulfide.

Difference in reactivity between bentonites

Present data indicates that sulfate and methane may coexist in deep fluids, indicating that methane is not a very effective electron donor for microbial sulfate reduction.

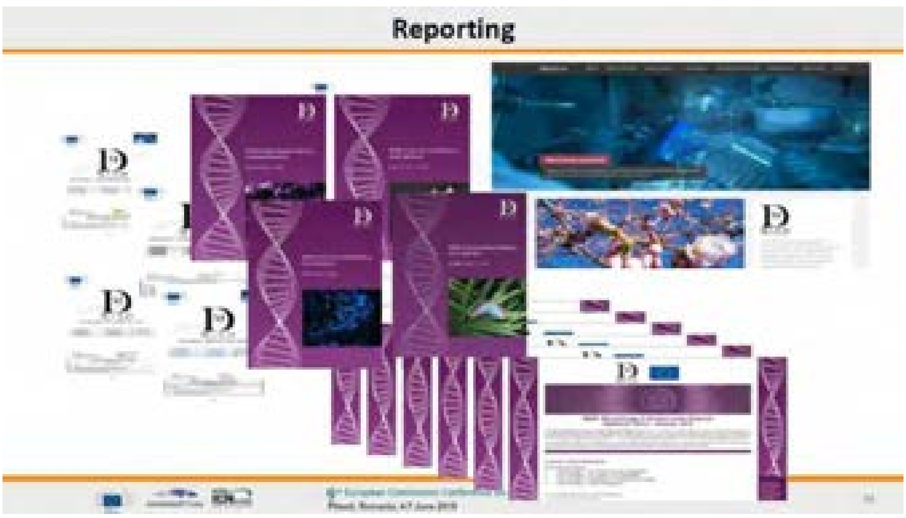
The microbial activity highly influences carbon steel corrosion under anaerobic conditions. The biofilm formation differed depending on the temperature (~20 and 35 °C).


EURADWASTE '19
WP3: Integration -
Communication -
Dissemination


Final integration and synthesis
micans
Perception of lay public and professional:
waste disposal design with and without
microbial processes by interviews,
questionnaires
professionals, the scientific community, stakeholders
and the lay community.
Exchange opportunities and conferences
To enhance a cross-border dissemination of expertise
for Master and PhD students and professionals
http://www.mind15.eu/exchange_table/
mind.project@sckcen.be


Dissemination
Scientific papers
Mobility and reactivity of sulphide in bentonite clays – Implications for engineered bentonite barriers in geological repositories for radioactive wastes
activates deep subsurface fracture fluid
ial communities in Olkiluoto, Finland
samples
Long-term experiment with compacted bentonite
The anaerobic corrosion of carbon steel in compacted bentonite exposed to natural Opalinus Clay porewater containing native microbial populations


EURADWASTE '19
WP4: Project management


Reporting

MIND IN NUMBERS

- 661880 MIND-Project

In almost 48 months, 15 organizations from 8 countries have managed to produce:

- 52 Quarterly reports delivered to the Coordinators
- 35 Deliverables (a few more to come)
- 37 Milestones have been reached
- 2 Periodic reports have been approved by the EC (the last one to come)
- 6 Newsletters
- More than 20 publications
- 2 Advanced courses
- About 20 WP-leaders' meetings
- 4 Project Annual Meetings

All to the cost of: **EUR 4,160,234.50** (four million one hundred and sixty thousand two hundred and thirty four EURO and fifty eurocents) and in 490.50 (four hundred and ninty and a half) person months.

Thank you!

IGD-TP - *Robert Winsley (RWM, UK)*


IGD-TP WMO's committed to:
• building confidence in the safety of geological disposal solutions among European citizens and decision-makers
• encouraging the establishment of waste management programmes that integrate geological disposal as the internationally accepted solution for the safe long-term management of long-lived and/or high-level waste
• facilitating access to expertise and facilities, and maintain competences in the field of geological disposal
Implementing Geological Disposal of Radioactive Waste Technology Platform


SRA 2011 highlighted main WMO RD&D needs
• Identified main RD&D issues that needed a coordinated effort in order to realise our 'Vision 2025'
• Also provided valuable input to identifying topics for future EURATOM calls
• Comprised 7 key topics and various cross cutting activities
VISION 2025
Requirements to reach the VISION
Demonstration of long term safety
Demonstration of disposal techniques and components
Characterisation and confirmation of site
Cross-cutting activities
Topics of importance & urgency
SRA 2011


IGD-TP/SRA helped to define and direct EURATOM Framework calls
• Spent fuel
• Wasteform
• Buffers, backfill, host rock
• RNs, colloids, microbes
• Large-scale demonstration
• Monitoring
• Modelling tools
• Networking studies
• FP7 (2009-2013): 9 projects, (~61M€/29M€ EC)
• H2020 (2014-2015): 4 further projects (~21M€/15M€ EC)
• H2020 (2016-2017): 4 more projects (~16M€ EC)
17 projects, ~€100M

Progress towards implementation

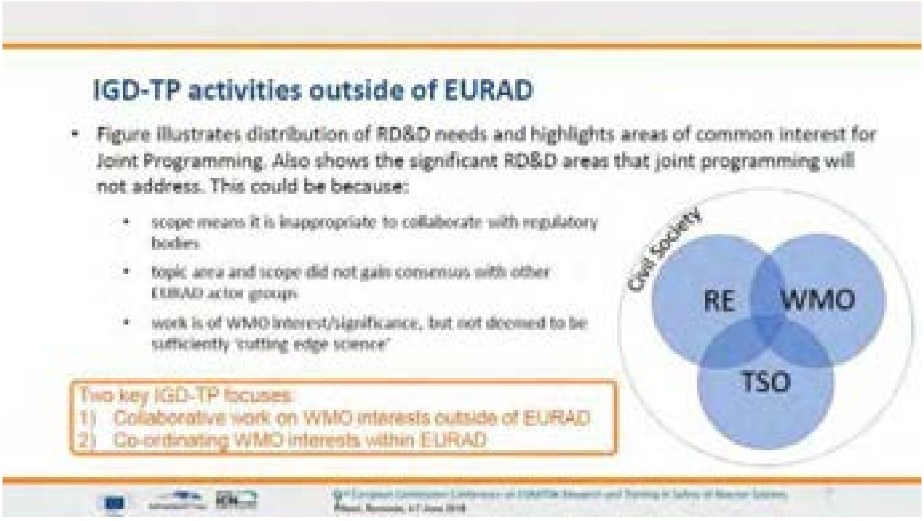
- Initially established with the financial support from the EC. IGD-TP is now funded by 11 European WMOs and organisations responsible for implementation-related RD&D that form the **IGD-TP Executive Group** (EG)
- **Posiva** has a construction license and plans to submit its operation licence application in **2020**; **SKB** submitted its construction licence application in **2011**; Andra expects to follow in **2020**

Evolution of the IGD-TP: 2009 to today

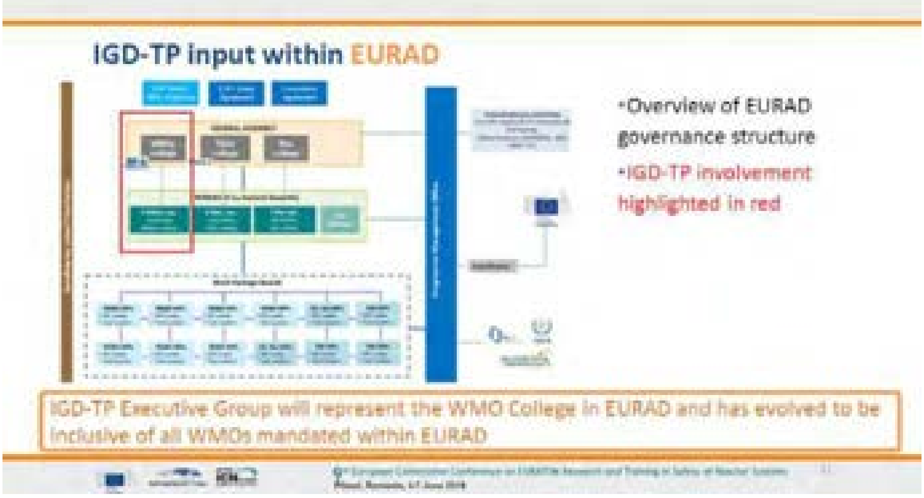
- Despite significant steps forward, sustained RD&D is still needed to ensure that all countries (at various stages of advancement) continue to progress towards implementation
- IGD-TP remains a technical/scientific group focused on deep geological disposal (but adding wider radioactive waste management interests to expand WMO coverage)
- 120+ member organisations / 600+ individual members
- Historically, primary focus has been steering EURATOM RD&D, but we want to broaden our remit to include both EURATOM and non EURATOM RD&D activities

Recently...

- The EC called for a 'step change' in RD&D cooperation involving all parties. To achieve this, a European Joint Programme (EJP, called "EURAD") on Radioactive Waste Management, founded on agreed common objectives, was proposed (more on this from M. Garcia later)
- The IGD-TP is fully supportive of EURAD. However, important to recognise that WMO RD&D programmes have a much wider scope of activities than the commonly-agreed EURAD strategic research agenda will address


IGD-TP activities outside of EURAD
Figure illustrates distribution of RD&D needs and highlights areas of common interest for Joint Programming. Also shows the significant RD&D areas that joint programming will not address. This could be because:
scope means it is inappropriate to collaborate with regulatory bodies
topic area and scope did not gain consensus with other EURAD actor groups
work is of WMO interest/significance, but not deemed to be sufficiently 'cutting edge science'
Two key IGD-TP focuses:
1) Collaborative work on WMO interests outside of EURAD
2) Co-ordinating WMO interests within EURAD
Civil Society
RE
WMO
TSO


Proposed new IGD-TP operating model:
igd-tp
National WMO RD&D programmes
RD&D not co-funded by EURATOM
(~90-95% of the total RD&D budget)
National projects
Bilateral projects
- international consortia
IGD-TP collaboration
EURAD
TSO - college
WMO - college
RE college
Executive Group
Joint activities
EURAD WMOs
Intensified WMO collaboration: workshops, reviews, collaboration projects


IGD-TP input within EURAD
•Overview of EURAD governance structure
•IGD-TP involvement highlighted in red
IGD-TP Executive Group will represent the WMO College in EURAD and has evolved to be inclusive of all WMOs mandated within EURAD

Conclusions

- The IGD-TP coordinates joint WMO RD&D interests both within and outside of EURAD
- Focus remains on geological disposal, but we have expand our remit to also accommodate more upstream interests and a wider inventory coverage (e.g. sealed sources and borehole disposal).
- We aim to enhance coordination of relevant scope in national WMO RD&D programmes
  - Identify and pursue WMO multilateral/bilateral projects /peer review and knowledge sharing within the WMO community outside of EURAD
- Continue to communicate the implementers RD&D requirements to society and our members
- Strong focus remains on the ultimate goal of the RD&D -> realising safe geological disposal in Europe (if one of us succeeds we all benefit)

Look ahead

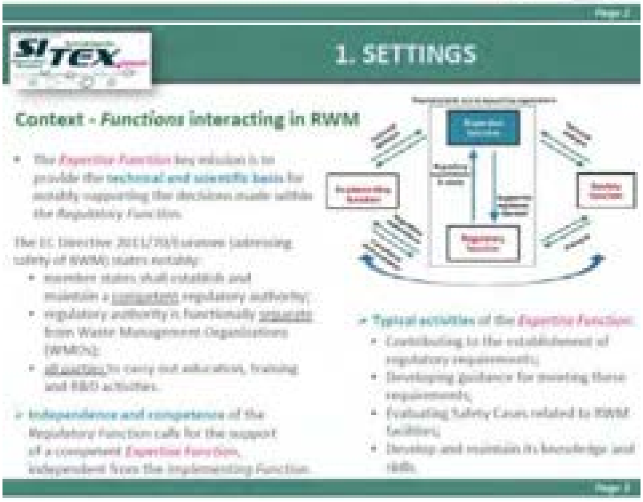
- Major progress has been made towards achieving our Vision 2025
- In order to meet the challenges of the next phase we are in the process of updating the groups vision
- The new vision needs to consider the next step towards industrialisation of radioactive waste disposal in Europe. The focus should lie on the safe operation of the first geological disposal facilities in Europe, the required optimisation and the development of individual solutions to meet the requirements of the diverse range of waste inventories
- An update of our vision will be announced at our 10 year anniversary in November 2019
- Our revised vision will be followed by the publication of the second version of the IGD-TP strategic research agenda in 2020

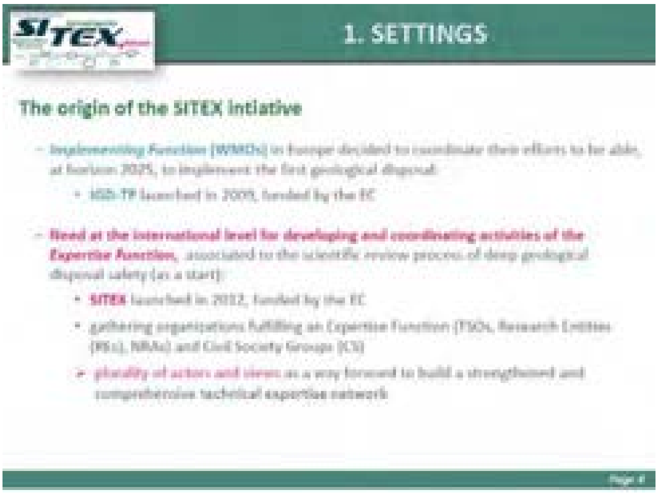
thank you for your attention

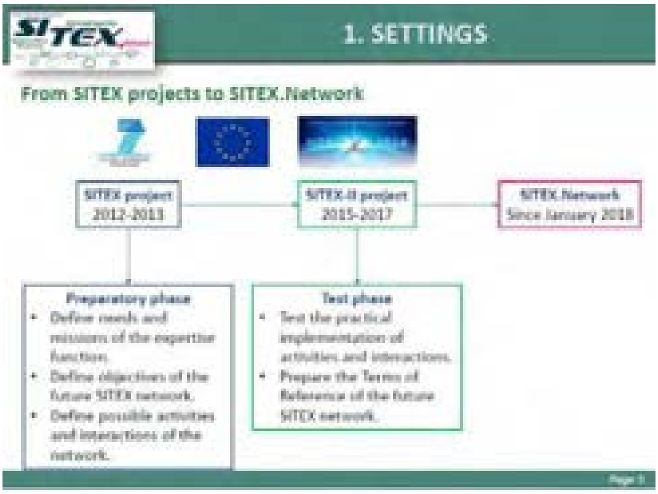
https://igdtp.eu/

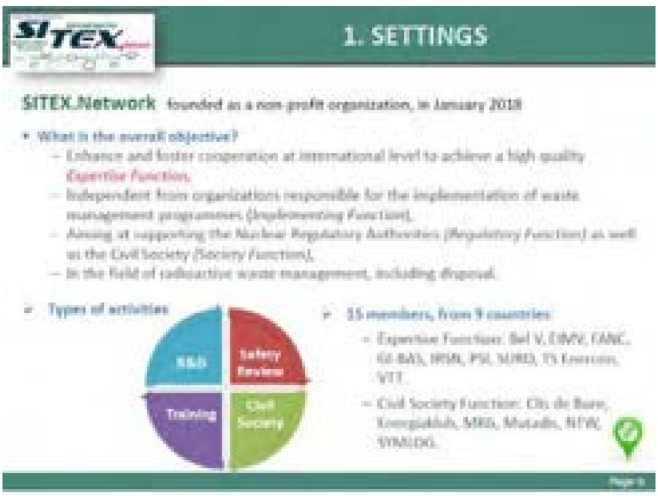
Secretariat@igdtp.eu

SITEX - *Delphine Pellegrini (IRSN, FR)*




1. SETTINGS
The origin of the SITEX intiative
Implementing Function (WMOs) in Europe decided to coordinate their efforts to be able, at horizon 2025, to implement the first geological disposal
IGD-TP launched in 2009, funded by the EC
Need at the international level for developing and coordinating activities of the Expertise Function, associated to the scientific review process of deep geological disposal safety (as a start)
SITEX launched in 2012, funded by the EC
gathering organizations fulfilling an Expertise Function (TSOs, Research Entities (REs), NRAs) and Civil Society Groups (CS)
plurality of actors and views as a way forward to build a strengthened and comprehensive technical expertise network


1. SETTINGS
From SITEX projects to SITEX.Network
SITEX project 2012-2013
SITEX-II project 2015-2017
SITEX.Network Since January 2018
Preparatory phase
Define needs and missions of the expertise function.
Define objectives of the future SITEX network.
Define possible activities and interactions of the network.
Test phase
Test the practical implementation of activities and interactions.
Prepare the Terms of Reference of the future SITEX network.


1. SETTINGS
SITEX.Network founded as a non-profit organization, in January 2018
What is the overall objective?
Enhance and foster cooperation at international level to achieve a high quality Expertise Function,
Independent from organizations responsible for the implementation of waste management programmes (Implementing Function),
Aiming at supporting the Nuclear Regulatory Authorities (Regulatory Function) as well as the Civil Society (Society Function),
In the field of radioactive waste management, including disposal.
Types of activities
R&D
Safety Review
Training
Civil Society
15 members, from 9 countries
Expertise Function: Bel V, FANC, IRSN, PSI, SURO, VTT
Civil Society Function: Mutadis, NTW, SYMLOG


2. MAIN ACHIEVEMENTS
R&D related activities
Expertise Function Strategic Research Agenda (SRA) in the field of RWM
– 36 Topics distributed in 7 Main Topics, with:
– Importance of the main topic to safety
– Rationale for developing joint activities
For each topic: Research activities (experiment and/or modelling works) and/or Horizontal activities (SoTA, exchanges on practices/common position, transfer of knowledge/training)
Conditions for implementation in an EJP whilst preserving the independence of the Functions, eg. :
– impartiality in establishing SoTA
– transparency of codes/data/results
– independent analysis of the results
– say on the design of shared experiments
Main topic 1: Waste inventory and source term
Main topic 2: Transient THMC conditions in the near-field
Main topic 3: Evolution of EBS-material properties
Main topic 4: Radionuclide behaviour in disturbed EBS and HR
Main topic 5: Safety-relevant operational aspects
Main topic 6: Managing uncertainties and the safety assessment
Main topic 7: Lifecycle of a disposal programme and its safety case


2. MAIN ACHIEVEMENTS
R&D related activities
SITEX was involved in the development of the EJP EURAD proposal:
SITEX SRA was an input to the JOPRAD project
– the TSO group of JOPRAD worked in close collaboration with SITEX
– based on the SRA's, assessments of commonalities among WMOs, REs and TSOs needs in R&D were done → Programme Document issued by JOPRAD → EURAD SRA
SITEX coordinated the TSOs reviews of EURAD WPs
– 2 reviews organized (Jan-Feb 2018 and May 2018)
– Internal review by the mandated TSOs
– External review by other SITEX Network members (Expertise and Society Functions separately)
SITEX coordinated the election of the 3 TSO representatives in the EURAD Bureau
Page 8

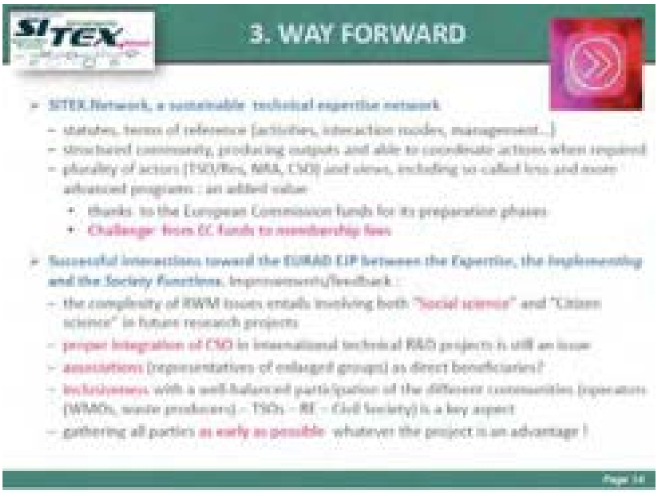

2. MAIN ACHIEVEMENTS
Safety review related activities
A guidance for the technical review of Safety Cases for geological disposal facilities was issued;
Position papers were developed on the 4 aspects of geological disposal
Training activities
SoTA on practices, experiences and prospective views on training and tutoring
a training module for generalist experts in geological disposal, with the safety review perspectives, was developed
1-week pilot training session implemented in Kaunas (Lithuania) in 2017
Proposal by SITEX as an association for the EJP unsuccessful → SITEX/ENSTTI course
Page 9


2. MAIN ACHIEVEMENTS
Interaction between Expertise and Civil Society functions
• A small group of CSOs was directly involved in SITEX II and interacted with a larger group of 35 NGOs from 18 European countries ("double wings" concept), to explore the possible modes of interaction via 3 specific issues
1. How could CSOs concerns be integrated in R&D activities of the Expertise Function?
– CSOs formulated R&D key issues they expected to be covered
– these issues were discussed with the other SITEX partners and considered to produce the final version of SITEX SRA
– e.g. based on the input from CSOs, a first list of socio-technical topics for which both technical and societal aspects need to be investigated in an integrated manner, were identified and included in the SRA (eg. conditions for closure)
– Following notably the successful interactions between Society, Expertise and Implementing Functions, CSOs are now engaged in :
• the BEACON R&D project
• the CIPS EURAD
– though initial proposals evolved to account for EC requests
➢ Interactions between institutional and non institutional organizations needed rather than external (one shot) reviews or "communication"


2. MAIN ACHIEVEMENTS
Interaction between Expertise and Civil Society functions
2. How safety culture for RWM can be shared through different stakeholders, including CS?
– commonalities and differences in the vision of safety culture in RWM identified through a questionnaire
– conditions and means for developing interactions with CS
CONDITIONS FOR PUBLIC PARTICIPATION
FUNDING
TRANSPARENCY
ACCESS TO JUSTICE
INFORMATION
ACCESS TO EXPERTISE


2. MAIN ACHIEVEMENTS
Interaction between Expertise and Civil Society functions
3. Issues on intergenerational governance
– Review and analysis of the literature on past and on-going research projects devoted to intergenerational aspect of RWM were performed
– A new approach was developed to stimulate exchanges on the different possible routes (aboveground or underground storages, deep geological repository…) for the long term management of HLW & SF - a serious game called PEP « Pathway Evaluation Process » - and implemented
• with SITEX-II partners + enlarged group of NGOs
• for educational purpose by a NGO with students in Czech republic
• recently by the French Public Debate Commission for 40 students, with the support of SITEX as facilitator


3. WAY FORWARD
SITEX.Network Work Programme
R&D related activities
update of SITEX SRA produced in 2015, notably in the perspective of the definition of further projects in the framework of the EJP,
coordination of the TSO community for the EJP EURAD when needed
PhD Day related to recent social sciences on governance
Safety review related activities
Benchmark on reviewing approaches (exchange on review practices)
State of knowledge related to deep borehole disposal
Training
on regulatory review and assessment of the safety case for geological disposal : SITEX/ENSTTI course, module 1 on September 23-27, 2019, modules 2&3 in 2020
Civil Society
PEP sessions (of two days each) in 2019 proposed to participants, internal or external to SITEX.
https://www.sitex.network/


3. WAY FORWARD
SITEX.Network, a sustainable technical expertise network
statutes, terms of reference (activities, interaction modes, management...)
structured community, producing outputs and able to coordinate actions when required
plurality of actors (TSO/RES, NRA, CSO) and views, including so-called less and more advanced programs : an added value
thanks to the European Commission funds for its preparation phases
Challenge: from EC funds to membership fees
Successful interactions toward the EURAD EJP between the Expertise, the Implementing and the Society Functions. Improvements/feedback :
the complexity of RWM issues entails involving both "Social science" and "Citizen science" in future research projects
proper integration of CSO in international technical R&D projects is still an issue
associations (representatives of enlarged groups) as direct beneficiaries?
inclusiveness with a well-balanced participation of the different communities (operators (WMOs, waste producers) – TSOs – RE – Civil Society) is a key aspect
gathering all parties as early as possible whatever the project is an advantage !


THANK YOU FOR YOUR ATTENTION !
VTT
FANC
BEL V
PSI
NTW
SYMLOG
mkg
IRSN
Clis
http://sitex.network

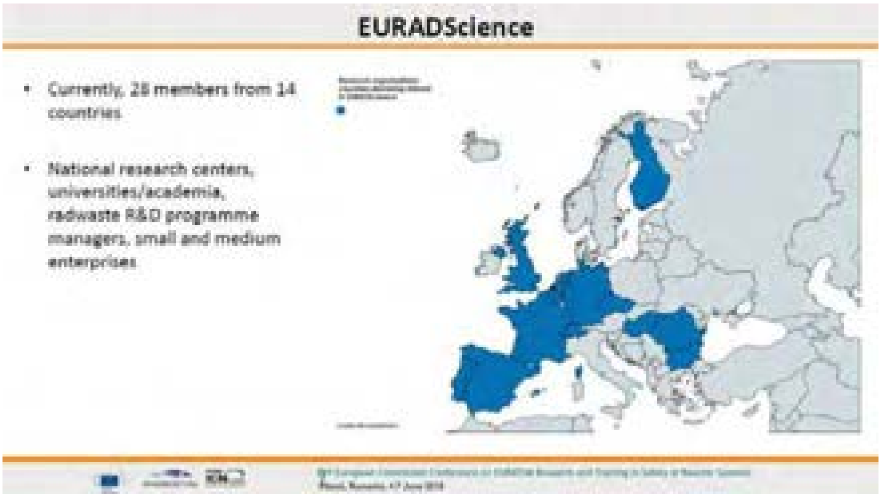
EURADSCIENCE - *Christophe Bruggeman (SCK-CEN, BE)*

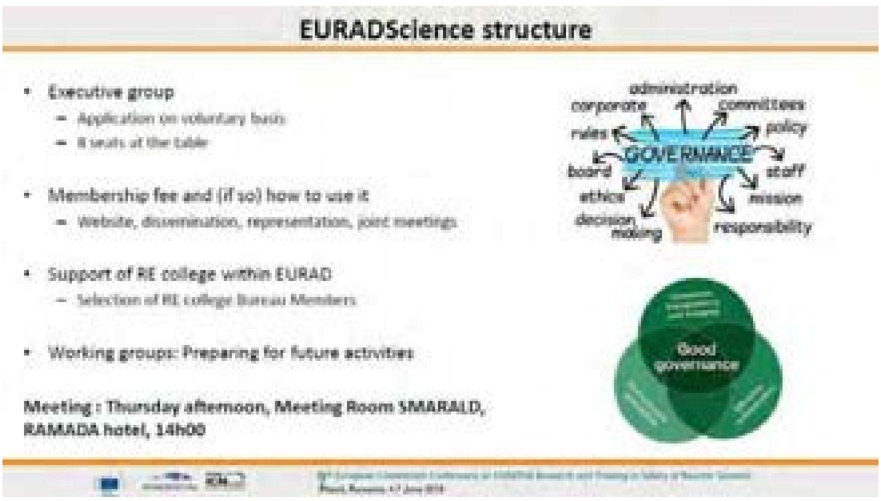

Why RE grouping? - Vision
Key challenge: continuously developing the scientific frontier in view of the extremely long timescales associated with the generation and storage of radioactive wastes, and the development, operating and closing of geological repositories
Vision: To act as an independent, cross-disciplinary, inclusive network ensuring scientific excellence and credibility to radioactive waste management
VALUES


Why RE grouping? - Mission
Mission:
Research organisations are at the centre of developing a long-term vision for the scientific and technical challenges that are inherently linked to safe waste management and disposal, beyond national borders and specific implementation programmes
Research organisations have a primary focus on long-term knowledge management and development, and are key to maintaining competence and know-how
Nationally funded research organisations identified as Mandated Actors within EURAD form the membership of the Research Entities College
– EURADScience will support the functioning of this college
MISSION
VISION
VALUES


Welcome to…
The EuradScience Network
Born December 2018, Berlin, Germany


EURADScience
• Whom do we address?
• Aim
– To work inclusive towards mandated actors within EURAD
• Importance with respect to EURAD governance
– To selectively involve other research organisations
• Setting up a structure and reflection on role of the grouping
– Transparency
• Invited research organisations
– Formally mandated actors under EURAD
• 20 individual organisations
– Linked Third Parties, identified as (important) research organisations
• Link also to academia
– Some TSOs, identified as research organisations, if interested
• VTT, CIEMAT


EURADScience
• Currently, 28 members from 14 countries
• National research centers, universities/academia, radwaste R&D programme managers, small and medium enterprises


EURADScience structure
• Executive group
– Application on voluntary basis
– 8 seats at the table
• Membership fee and (if so) how to use it
– Website, dissemination, representation, joint meetings
• Support of RE college within EURAD
– Selection of RE college Bureau Members
• Working groups: Preparing for future activities
Meeting : Thursday afternoon, Meeting Room SMARALD, RAMADA hotel, 14h00
administration
corporate
committees
rules
policy
GOVERNANCE
board
staff
ethics
mission
decision making
responsibility
Good governance

Research organisations' interest in EURAD

- Embedding techno-scientific research in a progressively demanding societal context
  - Serving society with independent science/building confidence and credibility in radioactive waste management
  - Define state of the art in understanding of system components behaviour, beyond national programme boundaries
  - Building confidence in safety assessments and underlying scientific assumptions for many decades to come
- EURAD as a tool for Building a European knowledge platform on waste disposal
  - Safeguarding existing knowledge and attracting next generation of experts
- EURAD as a tool for structured, long-term R&D commitment
  - Develop and maintain high level research infrastructures across Europe
  - Continuously further develop scientific knowledge promoting confidence building and keeping up to speed with scientific progress in a pro-active manner
- Structured communication and interaction with other Platforms (IGD-TP, SITEX, waste producers)
  - Multilateral rather than bilateral

Development of a Strategic Research Agenda

- Associated to the JOPRAD project, research organisations grouped to define their own Strategic Research Agenda (SRA) in a record time
  - Meetings in Brussels (June 2015), Paris (September 2015), Nantes (November 2015), Paris (March 2016)
  - Final draft in May 2016
- Research organisations working group (22 partners)
  - Representatives from advanced and less advanced programmes

Organisation	Country
[illegible]	France
CVŘ, ÚJV ŘEŽ	Czech Republic
SCK CEN	Belgium
[illegible], Karlsruhe, Dresden	Germany
ENEA, INFN	Italy
LEI	Lithuania
TU Delft, TNO	Netherlands
RATEN ICN	Romania
TU Sofia	Bulgaria
ITU	JRC
PSI	Switzerland
IST	Portugal
[illegible]	Slovenia

Updating the Strategic Research Agenda

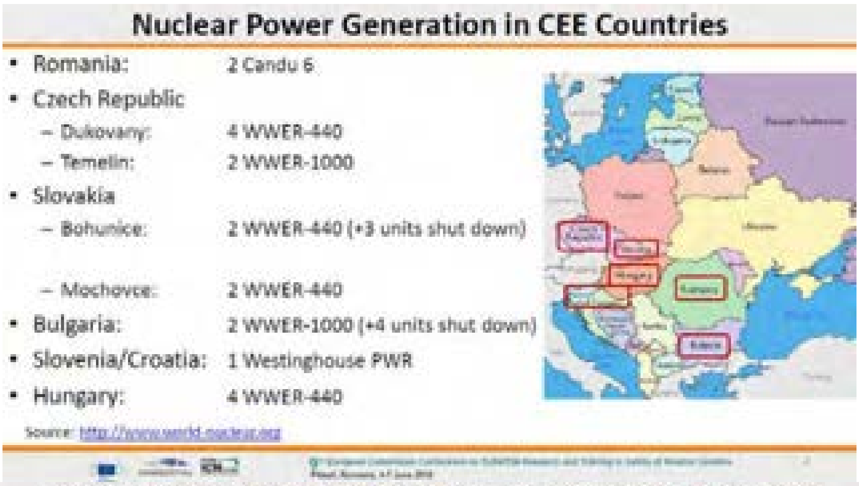
- Focus shift from "geological disposal" (JOPRAD) to "from cradle to grave" (nuclear back-end, EURAD), including
  - Pre-disposal activities
  - Legacy waste, including small (problematic) inventories
  - (Near-)surface disposal
  - (New) nuclear developments
  - → Holistic view on nuclear activities

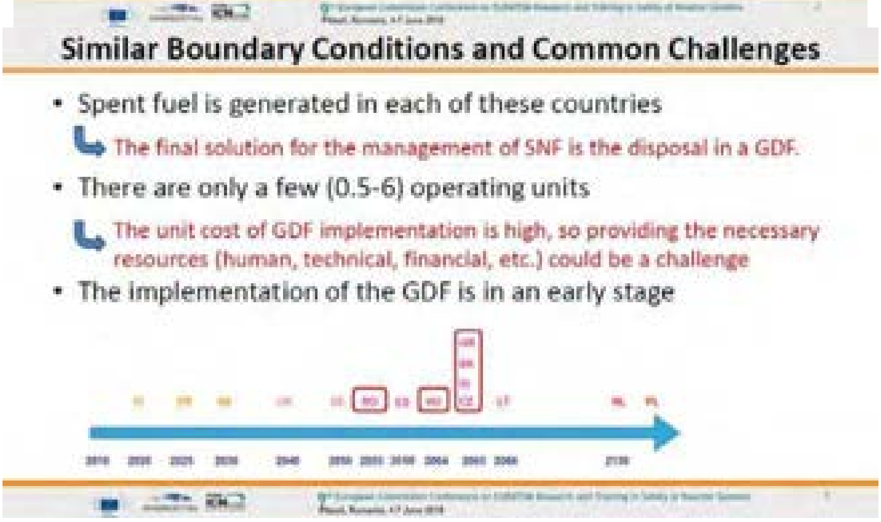
- Providing and developing cutting-edge nuclear research facilities and instrumentation (for applied and fundamental scientific studies)
- Attracting young scientists' interest (educating and training of next generation experts)
- Re-thinking priorities in view of EURAD research programme


Updating the Strategic Research Agenda
• Some examples (non-exhaustive, non-binding)
– Innovative fuels (ATF fuels and claddings)
– Innovative waste forms (ceramic, geopolymers, plasma, spray coatings, organo-mineral composites, etc.)
– Innovative waste disposal concepts (including effect of next generation fuel cycles)
– Natural analogues/site-specific analogues
– Biosphere models and impact of climate change/extremely long time scales
– Further development of complete, transparent and quality assured thermodynamic databases
– Linking bottom up to top down approaches using very complex systems, including mineral assemblages, competition effects, micro-organisms, redox, colloids
– Develop and evaluate concepts and methods for handling (including retrieving), characterization, treating, conditioning, storing and re-disposal of historical (very old) wastes
– Integral experiments (including mock-ups)
– Deep Borehole disposal
– Atomistic simulations and how they can contribute to the safety case
• Networking and sustaining the European research infrastructures


The EuradScience Network
Be at the heart of your community

KEY NOTE - *Bálint Nos (PURAM, HU)*



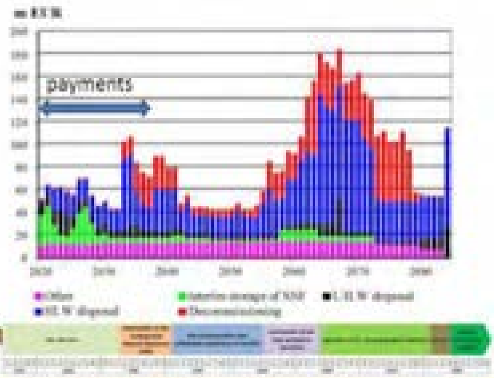


Hungary

an example for a country with early stage programme for the development of geological disposal facility

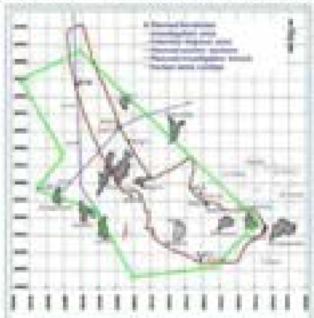
Programme Development

- It is important in an early stage as well,
  - to develop the conceptual plan for the disposal system
  - to define an implementation programme with milestones
  - to establish an R&D plan to support the implementation and
  - to carry out the cost calculation linked to the technical content



Current Status of Site Selection in Hungary

- Currently a surface based geological research program is ongoing
- A staged (stepwise) site investigation program has been developed



Boundary Conditions of R&D Planning

- The R&D framework programme was compiled within the national framework, taking into account the National Policy and National Programme
  - Reference scenario for the back-end is the open fuel cycle
  - The final solution for the HLW (SNF) management is the disposal in a domestic deep geological repository, implementing the multi-barrier system
  - Public hearing is an element of the licensing procedure for R&D plans

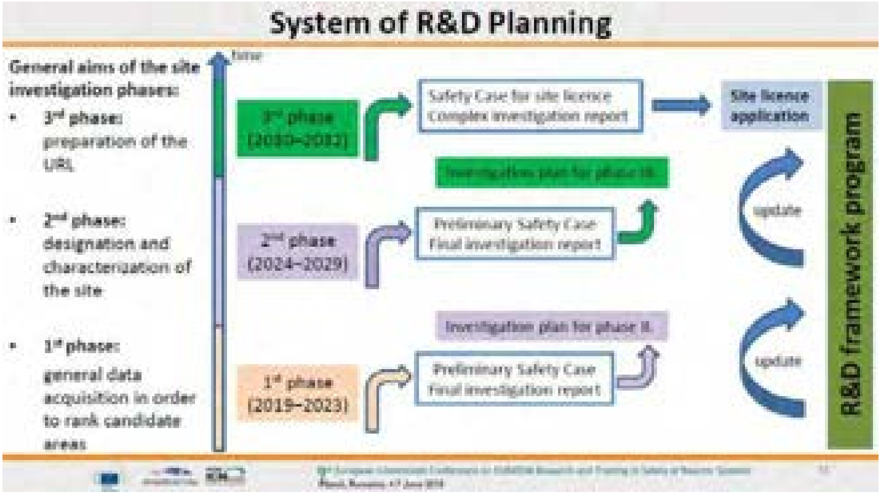
Assistance for Drafting the R&D Plan

- During the development of the R&D framework programme the PLANDIS guide was effectively used to structure the plan
- The methodological advice of ANDRA was really useful
  - to define the system boundary conditions,
  - to identify the safety functions and other requirements for the system elements and
  - to link the planned R&D activities to this functional breakdown system

R&D Framework programme - Topics

- An R&D Framework Programme was carried out for the surface based investigation structured into the following areas

Waste inventory	Waste package (waste form and package)	Engineered barrier system (buffer, backfill, seals and plugs)	Geological (plus natural and societal) environment of the facility
Preliminary design and layout of the surface and underground part of the facility	Operation of the facility, transport and transfer of waste packages, retrievability, reversibility	Methods for R&D investigations, models, evaluation	Data management, and long-term information preservation



Needs of Countries in Early Stage of DGR Development

- Strategical assistance
  - Lessons learned by countries with advanced programmes (what is working and <u>WHAT ISN'T</u>)
  - Site selection and site characterization strategy (criteria, methodology, techniques)
  - Using the safety case (and safety functions) to develop the disposal system and to prioritize R&D
  - The implementation strategy for the URL (part or not part of the future DGR)
- **Adaptation instead of „copy and paste": the way of reaching the decisions (rationale behind) could be more important than the decision itself**

Needs of Countries in Early Stage of DGR Development

- Competence and knowledge management
  - Core competences should be developed and maintained by the countries in early stage of DGR implementation
  - The collection of existing knowledge (state-of-knowledge) in different key topics could be a sound basis in knowledge management
  - Training modules and access to EU wide R&D infrastructure could help in attracting young professionals to join to the RadWaste arena

The educated, experienced workforce will be needed over generations!

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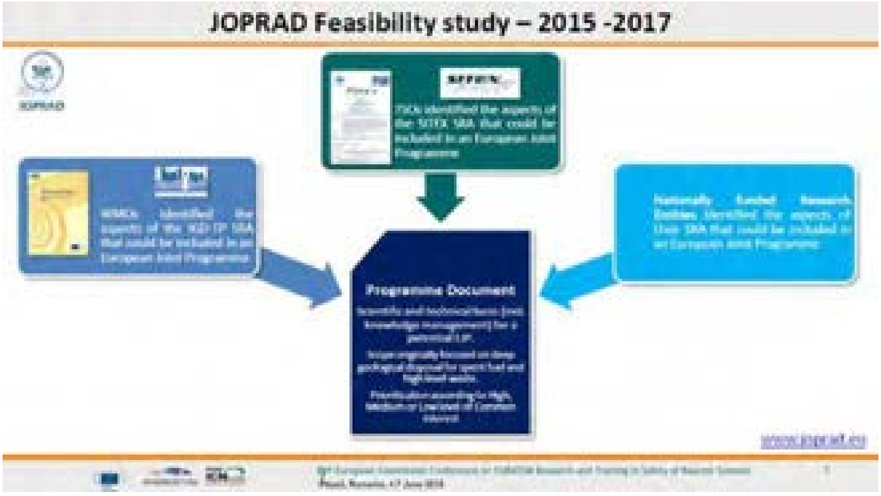
  - The collection of existing knowledge (state-of-knowledge) in different key topics could be a sound basis in knowledge management
  - Training modules and access to EU wide R&D infrastructure could help in attracting young professionals to join to the Radwaste arena
- **The EURAD Project could assist these countries to reach their goals in this respect!**

Thank You for Your Attention!


EURADWASTE '19
European Joint Programme on Radioactive Waste Management
Frédéric PLAS (Andra, France - Head of R&D Division)
Marie GARCIA (Andra, France - Coordinator of EJP EURAD)


Background – European RD&D
For more than 40 years, considerable scientific and technical knowledge has been acquired in Europe in the field of radioactive waste management (RWM).
Through EURATOM, EC has supported EU collaborative RD&D ad-hoc projects and enhanced coordination by supporting IGD-TP platform and SITEX network.
Leap forward: EC Policy & Strategy for integration of EU Member-States R&D programmes
– Replace EU competitive calls for projects by inclusive European Joint Programmes (EJP)
In 2014, EC called for a feasibility study of creating such an EJP in RWM field: JOPRAD (2015-2017)
– Identified those actors with key responsibility for directing RD&D on safe RWM; and
– engaged them in the development of a shared Vision and the basis for a shared Strategic Research Agenda


JOPRAD Feasibility study – 2015 -2017
TSOs identified the aspects of the SITEX SRA that could be included in an European Joint Programme
WMOs identified the aspects of the IGD-TP SRA that could be included in an European Joint Programme
Nationally funded Research Entities identified the aspects of their SRA that could be included in an European Joint Programme
Programme Document
www.joprad.eu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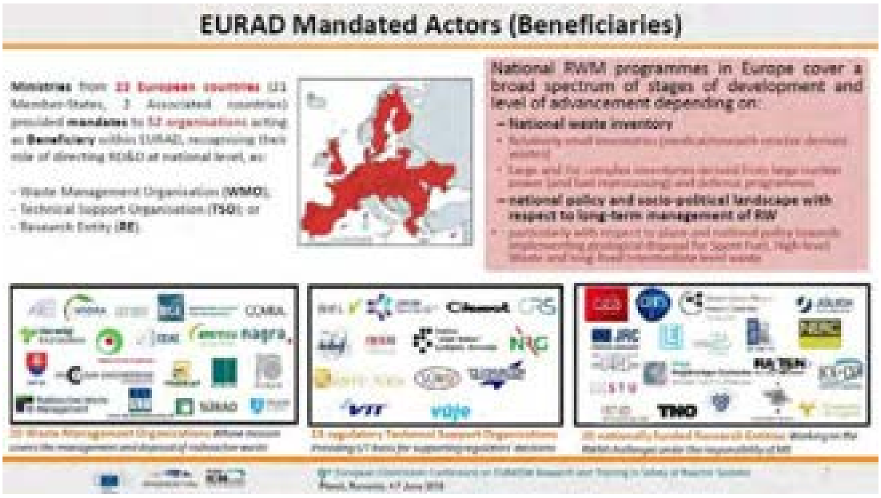
engaged them in the development of a shared Vision and the basis for a shared Strategic Research Agenda
In 2017, H2020 EURATOM WP2018 – EC called for the establishment of an EJP on RWM (NFRP6)
2017 – 2018: Further development of the founding documents of the EJP on RWM
Official launch: June 2019 !

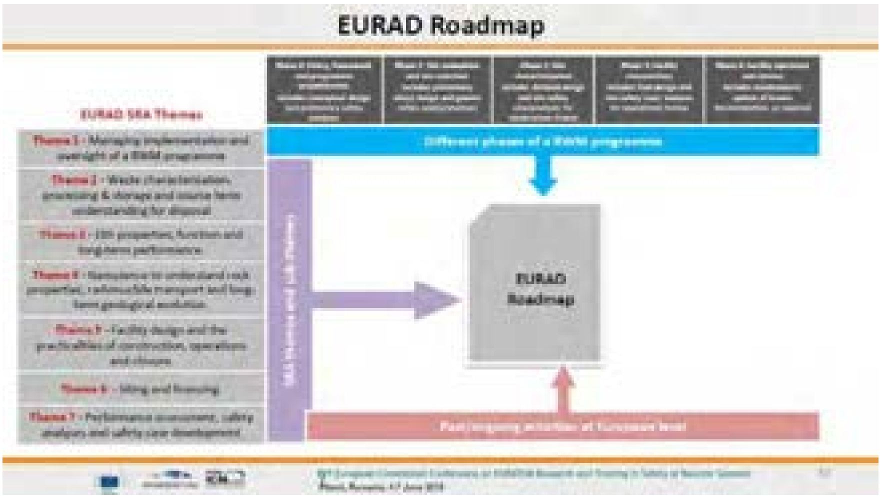

eurad
European Joint Programme
on Radioactive Waste Management
The project leading to this application has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement


EURAD Vision and goals
Vision
A step change in European collaboration towards safe radioactive waste management (RWM), including disposal, through the development of a robust and sustained science, technology and knowledge management programme that supports timely implementation of RWM activities and serves to foster mutual understanding and trust between participants.
Goals
Support the implementation of the Waste Directive in EU Member-States (MS), taking into account the various stages of advancement of national programmes:
• Support MS in developing and implementing their national RD&D programmes for the safe long-term management of their full range of different types of radioactive waste;
• Develop and consolidate existing knowledge for the safe start of operation of the first geological disposal facilities for spent fuel, HLW, and other long-lived radioactive waste, and supporting optimization linked with the stepwise implementation of disposal;
• Enhance knowledge management and transfer between organisations, MS and generations.

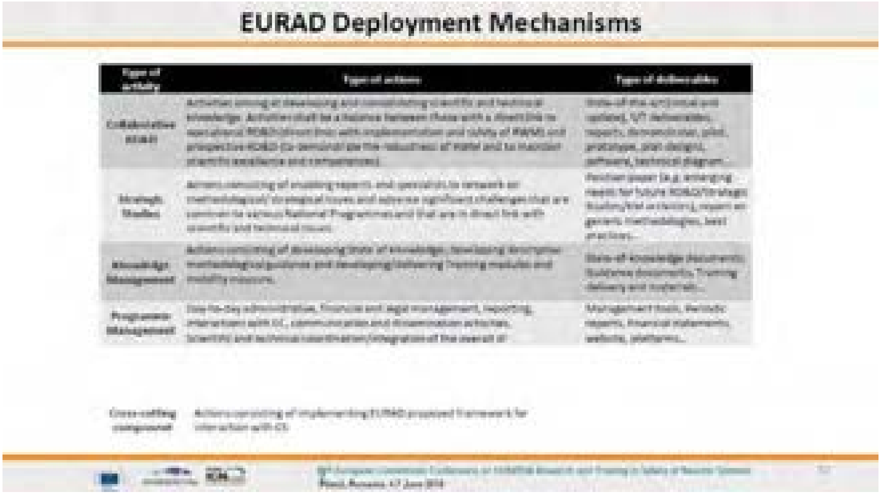

EURAD Mandated Actors (Beneficiaries)
- Waste Management Organisation (WMO),
- Technical Support Organisation (TSO); or
- Research Entity (RE)
National RWM programmes in Europe cover a broad spectrum of stages of development and level of advancement depending on:
– National waste inventory
– national policy and socio-political landscape with respect to long-term management of RW

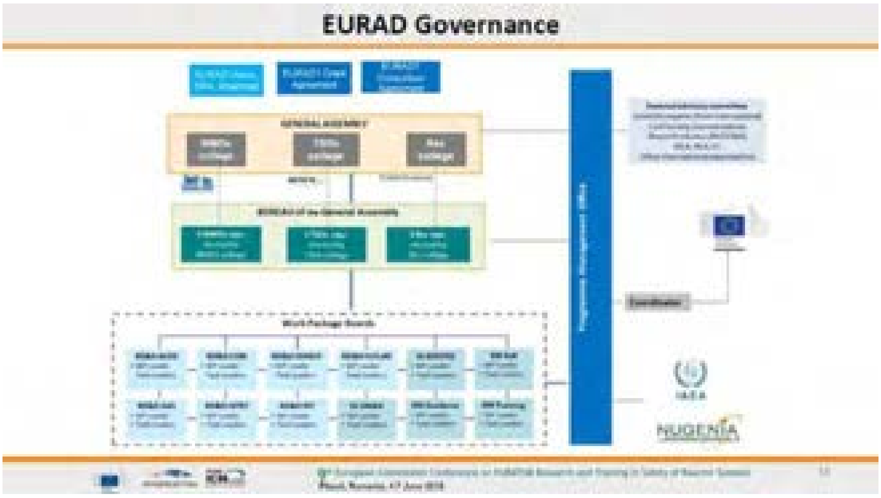

EURAD other participants
• 53 additional organisations (mostly universities and research centres) will also be involved in the implementation of tasks as third parties with a legal link to a Beneficiary (Linked Third Parties).
• Group of Civil Society organisations such as local communities having interest in RWM (local association, local Committee of Information, local partnership), national or European CS Organisations taking part in interactions in the field of RWM.
• Waste Producers and those with a pre-disposal waste management remit are engaged via the NUGENIA association.
– Although not direct contributors or participants of EURAD yet, continued engagement via dissemination and consultation with NUGENIA will set a foundation for future collaboration in projects influencing the waste form for final disposal.
• International Organisations
– Already EURAD has established close links with IAEA from inception to avoid duplication of effort and resources. Such co-operation will continue, e.g. with the establishment of a Memorandum of Understanding;
– and extend to other organisations, including OECD-NEA, to strategically direct and offer clear added-value to EURAD objectives.

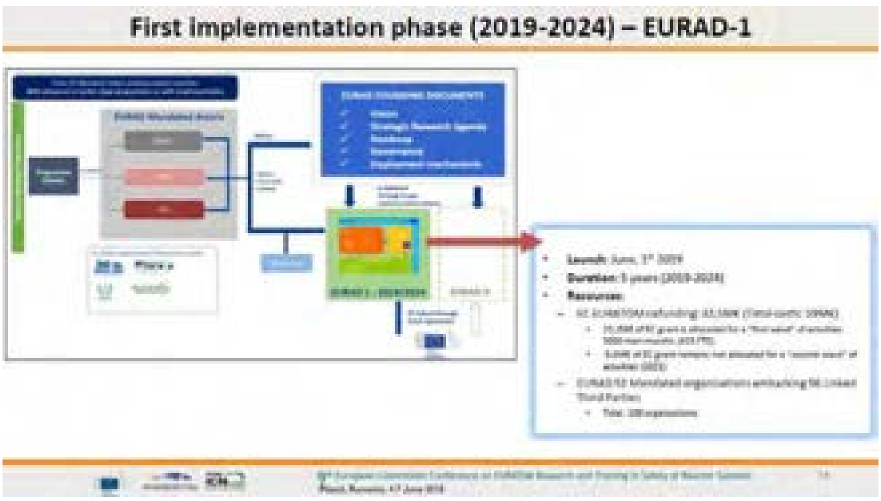

EURAD Strategic Research Agenda
Scope
EURAD SRA is a shared SRA building on the SRAs of the three colleges of Actors:
IGD-TP SRA for WMOs;
SITEX SRA for TSOs;
RE (EURADScience) SRA for REs.
It covers:
All waste types;
Pre-disposal - waste characterisation and processing (incl. treatment/conditioning/packaging) and interim storage;
Disposal - primarily geological disposal, and also other types of disposal
It does not cover decommissioning
It is split into 7 scientific themes (see next slide)
It is a dynamic and living document that will be regularly updated


EURAD Roadmap
EURAD SRA Themes
Different phases of a RWM programme
EURAD Roadmap
Past/ongoing activities at European level

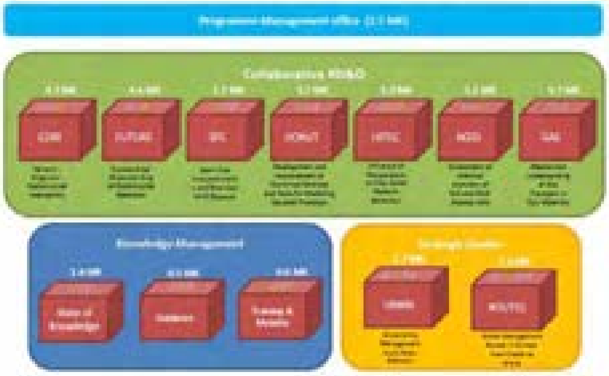

EURAD Roadmap (illustration)


EURAD Deployment Mechanisms


EURAD Governance
NUGENIA


First implementation phase (2019-2024) – EURAD-1
Launch: June, 1st 2019
Duration: 5 years (2019-2024)
Resources:

First implementation phase (2019-2024) – EURAD-1



Conclusion – Ambition (1/3)

- Fruit of determination, tremendous amount of work from European RWM R&D actors since 2013;
- Establish a **sustainable, inclusive, transparent, leading-edge scientific** and **goal-oriented, entirely new approach on European collaboration towards safe RWM**
  - Sustainable approach particularly pertinent in view of long lead-times & operational time-spans
- **Holistic and multi-disciplinary programme between generations** that shall guide cooperative research and investments in the RWM field over the coming decades in Europe:
  - Predisposal and disposal activities, full range of waste, during all phases of a disposal programme
- **Gather organisations in Europe with key responsibility for directing RD&D on safe RWM irrespective of the stages of development of their national programmes.**
  - Small and early stage programmes are especially strongly involved in the Strategic Studies WP ROUTES and will also benefit from the Knowledge Management programme

Conclusion – Ambition (2/3)

- Implement a **robust & sustained state-of-the-art science & technology programme** established to :
  - complement national R&D programmes for safe long-term management of their full range of radioactive waste,
  - carry out activities of high common interest between the actors where there is added-value at European level.
  - Support research needs of advanced and early stage programmes
- **Elaborate upon complex issues and identify emerging ones** by bringing together all interested actors to jointly conduct Strategic Studies.
  - May be referred to as 'think-tank' activities to determine if there is a RD&D need on an emerging issue, if there is a need of a position paper or if it is considered mature and suitable for knowledge management activities.
- Foster **mutual understanding/trust** between participants and other stakeholders, incl. from Civil Society.

Conclusion – Ambition (3/3)

- **Consolidate efforts across Member-States on Knowledge Management** – this includes:
  - access to existing Knowledge (State-of-Knowledge);
  - guiding the development of capability in line with core competencies (Guidance and Training);
  - improving access to quality tools, resources and communities of practice to share and learn from each other.
- **Deepen the interaction/cooperation** that have been established since JOPRAD with:
  - **Waste Producers** to set the foundation for future collaboration in **predisposal activities** (link with EURATOM Call NFRP 10);
  - **IAEA** to avoid duplication of effort/resources and identify possible joint development and implementation of actions
  - Such co-operation shall extend to other organisations, including **OECD-NEA** to strategically direct and offer clear added-value to EURAD.

EURAD – Challenges for Year 1

- **Launch EURAD** and experiment initial learning phase with respect to the governing bodies and mechanisms which may require some fine-tuning.
- **Extend the Roadmap** to support identification of the key need-gaps, which will then be used to prioritise the scope of KM activities:
  - Competency Matrix to identify necessary competencies against Roadmap themes and phases;
  - Mapping of existing/available state-of-knowledge, training, guidances, etc.;
  - Identification of subject matter Experts against each of the Roadmap topics.
- Establish **SOTA reports** of the 7 **RD&D projects** and start implementing the R&D work.
- Initiate the **two Strategic Studies** and start implementing planned work
- **Set the scene** for the launch of the **Knowledge Management** Activities

Thanks for your attention!

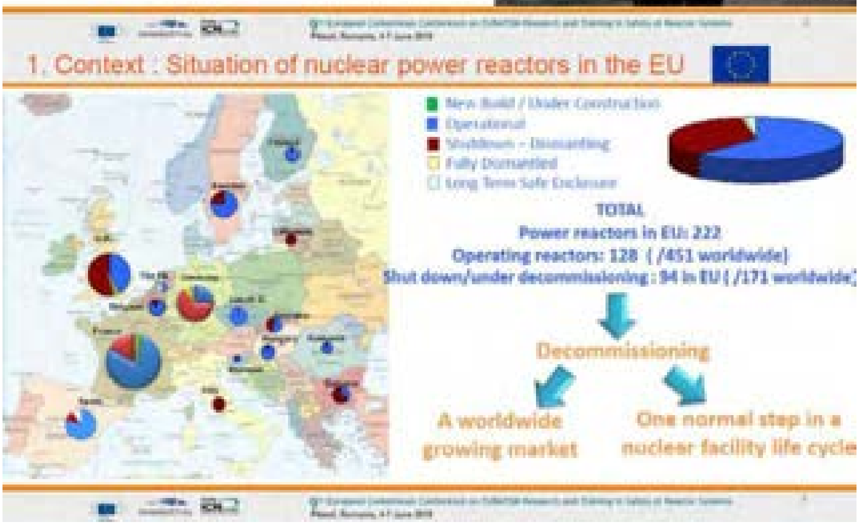
Contact:

For further information, please contact

Marie GARCIA, Andra, France

marie.garcia@andra.fr

KEYNOTE - *Michel Pieraccini (EDF, FR)*



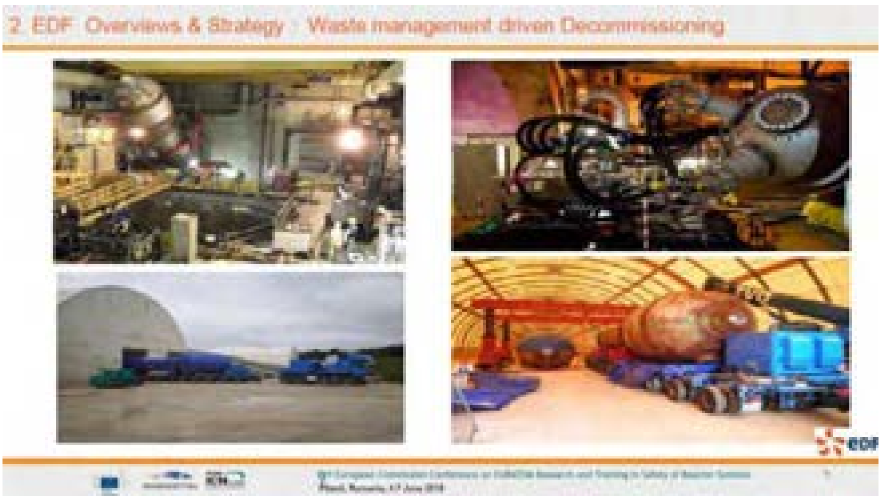

1. Context : Decommissioning a normal step of Nuclear Facilities life cycle
3 steps in a Nuclear Plant Life cycle :
Design & Build,
Operation,
Decommissioning & Dismantling (D&D)
Materials and Waste are generated all along the 3 steps.
Materials to be characterized and sorted
Real Radioactive Waste to be disposed of
Inventories,
Characterization,
Treatment,
Reuse,
Recycling, ...
Waste volume reduction,
Environmental impact mitigation,
Preservation of storage capacities as rare resources,
Packaging, control, Transportation,
edf


1. Context : Decommissioning a normal step of Nuclear Facilities life cycle
Technical & Financial Mastery at each step , , are key to strengthen :
- nuclear industry credibility ,
- Public Acceptance.
Waste Management Capabilities, "From cradle to grave" , (Skills, Labs, treatment facilities, disposals, ...)
have become the cornerstone of this mastery.
D&D appears as the main source of radioactive waste production ,
Improving Techniques & Means, including devoted R&D, Environmental considerations are a worldwide stake
Fostering International Cooperation to mutualize tools, techniques and to share experiences enables optimisation, risk mitigation approach, ... leading to :
Greater efficiency, Safety, Sustainability and gain productivity,
Stakeholders' confidence,
Public Acceptance


2. EDF Overviews & Strategy in Radioactive Waste Management & Decommissioning Activities
NPPs owners or operators are responsible for the safe and efficient running of each of the 3 phases
As NPPs owner/operator, edf ensures its role through an Architect integrator model all along these 3 steps, applying, for each of them, the same quality consideration and level of requirements.
edf : - is currently operating 58 NPPs in France + 15 in UK
but
- has also acquired a sound robust experience in Waste management & Decommissioning, particularly during the last 2 decades .
Strong of this OPEX in WM&D, EDF created a dedicated directorate : DP2D in charge of all decommissioning and Waste Management Projects completed by its holding : cyclife


2. EDF Overviews & Strategy 4 technologies, 6 sites, 9 reactors, Services to customers & Internal* Cooperat*
DP2D, and its holding cyclife gather :
All WM&D projects addressed within the Group
All Skills, Resources and Industrial means,
In order to :
Reinforce EDF Capacity & leadership in this field,
Identify & Address pragmatically R&D aspects,
Include wise and adapted operators' training,
Experiment, test, adjust innovative technologies,
Prepare Future internal challenges,
Provide services to partners,
Enhance complementary partnerships,
Foster International Cooperation and the share of experiences...
Partial Dismantling Decree: 2011
Dismantling Decree: 2007
Dismantling Decree: 2010
Dismantling Decree: 2006
edf

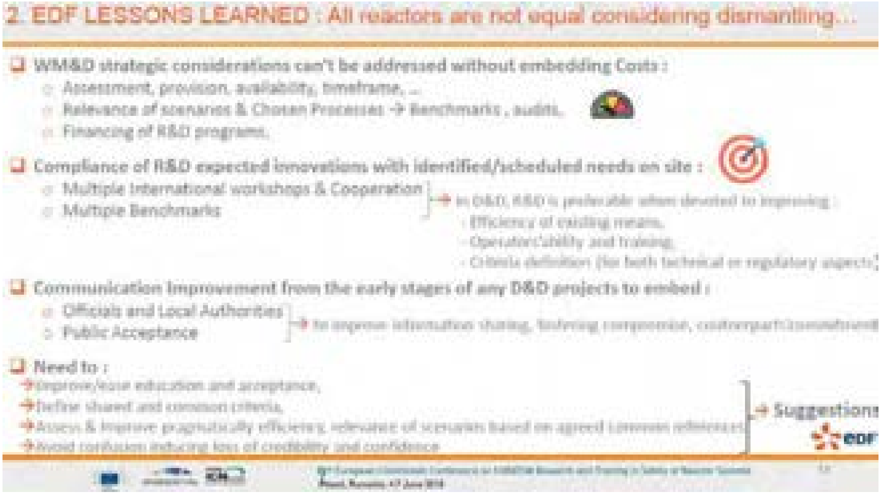

2. EDF OVERVIEWS & STRATEGY : Managing an industrial organisation for French & International market
DP2D industrial organisation encourages International cooperation to :
Continuously improve its know-how and operators' ability,
Foster the share of experiences, identify partnerships,
Be up-to-date regarding innovation, regulatory evolutions,
Understand Customers'needs and provide them tailored, optimised solutions,
Test, Qualify, Benchmark and optimise new techniques,
Support and adapt dedicated R&D, Operators'training,
DP2D
JAPAN
ITALY
SWEDEN
SPAIN
UK
CEA
VEOLIA
EDF SA
External partnerships
edf


2. EDF Overviews & Strategy : Waste management driven Decommissioning
edf


2. EDF Overviews & Strategy : ~20 years of experience in Waste management & Decommissioning
edf

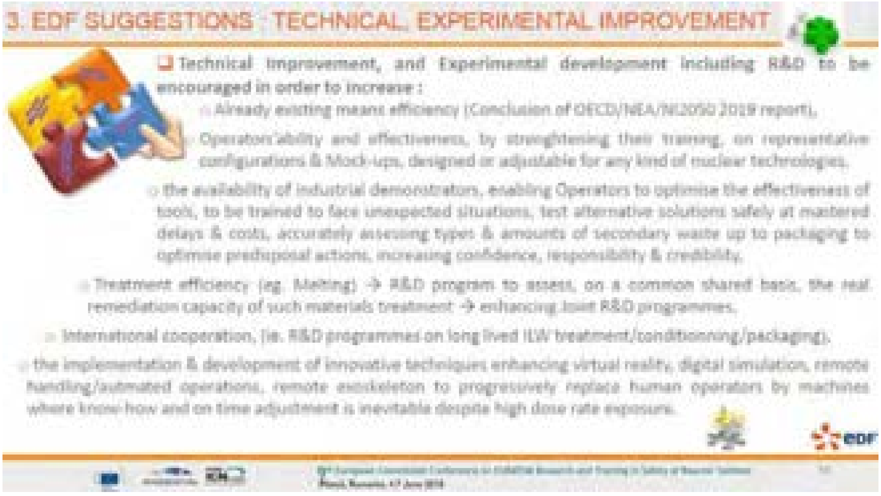

2. EDF LESSONS LEARNED : All reactors are not equal considering dismantling…
ILLUSTRATION OF GAS COOLED REACTOR COMPLEXITY
REACTOR CORE OF BUGEY 1
PRIMARY CIRCUIT OF A PWR
Mass ratio: around 20
REACTOR CORE
VESSEL
Graphite bricks
54 HEAT EXCHANGERS
Height:
12 m
4 STEAM GENERATORS
Height:
20 m
edf


2. EDF LESSONS LEARNED : All reactors are not equal considering dismantling…
Different Nuclear reactor technologies are not equal regarding decommissioning
PWR (Current operating French Fleet) : Scenarios & Feasibility regularly assessed & checked → focusing optimization and serial effect
EDF Graphite reactors dismantling will be a First of a kind for such huge structures :
→ means and innovative tools still under development
→ Graphite Management remains a stake
EDF Risk Mitigation Approach allows anticipation, flexibility, reactivity, …
Experience in Projects/program management + waste driven decommissioning are keys
Complete and efficient national Waste Management system is essential for nuclear decommissioning
improvements can still be envisaged :
edf


2. EDF LESSONS LEARNED : All reactors are not equal considering dismantling…
WM&D strategic considerations can't be addressed without embedding Costs :
Assessment, provision, availability, timeframe, …
Relevance of scenarios & Chosen Processes → Benchmarks , audits.
Financing of R&D programs.
Compliance of R&D expected innovations with identified/scheduled needs on site :
Multiple International workshops & Cooperation
Multiple Benchmarks
Communication Improvement from the early stages of any D&D projects to embed :
Officials and Local Authorities
Public Acceptance
Need to :
→ Suggestions
EDF


3. EDF SUGGESTIONS :
Experience Lessons Learned
Communication, Education, Training, R&D
Suggestions of Improvement
Regulatory Considerations :
- to foster Circular economy
- to improve international cooperation
Technical, Experimental Improvements
EDF


3. EDF SUGGESTIONS : REGULATORY IMPROVEMENT
Regulatory Considerations evolutions to be taken into account :
Common and agreed International Guidelines / Directives leading to national adjustments
Need to harmonise regulations between countries to :
→ Foster circular Economy, particularly in Waste Management & Materials recycling
→ Improve Environmental and raw resources preservation,
→ Avoid any risk of confusion in population's perception leading to dwindling confidence in nuclear industry, including regulators !!!
→ Allow, thanks to common rules & criteria, realistic, sound and representative assessment of :
EDF


3. EDF SUGGESTIONS : TECHNICAL, EXPERIMENTAL IMPROVEMENT
Technical improvement, and Experimental development including R&D to be encouraged in order to increase :
Already existing means efficiency (Conclusion of OECD/NEA/NI2050 2019 report),
Operators'ability and effectiveness, by strenghtening their training, on representative configurations & Mock-ups, designed or adjustable for any kind of nuclear technologies,
the availability of industrial demonstrators, enabling Operators to optimise the effectiveness of tools, to be trained to face unexpected situations, test alternative solutions safely at mastered delays & costs, accurately assessing types & amounts of secondary waste up to packaging to optimise predisposal actions, increasing confidence, responsibility & credibility,
Treatment efficiency (eg. Melting) → R&D program to assess, on a common shared basis, the real remediation capacity of such materials treatment → enhancing Joint R&D programmes,
International cooperation, (ie. R&D programmes on long lived ILW treatment/conditionning/packaging),
the implementation & development of innovative techniques enhancing virtual reality, digital simulation, remote handling/automated operations, remote exoskeleton to progressively replace human operators by machines where know-how and on time adjustment is inevitable despite high dose rate exposure.
edf


3. EDF SUGGESTIONS : TECHNICAL, EXPERIMENTAL IMPROVEMENT
EDF Fosters and leads 2 New projects in compliance with these suggestions:
Future Centralized Treatment Facility
Decommissioning Industrial Demonstrator
edf


3. EDF SUGGESTIONS : TECHNICAL, EXPERIMENTAL IMPROVEMENT
EDF Decommissioning Industrial Demonstrator
First designed for graphite reactors Decommissioning, this scalable facility will enable operators from all potential stakeholders to :
Check the feasibility of new decommissioning scenarios, including alternative solutions to face unexpected situations that will undoubtedly occur,
Allow intense use of realistic 3D modelling based on on-site 3D scanning,
Train workers to the choice and use of most suitable techniques,
Increase safety, control delays and costs : determining appropriate tools, cutting speeds, volumes of secondary waste or releases, reducing dose rate exposure, optimising packaging, control and handling procedures
Implement automated means, remote handling tools, test the efficiency of cutting tools on real scale mock up, adapt and adjust to any kind of identified needs
edf


3. EDF SUGGESTIONS : TECHNICAL, EXPERIMENTAL IMPROVEMENT
EDF Decommissioning Industrial Demonstrator
Implementation of Automated Means will let us
envisage progressive replacement of humans by robots
remotely controlled using exoskeletons when need to:
require human know-how and on time analysis despite high dose rate exposure conditions,
improve safely Labor efficiency (up to ~2 times) increasing working time in ionized radiations conditions but reducing collective dose,
enable larger fragments without compulsory heavy handling means,
ease worksite preparation (no prior decontamination, no multiple airlocks ...),
better consideration to secondary induced waste volume reduction as a source (less washing, clothings, effluents, waste, ashes, drums...),
mitigate risk of injury, electric shock, falling objects, work from heights,
motivate and educate operators as well as public consideration towards back-end activities.
VS
edf


4. CONCLUSIONS :
EDF WM&D Strategy, including R&D aspects on pre-disposal, are strongly influenced by Lessons learned over the last 20 years of real sound worksite experience and future challenges,
Fields of Improvement remain regarding :
Suitable regulatory Criteria fostering :
Circular economy in materials & waste Management among countries,
Common basis of comparison of techniques efficiency (volume reduction for instance),
Operators'common certification and training rules (to address WM&D as a growing worlwide market),
To clearly identify remaining locks and needs worldwide leading to R&D developments
Experimental and technical innovations facilitating :
international cooperation and share of experiences,
implementation of new techniques,
operators'training, tools testing, multi criteria optimisation of scenarios including Waste volume reduction,
operators'commitment as well as Public acceptance towards back-end activities,
International Official Organisations continuous Support to operators'initiatives is key to promote EU Know-how in this very competitive market...
edf

FISA 2019
EURADWASTE '19

4-7 June, 2019
Pitesti, Romania

Annex III. EURADWASTE '19 Posters

FISA 2019
EURADWASTE '19

4-7 June, 2019
Pitesti, Romania

Fusion specific approach and critical aspects in suitable industrial-scale processes and techniques for radioactive waste management of nuclear fusion power activated materials

4-7 June 2019
Pitesti, Romania
romania2019.eu
ICN Pitesti
EURADWASTE '19
9th European Commission Conference on EURATOM Research and Training in Radioactive Waste Management

RINA
ENEA Italian National Agency for New Technologies, Energy and Sustainable Economic Development

Luigi Di Pace [1], **Teresa Beone** [2], **Patrizia Miceli** [2], **Antonello Di Donato** [2], **Franco Macci** [2], **Egidio Zanin** [2]

[1] ENEA Fusion and Technology for Nuclear Safety and Security Department, Frascati (Rome), ITALY

[2] RINA Consulting - Centro Sviluppo Materiali S.p.A, Castel Romano (Rome), ITALY

Abstract

Recycling feasibility of activated materials (structural metals and breeder) generated by the operation of commercial nuclear fusion plants is one of the most debated issues concerning the demonstrability of the ecological management of fusion radioactive waste. In that respect, ENEA and RINA are engaged in a study about the possibility of applying melting techniques (consolidated in the steel-making industry) aimed at their recycling or, as an alternative, to disposal in shallow-land repositories for low-level radioactive waste (LLW).

The feasibility analysis for melting is promising, showing that is possible to define an optimum set of process conditions depending on the final destination of the material; anticipated re-use, long-term storage for recycling or disposal and that the characteristics of products and by-products can be precisely defined.

1. Fusion specific approach for radioactive waste management

The mass of radioactive material estimated to originate from nuclear fusion plants is larger than one from fission plant (per unit of electricity produced) [1].

Much less radiotoxicity for fusion and more structurally stable and chemically durable waste form for final disposal, as activated solid (metal) does not require conditioning.

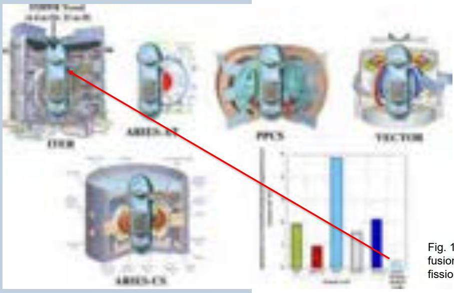


Fig. 1 Comparison between selected fusion devices and vessel of advanced fission reactor

Some treatment is often required (e.g..: decontamination, detritiation to recover tritium, cutting, compaction), generating secondary waste needing solidification.

Reprocessing of fission spent fuel generates a large share of secondary liquid waste highly radioactive, to be solidified (cementation or vitrification).

A fusion-specific, unique approach to control the volume of radwaste [2, 3] was developed at EU level since the beginning of this century. Recycling and clearance (i.e. declassification to non-radioactive material) are the two recommended options for reducing the waste amount, while disposal as a low-level waste (LLW) could be an alternative route for specific materials and components, if there were no technical/economic conditions for their pursuit.

Regulatory Route	Management Route	
	Recycling/Reuse	Disposal
Clearance (unconditional)	**Outside the nuclear industry. All final destinations are feasible (this can be after a certain decay storage time** [*this can happen within a licensed facility until specific conditions are met to allow clearance (i.e. in melting facilities to produce metal ingots)*]	**In a landfill** (for urban, special or toxic waste, depending on chemical toxicity of the waste)
Clearance (conditional)	**Within the nuclear industry and for specific applications. Materials must be subject to continuing regulatory control.** [*Examples: building concrete rubbles for base road construction or as an additive for manufacturing new concrete buildings; or metal used for making shielding blocks and containers*]	**In special industrial (and/or toxic) landfill**
No release	**Within the nuclear industry** (it can be direct reuse, or **after processing**)	**In a licensed repository for radioactive waste** (after an interim storage, if applicable)

Limit	D_R< 10 Sv/h	D_R< 2 mSv/h	DH<2000 W/m³
Handling	HOH	S-HOH	RH

Routes	Clearance	Recycling in foundries	Process to define
Limit	CI < 1	As< ~1000 Bq/g	DH< 2000 W/m³

Fig. 2 Diagram of recycling and clearance processes

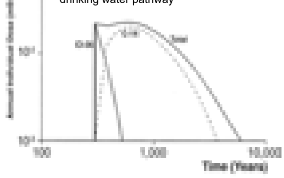
2. Decarburization to remove C-14 from Eurofer and AISI 316L

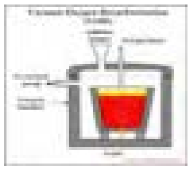
C-14 is a limiting radionuclide for waste acceptance in EU LLW repositories. In performance assessment for a reference LLW repository, it appears as a key radionuclide after few hundreds up to thousands of years, as shown in Figure 3.

	Bq/g		
Limit	Italy DIM 07-08-2015	France Repository CSA	UK (*)
H3	5,00E+06	2,00E+05	1,20E+04
C14	4,00E+02	9,20E+04	1,20E+04
Nb94	4,00E+02	1,20E+02	1,20E+04
Co60	5,00E+06	1,30E+08	1,20E+04
Mn54	5,00E+06	3,60E+08	1,20E+04
Fe55	5,00E+06	6,10E+09	1,20E+04
Ni59	4,00E+04	1,10E+05	1,20E+04
Ni63	4,00E+04	3,20E+06	1,20E+04

(*) LLW category in UK: Includes metals, soil, building rubble and organic materials, which arise principally as lightly contaminated miscellaneous waste. Metals are mostly in the form of redundant equipment. Organic materials are mainly in the form of paper towels, clothing and laboratory equipment. LLW is defined as: "radioactive waste having a radioactive content not exceeding four gigabecquerels per tonne (GBq/te) of alpha or 12 GBq/te of beta/gamma radioactivity".

Fig. 3 -Total annual dose to individuals as a function of time for a reference design of a shallow land repository: base-case scenario - drinking water pathway

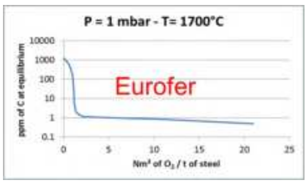


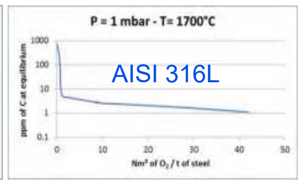


Steel decarburization is used in steelmaking for the production of Ultra Low Carbon (ULC) Steel and High Chromium Steel [4]. It is based on the reaction between C and O, dissolved in liquid steel, forming CO gas which is removed by operating under vacuum and/or with inert gas like Ar or Ni [5, 6].

Based on VOD process, a theoretical study on the decarburization process of Eurofer and AISI 316L steels was performed [7]. The assumed chemical composition of Eurofer and AISI 316L is taken from reference [8].

The initial inventory of C-14 in Eurofer reduces up to few tens of kBq/kg which is 2-3 orders < acceptance criteria for EU LLW waste repositories. For AISI 316L, it would be sufficient to reduce [C] to ~10 ppm to fully comply with those criteria and generate reduced secondary waste, similar to that for Eurofer (3% in mass).





3. Eurofer Nb behavior under severe oxidation conditions

Nb-94 is another cause of long term radioactivity in Eurofer, even if Nb is at very low concentrations (10-50 ppm). The feasibility of a severe oxidation process for removing Nb impurities, was evaluated taking into account the target value of Nb-94 activity concentration, the reduction of steel mass, and the large production of slag with separated Nb-94 (to be managed as MLW).

[Nb] reduces to ~ 5-10 times lower than the initial [Nb]. In most of the Eurofer activated components that should be enough to respect, i.e. the Italian legislation limit for LLW waste disposal in NSDF for Nb-94 (4E5 Bq/kg).

Another way to solve this issue is to control the level of Nb in the fabrication of Eurofer steel. Nb is an impurity entrained by iron.

4. Conclusions

Melting is a feasible technology to allow recycling of activated metals, but also in removing key limiting radionuclides forcing to, in case of disposal, manage them as MLW. These studies show that for each material an optimum set of recycling operating conditions can be set. The state-of-the-art of technology can be fruitfully adapted to remove C and possibly Mn. Thermodynamic constrains makes impossible the removal of Ni and Mo with this type of treatment, or large generation of slag penalizes it in case of Nb.

5. References

1. L. El-Guebaly, V. Massaut, K. Tobita, L. Cadwallader, Goals, Challenges, and Successes of Managing Fusion Activated Materials, Fusion Engineering and Design, 83 (2008) 928–935.
2. M. Zucchetti, L. El-Guebaly, R.A. Forrest, T.D. Marshall, N.P. Taylor, K. Tobita, The feasibility of recycling and clearance of active materials from a fusion power plant, J. Nucl. Mater. 367-370 (2007) 1355–1360.
3. L. El-Guebaly, Evaluation of disposal, recycling, and clearance scenarios for managing ARIES radwaste after plant decommissioning, Nucl. Fusion 47 (2007) S485–S488.
4. F. Oeters, Metallurgy of Steelmaking, Stahl Eisen.
5. L. Di Pace et al., Feasibility studies of DEMO potential waste recycling by proven existing industrial-scale processes, to be published in Fusion Engineering and Design 30th SOFT Special Issue
6. Elliott J. F., Gleiser M., Ramakrishna V., Thermochemistry for Steelmaking, Vol. II
7. ThermoCalc© Software, Royal Institute of Technology, Stockholm, Sweden
8. Reduced Activation Ferritic/Martensitic Steel Eurofer'97 as Possible Structural Material for Fusion Devices, Metallurgical Characterization on As-Received Condition and after Simulated Service Conditions, Technical Note CIEMAT, 1048, December 2004.

Predisposal of CANDU refurbishment waste

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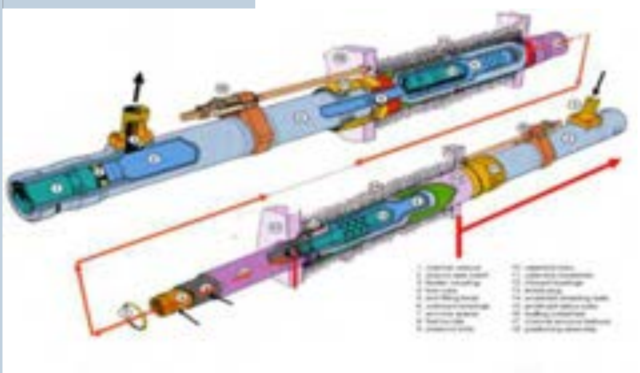
1. Refurbishment of CANDU reactors

Many CANDU reactors have been successfully refurbished until now in Canada, Korea and Argentina. In Romania, Unit 1 of Cernavoda NPP is approaching the moment of refurbishment and the owner has started preparations for this [1]. CANDU reactor refurbishment involves replacement, repair, and upgrade of several systems, structures and components throughout the power generating station. According to experience in the previous projects, the replacement of various components, defined as “retube” operation, is broken down into the five phases [2,3]:

- Retube Support operations
- Feeder Removal
- Fuel Channel Removal
- Fuel Channel Installation
- Feeder Installation

The retubing process start with removal of the Primary Heat Transport System, including sections of the feeders and the entire fuel channels including Pressure Tubes and Calandria Tubes in a defined order [4]:

- Feeders and associated fittings,
- Positioning Assemblies
- Closure and Shield Plugs
- End Fittings and associated components, and
- Pressure and Calandria Tubes



2. Refurbishment waste

There are two sources of radioactive contamination relating to the wastes removed during the retubing process:

- induced radioactivity in components due to the neutron activation processes;
- deposited radioactivity from fission radionuclides, activated contaminants and uranium atoms circulating in the reactor coolant.

For the purposes of temporary storage, the radioactive solids waste generated during "retubing / refurbishment" of NPP are sorted in the following groups [4]:

- Fuel channel components: Pressure tubes and calandria tubes, Calandria tubes inserts, End fittings and Shielding plugs, Spacer rings of fuel channels, HEPA filters used during the operation volume reduction;
- Solid wastes: Non-compactable (Feeder tubes, Hardware feeders, Plugs, Contaminated tools, Wood, Metal, Gas cylinders) and Compactable LLW-SL (paper, clothing, rags, glasses, Plastic)

The wastes containing the highest activities are pressure tubes, calandria tubes and inserts.

3. Predisposal of refurbishment waste

Predisposal management of radioactive waste, as the term is used in this Safety Requirements publication, covers all the steps in the management of radioactive waste from its generation up to disposal, including processing, storage and transport [6].

The principal approaches to the predisposal management of radioactive waste are commonly termed ‘delay and decay’, ‘concentrate and contain’ and ‘dilute and disperse’. ‘Delay and decay’ involves holding the waste in storage until the desired reduction in activity has occurred through radioactive decay of the radionuclides contained in the waste. ‘Concentrate and contain’ means reduction of volume and confinement of the radionuclide content by means of a conditioning process to prevent or substantially reduce dispersion in the environment. ‘Dilute and disperse’ means discharging effluent to the environment in such a way that environmental conditions and processes ensure that the concentrations of the radionuclides are reduced to such levels in the environment that the radiological impacts of the released material are acceptable.

In the predisposal management of radioactive waste, decisions often have to be made at a time when no disposal facility is available and the waste acceptance criteria for disposal are unknown. Consideration has to be given to whether, for the purposes of safety, the radioactive waste will be stored in a raw, a treated or a conditioned form.

The existing predisposal facilities at Cernavoda are authorized and regulated by a license issued by CNCAN to store the low and medium level radioactive wastes arising from the operation of the plant and spent fuel dry storage in DICA. A new storage facility is needed to accommodate retubing waste. In Romania there are no disposal facilities for radioactive waste arising from the operation and refurbishment of CANDU plants and no suitable acceptance criteria. Therefore, decisions on predisposal management of refurbishment waste will have to be based on the practice adopted in the countries that have implemented CANDU 6 refurbishment, as follows:

- All refurbishment waste is managed in rough state;
- High level waste, Medium level waste and Low-level waste are managed separately;
- Volume reduction is recommended to reduce storage facility size and cost;
- Appropriate shielding of packages to reduce the exposure rates and to permit handling and transportation;
- Transport to the storage site must be done without access to public roads;

The new storage facility should be designed and constructed to permit the retrieval of all the wastes generated during the retube work.

4. Conclusion

Decision on predisposal management of refurbishment waste will have to be based on the practice adopted in the countries that have implemented CANDU 6 refurbishment

5. References

[1] http://www.nuclearelectrica.ro/wp-content/uploads/2017/06/Item-2-EN-AGEA-Nota-pentru-aprobarea-Strategiei-si-Planului-de-retehnolo.._.pdf

[2] https://www.ifnec.org/ifnec/upload/docs/application/pdf/2017-03/r.o.semmoloni.life_extension_project_management.pdf

[3] http://www.isoe-network.net/publications/pub-proceedings/symposia/international-symposia/vienna-austria-october-2009/distinguished-papers-17/1316-alavi2009-pdf-1/file.html

[4]https://inis.iaea.org/collection/NCLCollectionStore/_Public/44/098/44098464.pdf

[5] http://www.jaif.or.jp/ja/wnu_si_intro/document/2010/shalaby_g3_candu.pdf

[6] IAEA SAFETY STANDARDS SERIES No. GSR Part 5

See refurbishment process video:
https://www.youtube.com/watch?v=dLgPhYIcgiU

CEA's research tools for the treatment and conditioning of radioactive waste by vitrification and high temperature processes

Contribution to the THERAMIN H2020 project

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A multidisciplinary Unit for the thermal treatment of radioactive waste

- The **Formulation Lab** designs, formulates, elaborates and characterizes glasses, glass ceramics and ceramics.
- The **Radioactive Materials Lab** determines the properties of radioactive materials using hot cells and HA glove boxes.
- The **Vitrification Processes Lab** designs and develops vitrification processes, and supports the industrial exploitation of nuclear waste vitrification.
- The **Innovating High Temperature Processes Lab** develops incineration-vitrification and plasma processes.
- The **Long Term Behavior Lab** describes and models the long term behavior of wasteforms in relation with their disposal.

Vitrification of fission product solutions

- Solutions of fission products coming from spent fuel reprocessing cannot be stored in the liquid state for a long time (acidic steam need to be cooled and agitated): **solidification** is required.
- The first ideas were to confine the fission products into a synthetic rock, such as naturally occurring silicate minerals.
- From the end of the 50s, **vitrification** has been developed with the choice of **borosilicate homogeneous glasses** in France.

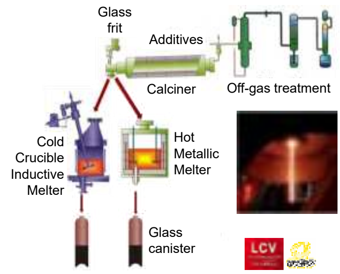
◢ Designing a glass formulation

Waste loading
Chemical compatibility with the waste

Process & Technology
Melting temperature, viscosity, reactivity, residence time, electrical conductivity

Glass performance
Thermal stability, chemical durability, resistance to self irradiation

◢ Calcination-vitrification continuous process



New sources of HL-IL waste, new processes

◢ Incineration-Vitrification process PIVIC

- **In-Can melting of a biphasic melt**
- **Plasma torches** for incineration of organic solids and **induction** technology for metal waste melting
- Full destruction of organic matter
- RNs conditioned in a mineral matrix

▶ Targeted waste

- **HLW coming from D&D operations** with poorly known compositions
- alpha bearing **ILW from MOX production**, mixing organics and metal

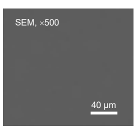
◢ In Can Melting process

- **One step** vitrification process
- **Adjustable** to poorly known waste
- Designed for **liquid** or **solid** feeding
- **Compact**, compliant with existing hot cells
- Low quantity of secondary waste
- Minimum investment and operation costs
- Container used as a crucible

Contributions to the THERAMIN project

◢ Incineration-vitrification of a mixture of absorbent media using SHIVA process

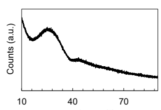
Feeds	**17% zeolites** **17% diatoms** **4% ion exchange resins** 62% Si-B-Al glass frit
Waste load	**38%** (25 kg waste, 40 kg frit)
Trial duration	24 h (3×8h feeding campaigns)

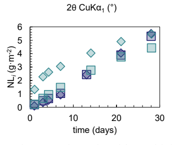


↗ The final product is a **vitreous and amorphous glass** mainly composed of Si, B, Nd, and Al.

← SHIVA is an incineration-vitrification process well suited for LILW organic and mineral waste.

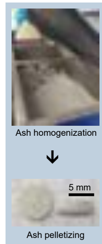
→ Leaching behaviour almost equivalent to ISG reference glass.



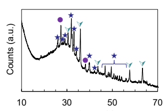


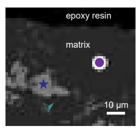
◢ In Can vitrification of ash

Feeds	**49% incineration ash** 2% bentonite (binder) 49% Si-B-Na glass frit
Waste load	**49%** (26 kg waste, 26 kg frit, ≈ 1 kg bentonite)
Trial duration	15 h

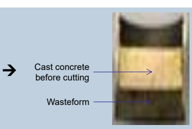


↗→ The final product is a vitreous matrix containing apatites (★), spinels (⋎), and Bi-Sn alloys (●).

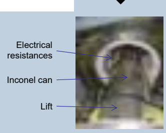




Lab-scale tests (10 g)
- Waste loading optimization
- Adjuvants selection



Bench-scale test (1 kg)
- Corrosion evaluation of the Inconel crucible
- Qualification of the behavior of the mix



In-Can trial (50 kg)
- Inconel 601 can
- T = 1100°C

4-7 June 2019
Pitesti, Romania

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EURADWASTE '19

9th European Commission Conference on EURATOM Research and Training in Radioactive Waste Management

New composite material based on heavy concrete reinforced by basalt-boron fiber for radioactive waste management

ІПБ АЕС
НАН УКРАЇНИ

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ABSTRACT

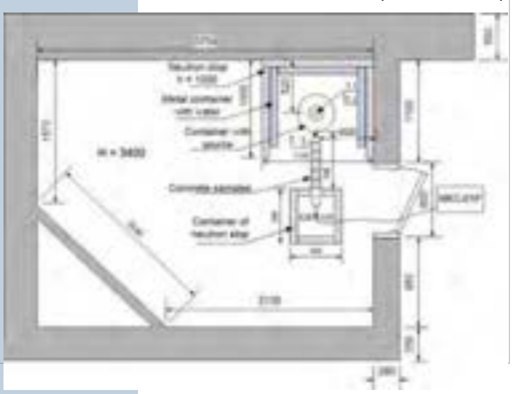
A new composite material for neutron radiation shielding properties is presented on the basis of heavy concrete with serpentinite aggregate and with basalt-boron fiber with different concentrations of fiber boron oxide, for using in biological shield in nuclear waste management applications. The protective properties of the new composite material were investigated with different neutron source, there are: 1) neutrons with 14 MeV energy; 2) fast fission neutrons for U-235; 3) fast fission neutrons for U-235 after passing a water layer. The simulation of the neutron radiation in presented composite material with adding crushed stone aggregate and serpentinite aggregate is performed with the help of the Monte Carlo Serpent code. It is shown that basalt-boron fibers in concrete are improves the protective properties of concrete from neutron irradiation for neutrons with different energies, but the most effective is the addition of a basalt-boron fiber in the case of thermal neutrons. Also, the basalt-boron fiber samples were produced at laboratory conditions. The several series of tests were carried out for prepared samples. The neutron experiment on radiation shielding properties of concrete reinforced by basalt-boron fiber was performed at Pu-Be neutron source.

BBF with various concentrations of boron oxide (6% and 12%)

Process of mixing concrete with basalt-boron fiber

Obtained samples of concrete reinforced basalt-boron fiber

Plan for premises and placement of equipment during measurement (Pu-Be source)

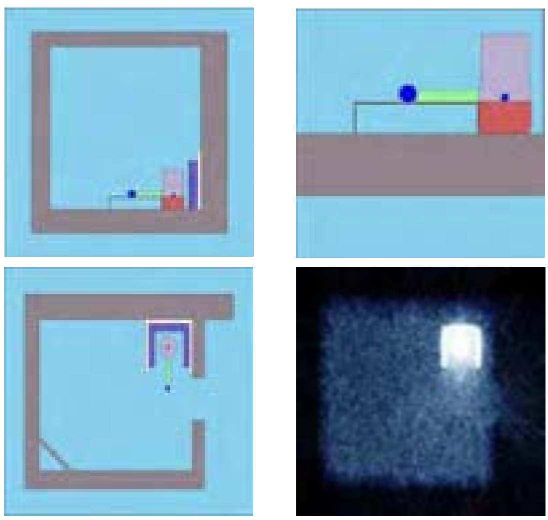


Major work performed:

- Development of methods for obtaining basalt boron fiber
- Production of samples of basalt roving and basalt boron fiber
- Testing the mechanical properties of the obtained samples of basalt boron fiber
- Tests of a new composite reinforced BBF
- Modeling of protective properties from gamma radiation, neutron radiation for various compositions of concrete with BBF
- Experimental studies of the protective properties of neutron radiation for composite concrete based on basalt boron fiber with various dosages of fiber
- Conducting micro-cracks tests in concrete reinforced by BBF
- Tests on the mechanical properties of composite concrete based on BBF with various dosages of fiber

Working points of measurement in experiment

Model in Serpent code



4-7 June 2019
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Experimental studies about disposal of radioactive wastes

ENEA

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Leaching experiments for evaluating the retention capacity of final waste forms

Leach studies are the most suitable to evaluate the retention capacity of solidified waste forms. For this reason, many efforts have been devoted to understanding basic leaching mechanisms and long-term leaching behavior. To this purpose, experiments have been made about the release of cesium from cemented boiling water reactor (BWR) evaporator concentrates (sulfates) under various experimental conditions. In particular, the variation of the following parameters has been evaluated: temperature; initial tracer concentration; leachant renewal; chemical composition of the leachant; specimen size. In addition, experiments were also carried out to assess the following influences on leaching: leachant volume; addition of an air entraining agent to the mix in order to increase the porosity of the sample; shorter curing times; different ways of carrying out the test (test under static conditions, without any leachant renewal). The leaching tests were conducted according to ANSI/ANS 16.1 standard. The main results obtained have been plotted as cumulative fractions of cesium released at increasing times (see Figures below).

The experiments demonstrate that the leaching of cesium from cemented BWR evaporator concentrates is diffusion-controlled and that many parameters among the ones tested do not influence the release of cesium at all. This is true for initial concentration of the tracer, volume of the leachant, presence of an air-entraining agent in the sample, curing time, and conditions of the test (static or dynamic). The diameter of cylindrical specimen on its own can influence the leach test only beyond a given interval of values. On the contrary, the release of the tracer is particularly influenced by a strong temperature increase and by the chemical composition of the leachant and its ionic strength. Much more influence, however, is shown by the method used to prepare the mix, which, in general, can strongly modify the final properties of cemented waste materials (mechanical strength, resistance to external agents, and so on). Consequently, the procedure followed to prepare the samples needs a careful control with the aim at obtaining reproducible data.

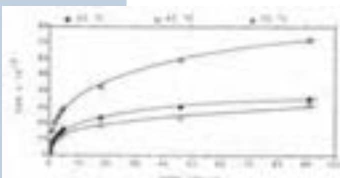


Fig. 1. Cumulative fractions of cesium released at various temperatures

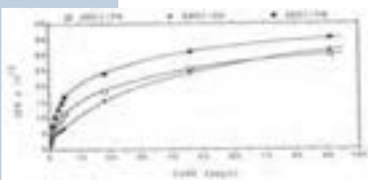


Fig. 2. Cumulative fractions of cesium released from samples immersed in different leaching waters (deionized water, DW; tap water, TW; synthetic seawater, SW)

Fig. 3. Cesium leaching from identical reference samples of pozzolanic-cemented sulfates coming from two different preparations.

Experimental studies related to disposal of low level waste (LLW) and medium level waste (MLW) in repositories at shallow depth: waste/soil interactions

The studies about waste/soil interaction show that even a very permeable soil is able to retain radionuclides usually considered highly mobile, like cesium, owing to its content of minerals capable of interacting with them. So, an accurate project design together with the choice of a suitable place and a correct monitoring program can assure a safety disposal of LLW and MLW. Some experiments have been conducted in order to determine the K_d for cesium, cobalt, and strontium, by using a very permeable soil for practical purposes. The results of the experiments are shown in Tab.1..

Cation	% of absorbed cation	Equilibration time	pH interval	K_d (ml/g)	K_d (literature data)
Co	96	2.5 days	3.2 – 4.0	—	3.2 – 3000
Sr	49	1 day	3.5 – 4.6	46	0.15 – 3300
Cs	93	2 hours	3.2 – 4.6	620	10- 52000

Tab. 1: Determination of the linear distribution coefficient

Disposal of high level wastes (HLW) in deep geological formations

Clays appear as the most suitable to dispose of HLW owing to their high confinement ability. The experimental works carried out both in situ and in laboratory scale confirm a low geochemical mobility of the main radionuclides, as well as the resistance to extreme thermal and thermomechanical stresses, together with the autosealing capacity and the mass impermeability.

Dissipation of the decay heat by high-level radioactive wastes without producing unacceptable temperatures is one of the main problems related to geological disposal. An in situ heating experiment has been carried out in a clay quarry in the area of Monterotondo (about 30 km from Rome) in order to discover the temperature field and the thermal effects caused by simulated high-level wastes emplaced in an argillaceous rock. The in situ experiment has been made by feeding an electric heater buried 6.4 m deep in a clay formation and by measuring the temperature rises in boreholes drilled between 50 and 200 cm away from the thermal source (Fig. 2). The theoretical temperature rises in the clay, calculated by means of the Belgian MPGST code, have been compared with the experimental results. The temperature rises measured in the clay agree quite well with the theoretical values and show that the clay is a homogeneous medium. The experiments demonstrated that the thermal conduction code seems sufficiently accurate to forecast the temperature rise caused by the decay heat generation in the clay and that the thermal conductivity deduced by a comparison between experimental and theoretical temperature rises ranges between 0.015 and 0.017 W.cm-1.°C-1.

Moreover, experiments made in laboratory scale by performing mineralogical and granulometric analyses on the same clay samples demonstrated that the thermal conductivity seems to rise as the percentage of clay minerals decreases and as the content of carbonate and quartz rises. The laboratory measurements brought to the conclusions (a) that the thermal conductivity along the direction perpendicular to the clay sedimentation plane is lower than the one on the sedimentation plane itself and (b) that the thermal conductivity decreases as the water content rises.

Fig. 2. Heater with assembled heating cables (*left*): borehole arrangement (distances in cm) (*middle*); location of TCs in boreholes 1, 2, and 4 (*right*)

Spent fuel alteration model integrating processes of different time-scales

Olga Riba, Emilie Coene, Orlando Silva and Lara Duro

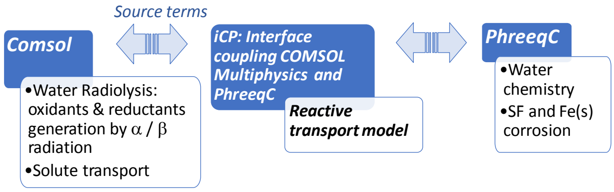
Amphos 21 Consulting S.L., Barcelona (ES)

The **DisCo European project** aims to enhance our understanding of Spent Fuel (SF) matrix dissolution under conditions representative of failed containers in reducing repository environments.

Amphos 21 has implemented a reactive transport model in iCP (interface coupling COMSOL Multiphysics and PhreeqC; Nardi et al., 2014).

Modelling approach

The integration of the different physico-chemical processes into iCP is achieved by a **two-way coupling approach** as shown in the scheme below:



The solid phase considered as SF matrix is the UO_2(am) and the thermodynamic database used is ThermoChimie v9b: https://www.thermochimie-tdb.com/pages/version.php

Kinetic reactions implemented in PhreeqC, SF and Fe corrosion

a) Generation of OH· by the decomposition reaction of H_2O_2 on the UO_2:$2H_2O$ surface according to Clarens et al. (2005)

b) Oxidation of UO_2:$2H_2O$ to UO_3(s) by OH· and O_2

c) Dissolution of UO_3(s) by H_2O and CO_3^{2-}

d) Non-oxidative dissolution of UO_2:$2H_2O$ according to Bruno et al. (1991)

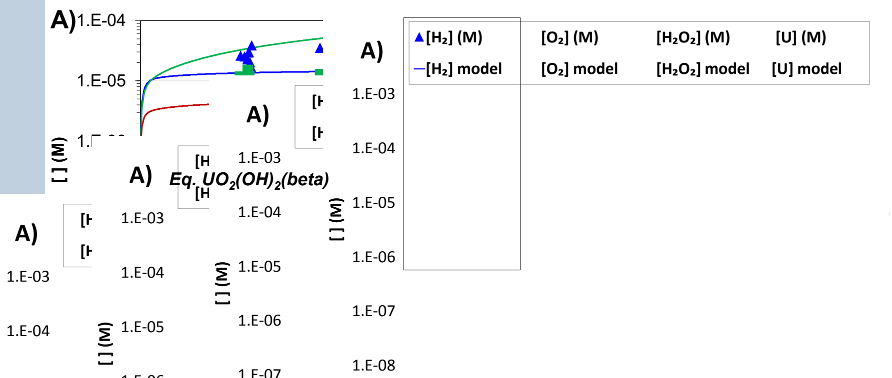
e) Activation of H_2 by Pd surface as suggested by Trummer et al. (2008)

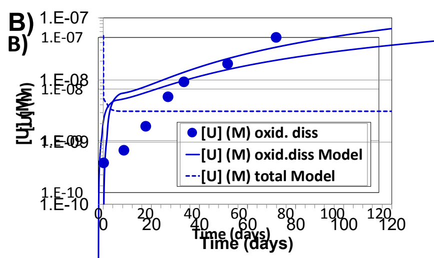
f) Reduction of UO_3(s) to UO_2:$2H_2O$ by H· according to Clarens et al. (2005)

g) Corrosion of Fe(s) to Fe^{2+} by O_2 and H_2O

Validation of kinetic constants

Validation of the kinetic constants of processes **b)**, **c)** and **f)**, occurring on the SF matrix, was performed with the experimental data found in Cera et al. (2006), also used in the MICADO European project (**Figure 1A**). The kinetic constants of process **g)** were validated with the experimental data generated in the REDUPP European project on UO_2 dissolution in natural groundwater in presence of a corroding iron strip (**Figure 1B**).





- Uniform DR = $2.86\cdot10^{-2}$ Gy·s^{-1} affecting 13μm from SF surface.
- Diffusion coefficient for all the species = 10^{-9} m^2·s^{-1}

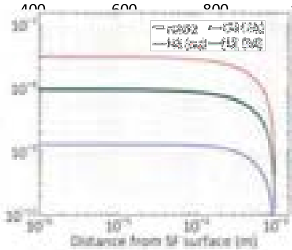


Figure 2. Simulated [H_2O_2], [O_2(aq)], [H_2(aq)] and [U] profiles after 0.1 years;

- Species generated by water radiolysis attained steady state very rapidly (in 4 hours), but [U] progressively increases, reaching a quasi-steady state concentration of [U] ~ 10^{-9} M, after 0.1 years.
- UO_2(am) dissolution rate determined with the model agrees with values considered in Performance Assessment when the inhibiting effect of H_2 on dissolution of SF is taken into account (10^{-7} y^{-1})

Future Work

- Extending the model to: i) include heterogeneity of the SF matrix to account for different concentrations of epsilon particles (Pd); ii) consider SF as a porous medium (porosity changes due to precipitation of secondary phases in the SF).

The research leading to these results has received funding from the European Commission Horizon 2020 Research and Training Programme of the European Atomic Energy Community (EURATOM) (H2020-NFRP-2016-2017-1) under grant agreement n° 755443 (DisCo project).

References

- Nardi et al. (2014). Interface COMSOL-PHREEQC (iCP), an efficient numerical framework for the solution of coupled multiphysics and geochemistry. Computers & Geosciences 69: 10-21.
- Clarens et al. (2005). The oxidative dissolution of unirradiated UO_2 by hydrogen peroxide as a function of pH. Journal of Nuclear Materials, 345(2-3), 225-231.
- Trummer et al. (2008). On the effects of fission product noble metal inclusions on the kinetics of radiation induced dissolution of spent nuclear fuel. Journal of Nuclear Materials, 378(1), 55-59.
- Bruno et al. (1991). The kinetics of dissolution of UO_2 under reducing conditions and the influence of an oxidized surface layer (UO_{2+x}): Application of a continuous flow-through reactor. Geochimica et Cosmochimica Acta, 55(3), 647-658.
- Cera et al. (2006). Experimental determination and chemical modelling of radiolytic processes at the spent fuel/water interface. SKB TR 06-07, Svensk Kärnbränslehantering AB.

CHEMISTRY OF BERYLLIUM IN CEMENTITIOUS SYSTEMS STUDIED WITHIN CEBAMA: SOLUBILITY, HYDROLYSIS, CARBONATE COMPLEXATION AND SORPTION

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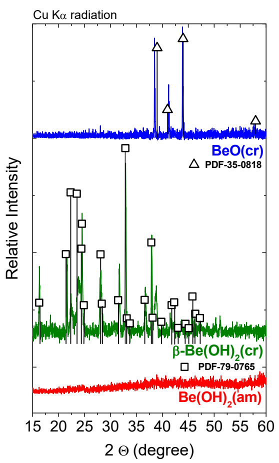
Introduction

Within WP2 of Cebama, the retention of Beryllium on cement-based materials was studied. Beryllium is a chemotoxic element expected in specific waste forms to be disposed of in repositories for radioactive waste [1]. Very limited information on the behaviour of Be(II) in alkaline cementitious systems was previously reported in the literature [2-3]. In this study, the solution chemistry of Be(II) was investigated in a comprehensive series of solubility and sorption experiments with focus on alkaline pH conditions and cementitious systems. All experiments were performed at KIT–INE. Based upon these studies, an improved understanding and quantitative description of Be retention processes in cementitious environments is developed. This provides important new inputs for the assessment of Be in the Safety Case, also providing input to modeling studies in WP3 of Cebama.

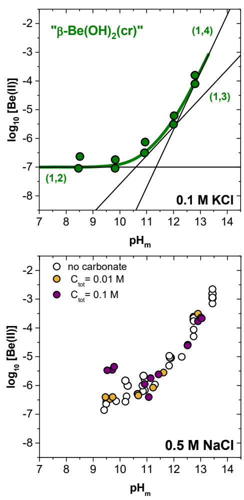
Solubility experiments

Solubility experiments are performed in Ar-gloveboxes using BeO(cr) and $Be(OH)_2$(s). Solubility is investigated in dilute to concetrated NaCl (5 ≤ pH_m ≤ 14.5), KCl (9 ≤ pH_m ≤ 14.3) and $CaCl_2$ solutions (9 ≤ pH_m ≤ 12). The effect of carbonate on solubility is investigated for 9 ≤ pH_m ≤ 13 and C_{tot} = $[HCO_3^-] + [CO_3^{2-}]$ = 0.01–0.4 M. Extensive solid phase characterization is conducted after finalizing solubility experiments.

Solid phase characterization



Solubility experiments



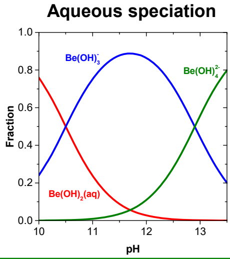
β-$Be(OH)_2$(cr) controls the solubility of Be(II) in alkaline systems. Solubility data confirms the amphoteric character of Be(II) with a solubility minimum at pH_m ≈ 9. The anionic species **$Be(OH)_3^-$ and $Be(OH)_4^{2-}$** dominate the aqueous speciation of Be(II) in cementitious systems (pH = 10–13.5). Experiments conducted with carbonate reveal a minor impact of this ligand in the solution chemistry of Be(II) in cementitious systems.

Thermodynamics and model calculations

The combination of solubility data determined in this work, slope analysis and solid phase characterization allows deriving comprehensive chemical, thermodynamic and (SIT) activity models for the system **Be^{2+}–Na^+–K^+–Ca^{2+}–H^+–Cl^-–OH^-–H_2O(l)**.

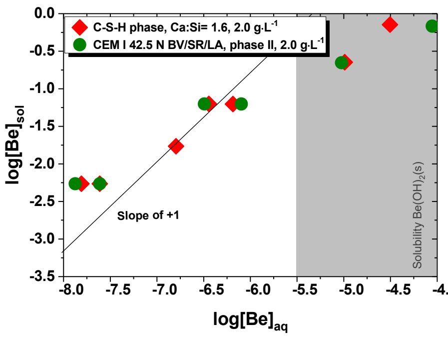
These models provide key information on the aqueous speciation of Be(II) in cementitious systems.

Aqueous speciation



Sorption experiments

Sorption experiments with cementitious materials are performed with solid-to-liquid ratios of 0.2–50 g/L and 10^{-6} M ≤ $[Be(II)]_0$ ≤ $10^{-2.5}$ M, considering the solubility limit of β-$Be(OH)_2$(cr) at the investigated pH conditions. The following materials are studied:
- "Low pH" cement, Cebama cement paste (CEM I 42.5 MH/SR/LA type)
- Ordinary Portland cement, CEM I 42.5N BV/SR/LA type (degradation phase I and II)
- C-S-H phases (Ca/Si: 0.6, 1.0 ans 1.6) (prepared by BRGM)



Sorption experiments with cement and C-S-H phases show a strong uptake of Be(II) by cementitious materials (**$\log_{10} R_d$ ≈ 3.5–5.5**). Relatively **slow sorption kinetics** are observed (sorption equilibrium achieved > 10 days), suggesting that additional processes beyond surface complexation might be involved in the uptake of Be(II) (***e.g.* incorporation**).

Summary and conclusions

This study provides valuable inputs for the safety assessment of repositories for the disposal of radioactive waste: (i) contributing to geochemical calculations under boundary conditions of relevance in the context of waste disposal; (ii) providing upper concentration limits for Be(II) based on solubility phenomena for source term estimations and; (iii) providing an extensive set of sorption values (as $\log_{10} R_d$) for a broad range of cement materials, degradation stages of cement and model compounds.

The research leading to these results has received funding from the European Union's European Atomic Energy Community's (Euratom) Horizon 2020 Programme (NFRP-2014/2015) under grant agreement, 662147 – Cebama.

References:

[1] Wilson, J. C., Thorne, M. C., Towler, G., Norris, S. (2011). Illustrative assessment of human health issues arising from the potential release of chemotoxic substances from a generic geological disposal facility for radioactive waste, Journal of Radiological Protection, 31, 411.
[2] Bruno, J. (1987), "Beryllium(II) hydrolysis in 3.0 mol dm–3 perchlorate", J. Chem. Soc. Dalton Trans., 2431–2437
[3] Wieland, E., Van Loon, L. R. 2003, Cementitious near-field sorption database for performance assessment of an ILW repository in opalinus clay. PSI report 03-06.

4-7 June 2019 Pitesti, Romania

EURADWASTE '19

9th European Commission Conference on EURATOM Research and Training in Radioactive Waste Management

Benchmark of reactive transport models within CEBAMA Application to a concrete / clay interface

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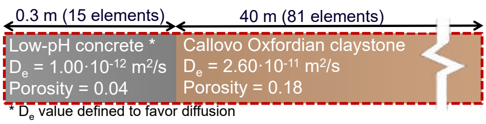
Introduction and objectives

A benchmark modelling study of interactions between low-pH concrete and clay rock is presented here, conducted within the framework of the EC Horizon 2020 CEBAMA [1]. The concrete composition corresponds to the reference low-pH concrete manufactured and characterized in CEBAMA as an experimental benchmark [2]. Different modelling approaches were used for modelling and interpretation of experimental data generated within CEBAMA, with focus on reactive transport processes that can impact the physical properties of cementitious materials and their interface with clayey systems. Model and experimental results were satisfactorily compared [3]. A common modelling task was conducted to build confidence in the consistency of the different modelling approaches. The work aimed at benchmarking the capabilities of reactive transport codes to simulate physical and chemical processes governing long-term interactions at the concrete-clay interface. The benchmark also considered a set of sensitivity cases to test the effect of key parameters on the results. The main outcomes of the collaborative study are described in detail in [4] and presented here.

Methodology and description 1D reactive transport model setup

The studied system considers a generic concrete structure in contact with a clayey host rock under isothermal (25ºC) and saturated conditions. Solute transport by Fickian diffusion and a simulation time of 100 kyr is considered. Several models of increasing complexity have been implemented and simulated, including a set of sensitivity cases.



* D_e value defined to favor diffusion

Partner	Modelling tool
AMPHOS 21 (A21)	iCP
KIT	iCP
JUELICH	OGS (OpenGeoSys-GEM)
PSI	OGS
NRG	ORCHESTRA
UDC	CORE2D
ANDRA	MIN3P

ID	Description of simulation cases
P1	Preliminary 1: diffusion of a tracer from concrete into the clay rock
P2	Preliminary 2: diffusion, cation exchange and aqueous speciation reactions
P3	Preliminary 3: idem case P2, and adding mineral reactions in equilibrium
FRC	Full Reference Case: full chemical description, including kinetics
S1	Sensitivity 1: different porosity-diffusion couplings considered
S2	Sensitivity 2: effective diffusivity of concrete reduced by 1 order of magnitude
S3	Sensitivity 3: electrochemical coupling (i.e. Nernst-Planck equations)
S4	Sensitivity 4: use of a different thermodynamic database (TDB)

Processes	P1	P2	P3	FRC	S1	S2	S3	S4
Tracer diffusion	×	×	×	×	×	×	×	×
Aqueous species + cation exchange		×	×	×	×	×	×	×
Minerals in equilibrium			×	×	×	×	×	×
Reaction kinetics				×	×	×	×	×
Chemical/Porosity couplings					×			
Lower diffusion coefficient in concrete						×		
Multicomponent diffusion							×	
Use of different TDB								×

Results

As an example, results of the FRC are presented and compared to the case P3 in terms of mineralogical evolution of the system (Fig. 1), as well as pH and porosity changes (Fig. 2) after 100,000 years of interaction. Very good agreement is observed between the different reactive transport models and between the FRC and P3 cases (differing in the incorporation or not of kinetically-controlled mineral reactions).

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Results - continued

Concrete degrades significantly over half of its thickness, with substantial dissolution of C-S-H, decreasing pH, and increasing porosity. Precipitation of calcite and brucite clogs the concrete porosity close to the interface. The high-pH plume into the claystone is negligible, also shown by the negligible dissolution of montmorillonite.

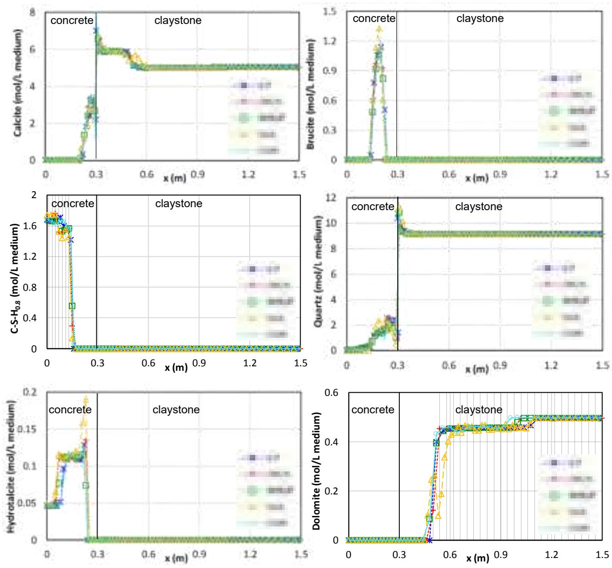

Fig. 1. Results comparison: mineral phases (in mol/L medium) in the concrete and clay domains at 100,000 years obtained with iCP, ORCHESTRA, and MIN3P for the FRC, and OGS and CORE for case P3.

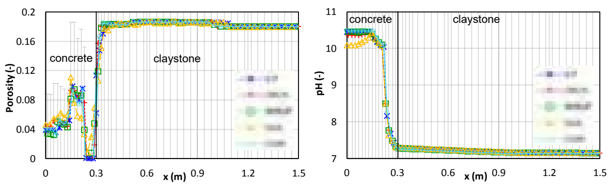

Fig. 2. Results comparison: pH and porosity profiles in concrete and clay at 100,000 years (iCP, ORCHESTRA, MIN3P: FRC / OGS, CORE: P3).

Conclusions

Within the CEBAMA project, the common modelling task has served to build confidence on the representation of cement-clay complex systems with reactive transport modelling tools when simulating the long-term behaviour of low-pH cementitious systems interfaced with a clayey host rock. The impacts of key parameters, such as diffusion coefficients, thermodynamic data or couplings between geochemical and transport parameters, have also been assessed.

The results show not only the high level of understanding of the governing processes but also the good agreement obtained with different codes, which is essential to demonstrate the applicability of reactive transport modelling to support the safety assessments.

References

[1] Altmaier M, et al. (2017). Proc. 1st Annual Workshop of the HORIZON 2020 CEBAMA Project. KIT-SR 7734, Karlsruhe, Germany.
[2] Vehmas T et al. (2018). Cebama reference mix design for low pH concrete and paste, preliminary investigations. In: Proc. 2nd Annual Workshop of CEBAMA Project. KIT scientific report (in press).
[3] Idiart A (Editor). Deliverable D3.06: Final results and interpretation of the modelling of experiments within CEBAMA. CEBAMA Project, p. 94.
[4] Idiart A, Laviña M (Editors). Deliverable D3.07: Final results and main outcomes of the Modelling Task. CEBAMA Project, p. 34.

Acknowledgement: The research leading to these results has received funding from the European Union's European Atomic Energy Community's Horizon 2020 Programme (NFRP-2014/2015) under grant agreement, 662147 - Cebama

4-7 June 2019 Pitesti, Romania

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Microbial degradation of organics and nitrate leaching from bituminized radioactive waste at high pH

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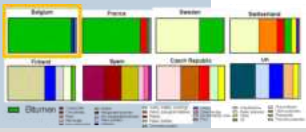
Introduction

Several countries have to deal with significant amounts of bituminized long-lived low- and intermediate level (LILW-LL) radioactive waste. In the MIND project, the Belgian disposal concept with Boom Clay as reference host rock and Eurobitum bituminized waste were selected to be studied in more detail.

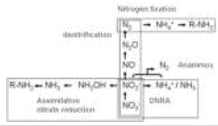


Relative amount of organics present in LILW-LL radioactive waste in European countries involved in the MIND project.

Geological disposal of nitrate-containing bituminized radioactive waste will leach large amounts of $NaNO_3$ and soluble organic bitumen degradation products, what could initiate several geochemical and biochemical processes in the clay and potentially affect the barrier function of the host rock.

Schematic overview of the composition of Eurobitum bituminized LILW-LL radioactive waste.

Such processes can additionally impact the microbial community present in the repository. Furthermore, microbial reduction of nitrate leads to the intermediate production of nitrite, and finally to nitrogen gases. However, high pH conditions present during geological disposal could hamper microbial nitrate reduction.



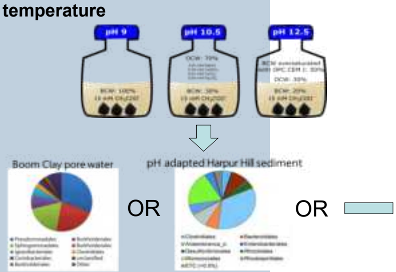
Different biological pathways involved in the anoxic reduction of nitrate.

Objectives

To investigate the potential of the microbial community present in Boom Clay borehole water and in Harpur Hill sediment (a natural analogue to a cementitious geological disposal facility), to reduce nitrate leaching from thermally aged inactive bituminized waste supplemented with acetate at different pH. pH 12,5 represent conditions within the disposal gallery, pH 10,5 reflects conditions at the interface between the gallery lining and the host formation and pH 9 represent conditions few meters within the host rock.

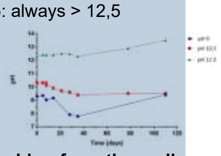
Methods & Results

Anoxic batch experiments at room temperature

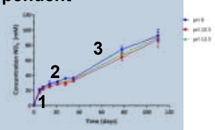


Evolution of pH in sterile conditions

- pH 9 & 10,5: small drop in pH probably due to $CaCO_3$ precipitation, re-increase at pH 9?
- pH 12,5: always > 12,5



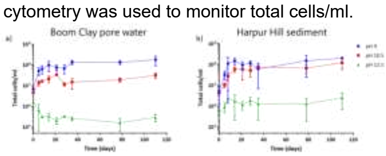
$NaNO_3$ leaching from thermally aged inactive Eurobitumen under free swelling conditions is pH independent



1. Fast leaching pores close to the surface
2. Slower leaching from deeper layers
3. Re-increase due to formation of interconnecting pores & cracks

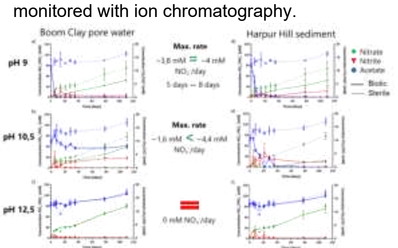
Total cells/ml in Harpur Hill sediment higher at increased pH

Sybr Green I staining combined with flow cytometry was used to monitor total cells/ml.



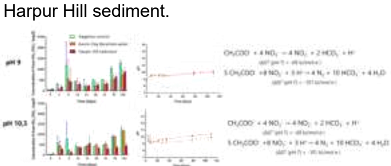
More nitrate removal by the Harpur Hill sediment at higher pH

Nitrate, nitrite and acetate concentrations were monitored with ion chromatography.

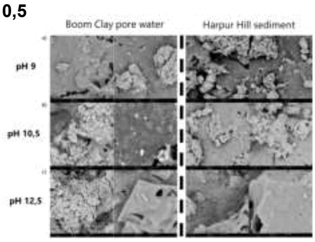


Different reactions occurred at pH 10,5

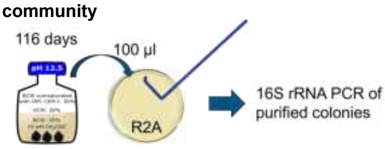
pH 9: both communities carry out full denitrification. pH 10,5: full denitrification only by Harpur Hill sediment.



Biofilm formation on Eurobitum at pH 9 and pH 10,5



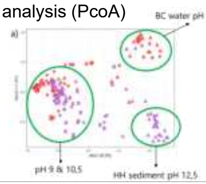
pH 12,5 does not eliminate the microbial community



Bacillus species and *Paenibacillus* species identified in respectively Boom Clay borehole water and Harpur Hill sediment.

PcoA analysis indicate that diverse populations are enriched at pH 12,5

Flow cytometry profiles were used to calculate β-diversity between all samples with principal component analysis (PcoA)



Conclusions

Microbial nitrate reduction was possible up to pH 10.5, reflecting conditions at the interface of the Boom Clay and the concrete liner of the disposal gallery. Contrary, pH conditions that are expected in the disposal gallery seem to inhibit microbial nitrate reduction. Nevertheless, microbial presence was not eliminated in thoseconditions, hence if niches arise with local pH decrease, microbial nitrate reduction can be induced.

Acknowledgements:

The authors want to thank Prof. Jonathon Lloyd from the University of Manchester for providing the Harpur Hill sediment. The MIND-project has received funding from the European Union's Euratom research and training program (Horizon2020) under grant agreement 661880 The MIND-project

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ESTIMATION OF ^{14}C RELEASE AND MIGRATION FROM RBMK-1500 REACTOR GRAPHITE DISPOSED OF IN A POTENTIAL GEOLOGICAL REPOSITORY IN CRYSTALLINE ROCKS IN LITHUANIA

LITHUANIAN ENERGY INSTITUTE

Dalia Grigaliūnienė, Povilas Poškas, Raimondas Kilda, Ernestas Narkūnas

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Main research directions:

- Development of energy economy planning methods, investigation of safety and reliability of the power plants, their impact on the environment, efficient energy consumption and the renewable energy sources;
- Investigations in the fields of thermal physics, fluid mechanics and metrology;
- Simulation of complex systems, development of their control methods and technologies;
- Investigation of energy systems' construction elements aging and development of new multifunctional materials;
- Investigations of combustion and plasma processes in the fields of fuel saving, reduction of environmental pollution and thermal decontamination of materials.

Nuclear Engineering Laboratory

Main research areas:

- Safety of spent nuclear fuel management: modelling of fuel characteristics, safety and environmental impact assessment of storage and disposal facilities, normative and legislative base;
- Safety of radioactive waste management: strategy, safety and environmental impact assessments of treatment, storage and disposal facilities, normative and legislative base;
- Evaluation of different factors related to decommissioning of nuclear power plants: planning and cost estimation of decommissioning and dismantling, radiological characterisation of buildings, systems and facilities, safety and environmental impact assessment, normative and legislative base;
- Fire hazard analysis in nuclear power plants and other facilities;
- Research related to the construction of new nuclear power plant in Lithuania;
- Heat transfer and hydrodynamics investigations for nuclear and non-nuclear applications.

The research presented in this poster was performed within the frame of European Project CAST and co-funded by Lithuanian Agency for Science, Innovation and Technology (MITA).

CAST – a European Project launched in October 2013 under the 7th EURATOM Framework Programme (FP7-604779) addressing the "CArbon-14 Source Term (CAST)" and terminated in March 2018.

The aim of this Project was the development of understanding of the generation and release of C-14 from radioactive waste materials under conditions relevant to waste packaging and disposal to underground geological disposal facilities.

1. Introduction

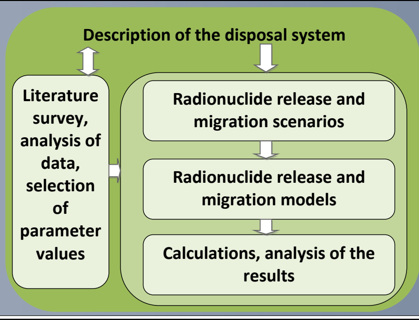
During operation and decommissioning of graphite moderator reactors large quantities of irradiated graphite are generated. The management and disposal of this waste is still an open issue. One of the key radionuclides in irradiated graphite is ^{14}C because of its long half-life and role in biological processes. The EC Project CAST aimed to develop understanding of the potential release mechanisms of ^{14}C from irradiated graphite under conditions relevant to underground geological disposal facilities.

Lithuania has two units with RBMK-1500 type reactors at the Ignalina nuclear power plant (NPP), where graphite was used as a neutron moderator and reflector. These reactors are under decommissioning now and Lithuania face a challenge of management of the large amount of irradiated graphite. Due to high ^{14}C activity it cannot be disposed of in a near surface repository; therefore a deep geological repository is considered as an option.

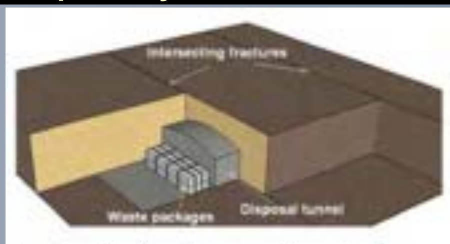
The outcomes of the investigations performed under the Project CAST and information gathered from the research carried out under national UK, French programs was integrated in the context of the safety assessment with the aim to:

- estimate potential ^{14}C release from irradiated graphite generated at Ignalina NPP;
- estimate ^{14}C migration through the engineered barriers;
- compare the results with the previous assessments;
- identify potential areas for conservatism reduction.

2. Methodology



3. Disposal system



Scheme of the disposal tunnel and intersecting fractures

4. Scenario

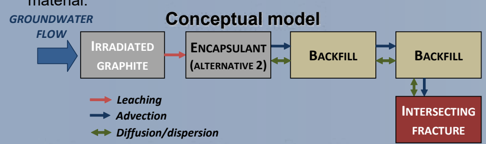
Normal evolution scenario:

- post-closure period;
- ^{14}C leaching from i-graphite; and
- transfer with the groundwater through the engineered barriers up to the intersecting fracture.

5. Conceptual and mathematical models

Two Alternatives analyzed:

- Alternative 1 – disposal of non-encapsulated waste;
- Alternative 2 – disposal of waste encapsulated in cement based material.



Mathematical model for transfer with groundwater

$$\frac{\partial}{\partial t}(\theta R C) = \frac{\partial}{\partial x}\left(\theta D \frac{\partial C}{\partial x}\right) - \frac{\partial}{\partial x}(qC) - \lambda \theta R C$$

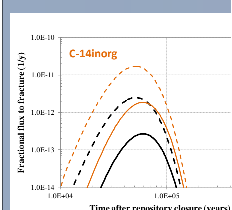
where C is ^{14}C concentration in water (Bq/m^3), θ - effective porosity (-), R - retardation coefficient (-), D - diffusion-dispersion coefficient (m^2/s), q - water flow rate (m/s), λ - radioactive decay constant (1/s), x - distance in the direction of water flow (m), t - time (s)

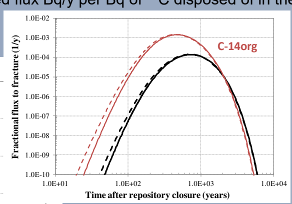
Parameter values updated based on information from CAST

Parameter	Before CAST	Based on CAST information
Inventory	Based on conservative modelling.	Based on updated modelling and experimental results.
Releasable fraction (f, -)	1	0.3
Rapid release fraction (f_r, -)	0 to 1	2E-04 (0 – 2E-03)
Rapid release rate (1/y)	0.1 (for 10 y) to instant	Instant.
Long-term (slower) release fraction (f_s, -)	1-f_r	f-f_r
Long-term (slower) release rate (1/y)	1E-03 (1.83E-05 – 0.1)	1E-02 (1E-03 – 0.1)
Organic ^{14}C fraction (-)	0 or 1	0.5 (0.2 – 0.8)
^{14}C sorption in cement (m^3/kg)	Inorganic: 0.2; Organic: 0.	Inorganic: 0.2 (0.02 – 2); Organic: 0 (0 – 1E-04).

6. Results

Base case. The effect of incorporation of the findings from the CAST Project in ^{14}C migration modelling is evaluated by comparison of fractional ^{14}C flux to the fracture (estimated flux Bq/y per Bq of ^{14}C disposed of in the repository) using best-estimate values.

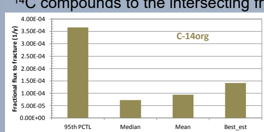


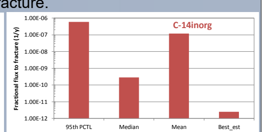


Dashed line – Alternative 1, solid line – Alternative 2; Colored lines – before CAST, black line – after integration of CAST information

The maximal fractional flux into the fracture estimated using the most recent information from the CAST Project is lower by about one order of magnitude. However, the information obtained during the CAST Project was for other types of graphite; therefore, investigations into RBMK-1500 graphite are needed.

Uncertainty analysis. Maximal fractional flux of organic and inorganic ^{14}C compounds to the intersecting fracture.





Difference between the median value and the 95th percentile for organic ^{14}C – factor of 5; between the best estimate value and the 95th percentile for inorganic ^{14}C – several orders of magnitude (main reason – uncertainties in sorption).

7. Conclusions

- Incorporation of the CAST Project information into ^{14}C migration model indicates that estimated flux from the near field can be reduced up to one order of magnitude; however, for confidence building investigations into RBMK-1500 graphite are needed.
- Additional investigations in partitioning of released ^{14}C between organic and inorganic compounds and their sorption on cement could significantly reduce the range of uncertainties.

EURADWASTE '19
9th European Commission Conference on EURATOM Research and Training in Radioactive Waste Management
4-7 June 2019 Pitesti, Romania

PRELIMINARY INVENTORY OF C-14 IN IRRADIATED GRAPHITE OF IGNALINA NPP UNIT 1 RBMK-1500 REACTOR

LITHUANIAN ENERGY INSTITUTE

Ernestas Narkūnas, Artūras Šmaižys, Povilas Poškas

Lithuanian Energy Institute, Nuclear Engineering Laboratory, Breslaujos str. 3, LT-44403 Kaunas, Lithuania

Main research directions:

- Development of energy economy planning methods, investigation of safety and reliability of the power plants, their impact on the environment, efficient energy consumption and the renewable energy sources;
- Investigations in the fields of thermal physics, fluid mechanics and metrology;
- Simulation of complex systems, development of their control methods and technologies;
- Investigation of energy systems' construction elements aging and development of new multifunctional materials;
- Investigations of combustion and plasma processes in the fields of fuel saving, reduction of environmental pollution and thermal decontamination of materials.

Nuclear Engineering Laboratory

Main research areas:

- Safety of spent nuclear fuel management: modelling of fuel characteristics, safety and environmental impact assessment of storage and disposal facilities, normative and legislative base;
- Safety of radioactive waste management: strategy, safety and environmental impact assessments of treatment, storage and disposal facilities, normative and legislative base;
- Evaluation of different factors related to decommissioning of nuclear power plants: planning and cost estimation of decommissioning and dismantling, radiological characterisation of buildings, systems and facilities, safety and environmental impact assessment, normative and legislative base;
- Fire hazard analysis in nuclear power plants and other facilities;
- Research related to the construction of new nuclear power plant in Lithuania;
- Heat transfer and hydrodynamics investigations for nuclear and non-nuclear applications.

The research presented in this poster was performed within the frame of European Project CAST and co-funded by Lithuanian Agency for Science, Innovation and Technology (MITA).

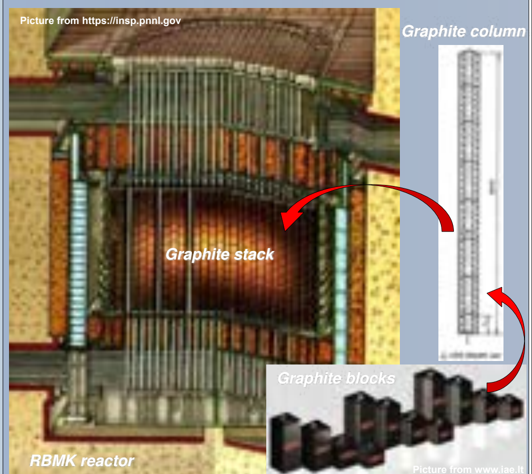
CAST – a European Project launched in October 2013 under the 7th EURATOM Framework Programme (FP7-604779) addressing the "CArbon-14 Source Term (CAST)" and terminated in March 2018.

The aim of this Project was the development of understanding of the generation and release of C-14 from radioactive waste materials under conditions relevant to waste packaging and disposal to underground geological disposal facilities.

1. Introduction

Ignalina NPP contains two Units with RBMK-1500 reactors. After shutdown, several Unit 1 systems and equipment were radiologically characterized and dismantled. The highest volume of reactor structures is attributed to the graphite stack of the reactor core, radiological characterization of which was not performed before the CAST Project.

Earlier studies revealed that the radiological inventory of irradiated RBMK-1500 reactor graphite could be dominated by the radionuclide C-14, however estimations were based on conservative assumptions and lacked experimental activity measurement data. Therefore, within the EC 7th FP project CAST, one of the tasks was to estimate C-14 inventory based on a combination of available radionuclide activity measurements and full 3D reactor graphite stack neutron activation modelling.

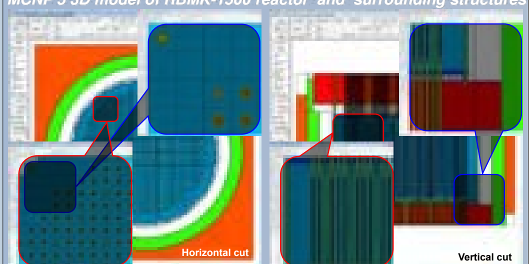


The stack of RBMK-1500 reactor can be visualized as a vertical cylinder 8 m high and 14 m diameter, made up of 2488 columns where each column is made up from several graphite blocks. The total mass of the graphite stack blocks is about 1700 tonnes.

2. Methodology

The spatial and energy distribution modelling of the neutron flux in the stack was performed using MCNP 5 ver. 1.6 code. Neutron activation modelling was performed using ORIGEN-S computer code employing COUPLE code (codes from the SCALE 6.1 codes system) for the preparation of the problem specific weighted cross-sections.

MCNP 5 3D model of RBMK-1500 reactor and surrounding structures

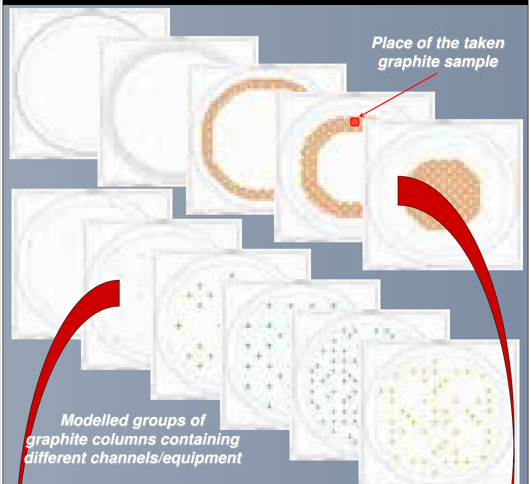


Using these newly developed numerical models, activity distribution of C-14 within the whole reactor graphite stack was obtained assuming maximal initial impurities content (as a conservative case).

Then, knowing the experimental value of measured C-14 activity in specific place of the graphite stack, the 'explanatory' concentration of nitrogen impurity in graphite was derived by reverse activation modelling at that specific measurement place. This was achieved by altering the concentration of an nitrogen impurity, whose activation leads to the generation of C-14, until the modelled activity of C-14 matched the measured one.

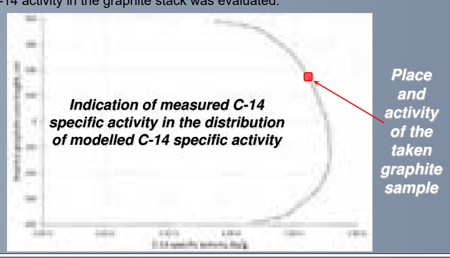
Finally, by employing the derived 'explanatory' concentration of nitrogen impurity, neutron activation modelling was performed once again and C-14 inventory in the whole graphite stack was obtained.

3. Results



A preliminary study to estimate experimental C-14 activity in several graphite sub-samples of the GR-280 grade graphite bushing from the temperature channel of the Ignalina NPP Unit 1 RBMK-1500 reactor revealed that the average value of C-14 specific activity in this graphite sample was 1.67E+05 Bq/g (study performed by Ignalina NPP and Nature Research Centre staff, Lithuania).

By having the modelled distributions of the specific C-14 activity in each group of the graphite columns (obtained by using explanatory nitrogen impurity content) and by applying quantities and masses of the graphite columns in the respective group, the integral C-14 activity in the graphite stack was evaluated.



4. Conclusions

Obtained results for the Ignalina NPP Unit 1 reactor show that, based on the combination of modelling and measurement techniques:

- ✓ 'Explanatory' nitrogen content in GR-280 grade graphite is ~50 ppm;
- ✓ Total inventory of C-14 in the graphite stack is ~3.22E+14 Bq;
- ✓ Average C-14 specific activity in the graphite stack is ~1.9E+05 Bq/g.

NOTE: These numbers are only for the reactor RBMK-1500 graphite stack consisting of GR-280 grade graphite blocks and are based on measurements of only one sample.

Chromium doped UO_2-based Model Systems: Model Materials for the Study of the Matrix Corrosion of Modern Spent Nuclear Fuels

4-7 June 2019, Pitesti, Romania
EURADWASTE '19
9th European Commission Conference on EURATOM Research and Training in Radioactive Waste Management

DisCo

Kegler, P.[1], Klinkenberg, M.[1], Bukaemskiy, A.[1], Deissmann, G.[1], Bosbach, D.[1], Alekseev E.V.[1], Delville, R.[2], Cachoir, C.[2], Mennecart, T.[2], Lemmens, K.[2], Verwerft, M.[2]

[1]Forschungszentrum Jülich GmbH, Institute of Energy and Climate Research - Nuclear Waste Management and Reactor Safety (IEK-6), 52428 Jülich, Germany

[2]Belgian Nuclear Research Centre, BE-2400 Mol, Belgium

Introduction

Within the EU-DisCo project (www.disco-h2020.eu) experiments on irradiated Cr-doped nuclear fuels are complemented with systematic dissolution studies carried out with carefully prepared and characterised, simplified UO_2-based model materials to understand the corrosion behaviour of modern Cr- and Al-doped spent nuclear fuel (SNF) in a geological disposal facility. A bottom-up approach is followed to understand how the addition of Cr-oxide into the fuel matrix affects the dissolution behaviour.

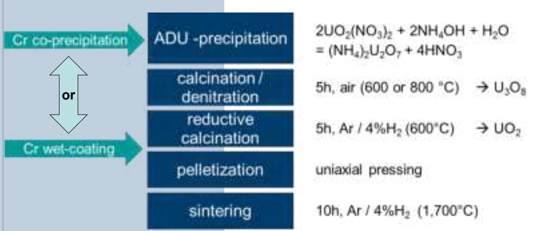
Here we present recent results on the development and optimisation of the process steps for a wet-chemical route to produce pure reference UO_2, Cr-doped UO_2, as well as Cr- and ^{238}Pu-doped UO_2 materials for dissolution studies, where the alpha-doped materials mimic the alpha-radiation field of aged SNF with ages between 1,000 and 10,000 years.

Requirements and challenges

- Fabrication of pellets for dissolution studies
- Target density of pellets ~ 95% of theoretical density (industry standard)
- Control on microstructure (grain size, fabric …)
- Eschewal of milling/grinding steps to minimise dust generation and carry-over of Pu
- Homogeneous dopant (^{238}Pu) distribution
- Avoidance of lubricants and sintering aids

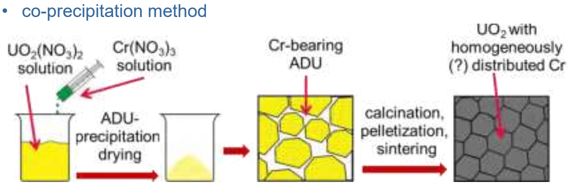
➢ Development and optimisation of a wet-chemical synthesis route

Production route for model materials

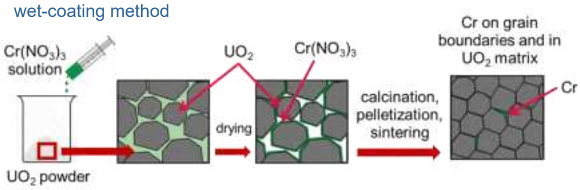


Alternative methods for Cr-doping

- co-precipitation method



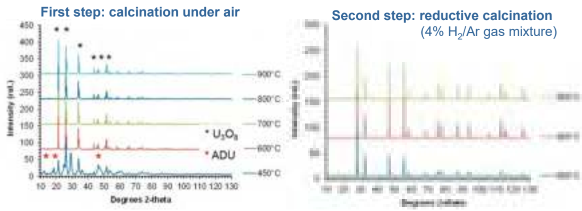
- wet-coating method



This project has received funding from the European Union's Horizon 2020 research and training programme of the European Atomic Energy Community (EURATOM) (H2020-NFRP2016/2017) under grant agreement n° 755443 (DisCo).

Systematic optimisation of various process steps and parameters

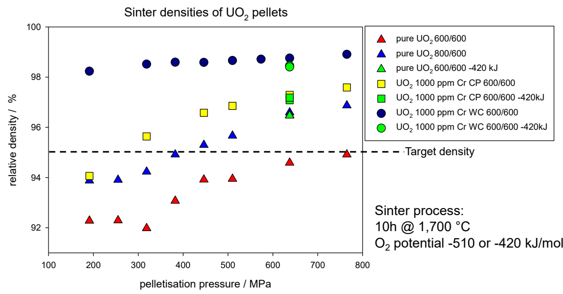
- **Calcination**



XRD-investigations of powders after stepwise calcination:

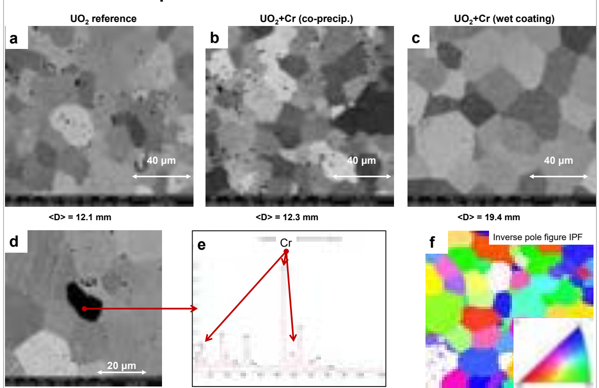
➢ Complete conversion of ADU to U_3O_8 at $T \geq 600$ °C
➢ Complete conversion of U_3O_8 to UO_2 at all tested temperatures

- **Pelletisation and sintering**



➢ Density of sintered pellets depends on pressure during pelletisation and temperatures during calcination steps

Microstructure of pellets



SEM/EDS and EBSD investigations:

➢ Cr co-precipitation → grain size similar to UO_2 reference (a, b)
➢ Cr wet-coating → significant increase in grain size (c)
➢ Co-precipitation method results in large Cr grains on grain boundaries and in pores (d, e)
➢ EBSD mapping shows no preferential orientation of UO_2 grains (f)

Conclusions

➢ Wet chemical route for production of Cr-doped UO_2 pellets and UO_2 reference materials established and optimised
➢ Cold tests for production of ^{238}Pu and Cr / ^{238}Pu doped pellets in a dedicated glove box line at SCK•CEN successfully accomplished

EURAD ACED

Assessment of Chemical Evolution of ILW and HLW Disposal Cells

D. Jacques[1], A. Dauzères[2], G. Deissmann[3], J. Govaerts[1], E. Holt[4], G. Kosakowski[5], M. Leivo[4], C. Martin[6] and E. Neeft[7]

[1]SCK-CEN, Belgium [2] IRSN, France [3] FZJ, Germany, [4]VTT, Finland [5]PSI, Switzerland, [6]Andra, France, [7]COVRA, Netherland

Work package and task leaders (see below for full consortium)

Background

The chemical evolution of a disposal cell, i.e. waste packages and their immediate surroundings such as other waste packages or near field components, forms an important input for the evolution of a repository for nuclear waste and the assessment of safety- and performance-related aspects.

Objective

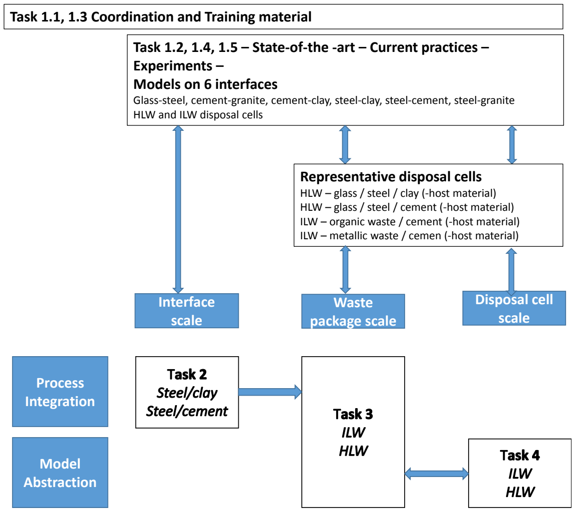
To improve methodologies for deriving multi-scale quantitative models for the description of the chemical evolution at the disposal cell scale

To derive robust mathematical models including the most relevant processes that drive the chemical evolution at the disposal cell scale

Aim

A better conceptual and mathematical representation of the chemical evolution in order to:

- Improve the assessment and quantification of generic safety functions such as isolation and containment of waste constituents
- Obtain a better substantiation of conservatism and reduction of uncertainty
- Increase the scientific basis for definition of requirements of materials



Interface Scale (Task 2)

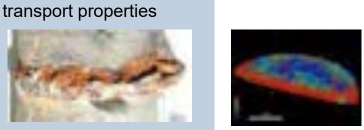
Evolution at the interface of
Steel-Cement or Steel-Clay

- Under different temperatures and chemical gradients
- Study of presence of heterogeneities at interfaces

Experimental

Dedicated experimental program combining **new** and **existing** experiments with a life-span from a few months up to more than a decade.

Variables: corrosion rate, corrosion products, physical-chemical evolution at interface, transport properties



10-year contact between carbon steel and Toarcian claystone – right picture shows CT of iron diffusion in the argillite (Dauzères et al., 2013)

Modelling

Integrate existing knowledge of corrosion at clay or concrete interfaces into reactive transport models

Validation with experimental studies

Upscaling information as input to waste package and disposal cell scale

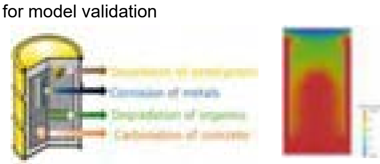
Waste Package Scale (Task 3)

Evaluation of process knowledge integration
and model abstraction techniques

- For representative ILW and HLW waste packages
- ILW concrete degradation – metal corrosion – organic matter degradation
- HLW glass alteration rate – chemistry of buffer – nature of corrosion products

Experimental

Existing long-running experiments for HLW and ILW will be analyzed to provide additional data for model validation



Modelling of interacting processes at waste package scale – right picture shows chemical reativity (Kosakowski, 2019)

Modelling

Stepwise approach

First model step using existing information

Second model step update with new knowledge and data

Derivation of abstracted models, upscaled processes and effective parameters

Disposal Cell Scale (Task 4)

Integration of state-of-the-art in full model
to simulate the chemical evolution of
ILW and HLW disposal cells

- Upscaling information from other scales
- Assessment of interaction of degradation processes
- Benchmark for abstraction methodologies

Waste package and its immediate surrounding - Schematic picture of possible chemical alterations (Maes, 2014)

Abstraction – turning full model
in robust and manageable modules

- That reflects the current state-of-the-art
- That reflects the key features of the complex model

Identify key interactive processes, parameters
and features affecting chemical evolution

- Sensitivity analysis of parameters
- Mapping critical parameters to performance targets or risks
- Analyzing the response of the system to different environmental conditions

Consortium

Budget: 5.1 k€ 25 partners from 11 countries – 2019-2023

Andra (FR), Bel-V (BE), BRGM (FR), CEA (FR), CIEMAT (ES), CNRS/GeoRess (FR), COVRA (NL), Ecole des Mines (FR), EDF (FR), FZJ (DE), IRSN (FR), LEI (LT), MTA-EK (HU), NRG (NL), PSI (CH), SCK•CEN (BE), SUBATECH (FR), SURAO (CZ), UAM (ES), UDC (ES), UFZ (DE), UJV (CZ), Ubern (CH), VTT (FI), ZAG (SI)

Integration of CAST results into safety assessment

Probabilistic uncertainty/sensitivity analysis of C-14 release and transport

Jaap Hart, Joris J. Dijkstra and Johannes C.L. Meeussen

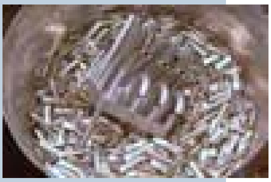
Nuclear Research and consultancy Group (NRG), P.O. Box 25, 1755 ZG Petten, The Netherlands – www.nrg.eu

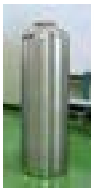
Introduction

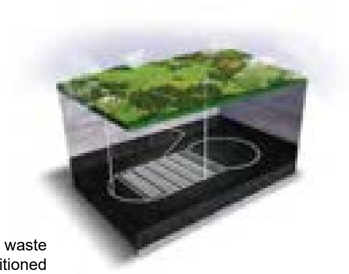
In 1984 the Netherlands has decided for a policy of long term interim surface storage of radioactive waste. This policy allows to develop a final disposal without undue hurry, and opens options that are less feasible for faster progressing countries, e.g. the long-term performance demonstration of safety-relevant elements of a disposal concept. The Dutch research program on the geological disposal of radioactive waste – OPERA (2011-2017) investigated the feasibility and the long-term safety of the OPERA disposal concept in Boom Clay host rock.

The CAST project (CArbon-14 Source Term) aimed to develop understanding of the potential release mechanisms of carbon-14 from radioactive waste materials under conditions relevant to waste packaging and disposal to underground geological disposal facilities. NRGs contribution to CAST focused on the release of C-14 from Zircaloy and its transport through concrete engineered barriers and the Boom Clay host rock.

NRG's Contribution to CAST focused on the impact of C-14 in the OPERA disposal concept

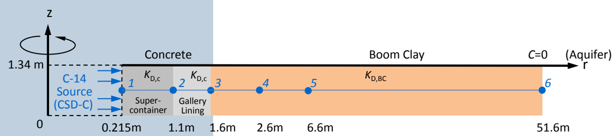






C-14 is present in Zircaloy hulls and end-pieces which are separated from spent fuel and compacted in standard waste containers: CSD-C Colis Standard de Déchets – Compacteés. Upon their final disposal the CSD-C containers will be conditioned in concrete Supercontainers and emplaced in disposal galleries of the OPERA disposal concept in Boom Clay host rock.

Considering the OPERA disposal concept and related system parameters, a radial slice of the repository was modelled with ORCHESTRA, conceptualizing one CSD-C (C-14 source), surrounded by concrete (Supercontainer and gallery lining) and Boom Clay host rock. The initial C-14 inventory amounts 13.8 GBq.

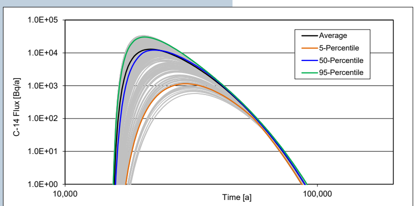


ORCHESTRA: Objects Representing CHEmical Speciation and TRAnsport - http://www.orchestra.meeussen.nl

NRG performed a probabilistic uncertainty/sensitivity analysis for assessing the impact of C-14 on safety-related parameters of:

1) Instant Release Fraction (IRF) of C-14 from Zircaloy
2) Corrosion rate of Zircaloy
3) Adsorption coefficient $K_{D,c}$ of C-14 in concrete
4) Adsorption coefficient $K_{D,BC}$ of C-14 in Boom Clay

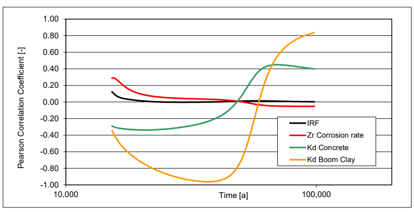
CAST Work Package 6 proposed ranges of parameter values for these quantities



C-14 flux at 5 m into the Boom Clay – Point 5

250 Simulations were performed, randomly varying the values of the four input parameters. Each combination of four parameters represents a different "state" of the disposal system

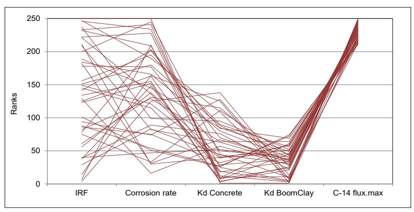
The plot shows the resulting variation of the C-14 flux, assuming a time of failure of the CSD-C container of 15'000 years



Pearson Correlation Coefficient for C-14 flux at 5 m into the Boom Clay – Point 5

The PCC indicates the strength of the linear relationship between input parameters and the calculated output

At 5 m into the Boom Clay the C-14 flux is strongly correlated with $K_{D,BC}$, moderately correlated with $K_{D,c}$, and uncorrelated with IRF and Zr corrosion rate



Cobweb plot for the maximum C-14 flux at 5 m into the Boom Clay – Point 5

Cobweb plots visualize qualitatively the dependency of output variables on multiple input variables

At 5 m into the Boom Clay the 40 largest values of the maximum C-14 flux are strongly correlated with the lower values of $K_{D,BC}$, and uncorrelated with IRF and Zr corrosion rate

Main findings of the uncertainty/sensitivity analysis

- In all simulation cases and at all locations in the disposal system the calculated C 14 fluxes hardly depend on (prescribed) values of the Instant Release Fraction (IRF) and the Zircaloy corrosion rate
- The K_D values of C-14 in concrete and Boom Clay do affect the C-14 fluxes throughout the disposal system. The influence of the K_D values of C-14 in Boom Clay increases further away from the C-14 source.
- Considering the half life of C-14 (5'700 years) compared to assumed CSD-C failure times and the C-14 transport rate through Boom Clay, an insignificant fraction of disposed C-14 may reach the outer Boom Clay boundary.
- The simulations performed in CAST are in line with the results of the OPERA safety assessment, indicating that the contribution of C-14 to various safety indicators (dose rate to biosphere, radiotoxicity fluxes / concentrations), is small compared to other radionuclides.
- The UA/SA analyses indicate that assessing the safety consequences of C 14 disposed in a deep geological repository in Boom Clay would benefit from enhancing the understanding of parameters and processes that determine the migration rate of C-14 in Boom Clay, and to a lesser extent in concrete.

The project has received funding from the European Union's European Atomic Energy Community's Seventh Framework Programme FP7/2007-2013 under grant agreement no. 604779, the CAST project.

EUDuC=N

Carbon-14 release from irradiated stainless steel

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OBJECTIVES

The objective of this work is to measure the rate and speciation of carbon-14 release from irradiated stainless steel on leaching under high-pH anaerobic conditions, representative of a cement-based near field for intermediate- and some low-level wastes (ILW/LLW).
In particular, this includes measurements of releases to the gas phase as well as to solution. The gas phase carbon-14 collection method allows for the discrimination of carbon-14 released as $^{14}CO_2$, ^{14}CO (and volatile oxidized species) or ^{14}C-hydrocarbons. The carbon-14 solution analysis method used to date has measured the inorganic carbon-14 release only. Work is in progress to measure the total carbon-14 release to solution that includes any dissolved organic carbon-14 species.

SAMPLES

- ❑ 316L(N) austenitic stainless steel from single sheet
- ❑ 6 compact tension (CT) specimens irradiated at HFR, Petten – SIWAS 07 experiment (2dpa, 80°C, 5 28-day cycles) in 1996/97
- ❑ C-14 and Co-60 inventory assessed by ORIGEN calculations
  - Co-60 in good agreement with γ-spec measurement
- ❑ 3 experiments each with 3 CT specimens
  - Un-irradiated from same sheet

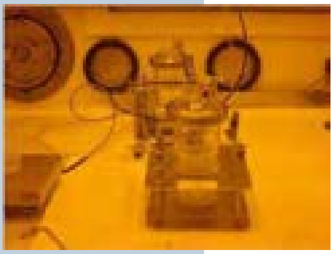
Container	1	2	3
Mass (g)	228	221	222
Geo.S.A. (cm^2)	104.4	114.4	114.4
C-14 (Bq)	0.1	4.9E+07	4.9E+07
Co-60 (Bq)	0	1.6E+10	1.6E+10

CT specimen
30x28.8x12 mm^3

LEACHING EXPERIMENTS

- ❑ Leaching in 0.1M NaOH (pH 13) under nitrogen at the ambient temperature in the hot cell
- ❑ Duplicate experiments on irradiated steel samples
- ❑ Identical experiment on un-irradiated steel sample (same batch)
- ❑ Gas and liquid phase periodic sampling
  - 1 week, 3 weeks, 6 weeks, 3 months, 5 and 13 months
  - Gas phase purged and passed through RCD sampler system to selectively capture $^{14}CO_2$, ^{14}CO (and volatile oxidized species) or ^{14}C-hydrocarbons
  - 2 liquid samples for γ-spec (Co-60) and C-14 analysis
- ❑ Blank tests to measure C-14 background
- ❑ On termination, the container will be acid leached to recover any sorbed radionuclides for γ-spec analysis

EXPERIMENTAL SETUP



RESULTS - SOLUTION PHASE RELEASE

- ❑ Fast initial C-14 release, then rate decreases
  - Container 2 – C-14 activity still increasing at steady rate
  - Container 3 – C-14 activity has changed little between 6 and 60 weeks, with an unexplained peak after 13 weeks
  - Container 1 – no C-14 measurable

- ❑ High Co-60 activity in leachates after 1 week
  - 1 part in 10^6 of Co-60 inventory
- ❑ Then solution activity decreases
  - possible solubility limitation and/or sorption

RESULTS – GAS PHASE RELEASE

- ❑ Unirradiated samples
- ❑ LoD <0.04 Bq
- ❑ 2 analyses give positive C-14 measurement above LoD

- ❑ **Majority C-14 release to gas phase as hydrocarbons**
- ❑ ~10% CO or volatile oxygenated organic compounds
- ❑ No measurable gas phase CO_2

- ❑ **Majority C-14 release to gas phase as hydrocarbons**
- ❑ ~6% CO and/or volatile oxygenated organic compounds
- ❑ No measurable gas phase CO_2

CONCLUSIONS

- ❑ There is a relatively fast initial release of accessible C-14 species from the surface of the steel on immersion in alkaline water
  - Predominantly to solution phase but also to gas phase
  - Higher proportion and rate of release to gas phase initially in Container 3
- ❑ Gas phase release predominantly hydrocarbons with up to 10% released as CO or volatile oxygenated compounds
- ❑ Rate of carbon-14 release declines beyond 3-6 weeks in both Containers 2 and 3
  - Release continues at measurable rate to both gas and solution phases in Container 2
  - Rate of release to the gas phase decreases more quickly in Container 3; little change in solution phase concentration between 6 and 60 weeks
- ❑ Reasons for differences in carbon-14 release between Containers 2 and 3 are not yet understood
- ❑ Release of Co-60 was investigated as a possible marker of the rate of steel corrosion, but is not suitable due to possible solubility limitation and/or sorption to the irradiated steel
- ❑ The experiments have been prolonged with further sampling after two years; once terminated, the leaching vessels were emptied and the walls acid washed to recover deposits for cobalt-60 analysis by γ-spectroscopy
- ❑ Measurements of total carbon-14 in the solution phase are planned using a pyrolysis method to investigate whether some of the dissolved release occurs as organic species; at present, total releases of carbon-14 to solution may be underestimated

The project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no. 604779, the CAST project. (www.projectcast.eu)
Co-funding from Radioactive Waste Management is gratefully acknowledged.

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Performance of compacted MX-80 bentonite and bentonite-sand mixture hydrated with brine

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Introduction

The Canadian Nuclear Safety Commission (CNSC), Canada's nuclear regulator, conducts regulatory research in order to build independent knowledge on safety aspects related to the deep geological disposal of radioactive wastes. In addition to the geological barrier, a major safety component of the repository system consists of engineered buffer and seal materials such as MX-80 bentonite containing highly expansive clay minerals that will swell when they interact with pore water. Site characterization at a candidate site in sedimentary rock in Southern Ontario, Canada shows very high salinity (200–350 g/L) in pore water at about 400 m below the ground surface (figure 1 and table 1). Experimental evidence shows that salinity plays an important role on the performance of bentonite buffer and seals by reducing the swelling potential of the bentonite clay mineral, increasing the bentonite permeability, and changing the bentonite water retention characteristics.

In this study, laboratory experiments were performed to investigate hydro-mechanical behaviour of MX-80 bentonite and bentonite/sand (70:30) mixture (MX-80/SP) using brine model water (MW) that mimics an *in situ* pore fluid geochemical condition, and deionized water (DI) as pore water. This poster presents the effect of brine on the compressibility, swell pressure, and permeability of the MX-80 bentonite and a 70:30 bentonite/sand mixture at different initial dry densities, which is compared with the behaviour of the bentonite and the bentonite/sand mixture hydrated with DI. A model based on the dual porosity concept was developed to interpret the swelling behaviour of MX-80 when hydrated with brine, and the dependence of hydraulic and mechanical properties of bentonite on factors such as porosity, salinity, and water content.

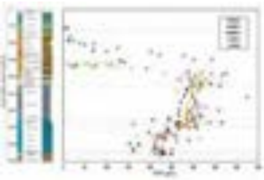

Figure 1. Total dissolved solids profile

Item	Unit	Measured values from DGR-1 to DGR-6						Proposed model water
		Max.	Min.	Mean	Std dev.	Mean + Std dev.	Mean - Std dev.	
Cl	g/L	257	92	195	35	230	161	197
Na	g/L	74	29	60	11	71	48	60
Ca	g/L	45	2	27	11	38	16	22
K	g/L	63	25	41	18	59	24	41
Mg	g/L	35	5	15	7	22	7	11
SO_4	g/L	13	4	9	4	13	4	0.6
Br	g/L	4	1	2	1	3	1	2
TDS	g/L	364	161	280	47	327	233	333
pH	pH	8.2	8.1	8.2	0.0	8.2	8.1	8.2

Table 1. Data of total dissolved solids and proposed model water

Basic properties of MX-80 bentonite

MX-80 bentonite is a natural Wyoming bentonite dominated by smectitic clay minerals. Its mineralogical composition and some basic physical properties are shown in tables 2 and 3.

Bentonite	SI (ml/2g)	Smectite	Feldspar	Mica	Quartz	Cristobalite	Zeolite
MX-80-QU-B2	20	83	7	1	3	2	4
MX-80-QU-B2	16	76[a] / 73[b]	14-15	5-6	3	1-2	1
GCL-NWL-QU	26	96	2	–	2	–	–
MX-80-WyR1	NR	83.5	0.7[c] / 2.9[d]	2.8	2.8	0.4	–

NR = Not reported
[a] if in the form of beidellite
[b] if in the form of illite/montmorillonite mix
[c] orthoclase
[d] plagioclase

Table 2. Semi-quantitative mineralogy (% of total material) of MX-80 from XRD

Bentonite	SI (ml/2g)	CEC (cmol/kg)	Exchange complex (mole fraction)			
			Na	K	Ca	Mg
MX-80-QU-B2	20	65	0.66	0.03	0.26	0.05
MX-80-QU-B2	16	65	0.51	0.03	0.37	0.09
GCL-NWL-QU	26	80	0.67	0.02	0.25	0.06
MX-80-WyR1	NR	75	0.75	0.02	0.16	0.07

Table 3. Cation exchange capacity (CEC) and exchangeable cations of MX-80

Experimental methods and results

The impact of brine was tested separately on pure MX-80 bentonite and a bentonite/sand mixture (MX-80/SP). In each test, the material was compacted with an initial moisture content of 11% and then loaded in a 38 mm diameter stainless steel test cell. The experimental apparatus for compression, swell, and permeability tests are shown in figure 2, (a), (b), and (c) respectively. The results of the compression test are shown in figures 3 and 4 and the results of the swelling tests are shown in figures 5 and 6, while the results of the permeability tests are shown in figure 7.

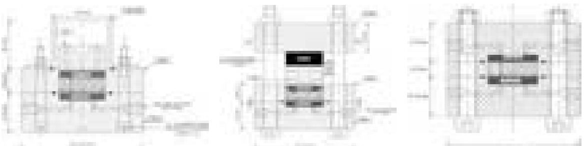

Figure 2. Experimental apparatus: (a) one dimension compression test, (b) constant swell test, and (c) permeation test

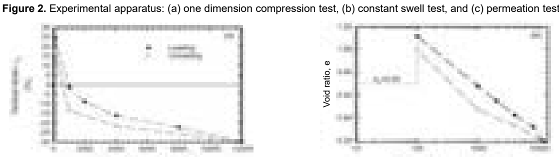

Figure 3. Compression curve of an MX-80 sample at a dry density of 1.61 Mg/m³ and hydrated with DI water

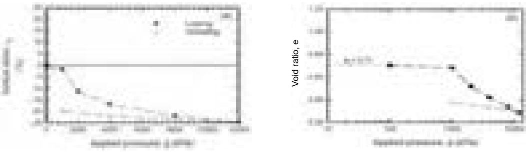

Figure 4. Compression curve of an MX-80 sample at a dry density of 1.61 Mg/m³ and hydrated with MW

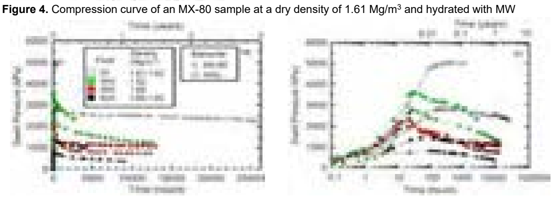

Figure 5. Swell pressure for MX-80 and NWL bentonites plotted versus: (a) time, and (b) logarithm of time

Figure 6. Summary of swell pressures: (a) peak, (b) last measured, (c) effect of pore water, bentonite, and density on last measured swell pressure

Figure 7. Hydraulic conductivities with respect to DI or MW for: (a) MX-80 & NWL (d=1.60 to 1.80 Mg/m³), and (b) MX-80/SP (d=1.63 to 1.67 Mg/m³)

Dual-Porosity Model

Figure 8 shows a dual-porosity conceptual model proposed to reflect the transient variation of swell pressure observed in MX-80 bentonite and considers the effect of salinity on hydraulic and mechanical properties. The governing equation for constant volume swell test is presented by equation 1. The modeling results of temporal evolution of swell pressure are shown in figure 9.

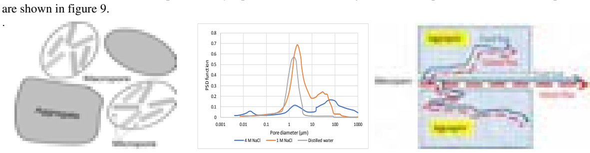

Figure 8. Concept of double porosity in bentonite buffer and seals

$$\begin{cases} \nabla\cdot\sigma = 0 \\ n^m \dfrac{\partial C^m}{\partial t} = (1-\omega)[\nabla D_0 \nabla C^m - \nabla(v^m C^m)] + Q_c^m - C^m \dfrac{\partial \varepsilon_v}{\partial t} \\ n^M S_e^M \dfrac{\partial C^M}{\partial t} = D_0 \nabla^2 C^M - \nabla(v^M C^M) + Q_c^M - C^M n^M \dfrac{\partial S_e^M}{\partial t} \\ \dfrac{\partial}{\partial t}(\rho_l n^m) - \nabla \dfrac{k_s^m}{\mu} \rho_l (\nabla p^m - k_c \nabla C^m) = Q_m \\ G_s \rho_l w^M \left(C_m \dfrac{\partial p^M}{\partial t} + C_s \dfrac{\partial C^M}{\partial t} \right) - \nabla \dfrac{k_s^M k_r}{\mu} \rho_l (\nabla p^M - k_c \nabla C^M) = -G_s \rho_l w \dfrac{\partial \varepsilon_v^M}{\partial t} + Q_M \end{cases} \quad (1)$$

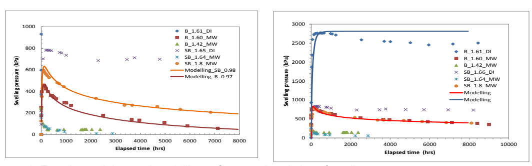

Figure 9. Experimental data and modellings of temporal evolution of swell pressures

Summary and conclusions

- MX-80 bentonite and bentonite/sand mixture are less compressible when hydrated with brine model water.
- The swelling pressure of the MX-80 bentonite and the bentonite/sand mixture is drastically decreased by high pore water salinity.
- The permeability of MX-80 bentonite and bentonite-sand mixture increased by two to three orders of magnitude when they are hydrated with MW.
- A dual-porosity Hydro-Mechanical-Chemical coupled model was developed, which can interpret swelling behaviour of MX-80 bentonite.

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Deterministic and Probabilistic Analysis Supporting the Safety Case for Deep Geological Repository

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INTRODUCTION

In order to evaluate the long-term safety of the deep geological repository for spent nuclear fuel, the primary model of the near field, geosphere in crystalline rock and reference biosphere was developed based on the recommendations provided in the BIOMASS methodology, considering the scenario of the agricultural habitat (normal evolutionary scenario) using the GoldSim simulation tool. Multiple scenarios have been developed for purpose of the deterministic safety analysis. Within consideration of uncertainties related to the selected scenario, also probabilistic analysis was performed using the Monte Carlo method, which is directly implemented in the simulation tool GoldSim. In the case of probabilistic simulations, log normal distribution was used for all selected parameter and the evaluation of the impact of selected uncertainties on the long-term safety of the deep geological repository was performed.

CREATION OF THE MODEL

The conceptual model of the reference biosphere was developed according to the BIOMASS methodology (IAEA, 1996). The ultimate goal is to calculate the effective dose for the individual without considering the evolution of the biosphere system. The model was developed using the **GoldSim** simulation tool.

Disposal system

- ✓ Disposal system was based on **multi-barrier concept**.
- ✓ Spent nuclear fuel:
  - initial average enrichment of 4.25 % of U-235,
  - burnup 60 MWd/kgU,
  - calculations of spent nuclear fuel inventory was performed for the radial profiled VVER-440 fuel assembly of the 2nd generation by using the depletion module TRITON included in SCALE 6.1.3 code system.
- ✓ Disposal container:
  - disposal container inspired by Czech proposal,
  - spent fuel assemblies from VVER-440 reactors,
  - disposal capacity of one container is 7 fuel assemblies,
  - container constructed of stainless steel (inner part) and carbon steel (outer part) with an outer diameter of 650 mm and a length of 3 670 mm,
  - fuel assemblies are inserted into the inner profiled pipes made of aluminium alloy.
- ✓ Disposal container was considered to be surrounded by a bentonite buffer with a wall thickness of 300 mm.
- ✓ Time of storage before the final disposal was set at 50 years.
- ✓ We assumed the theoretical scenario of 4 600 disposal containers in the repository space.
- ✓ The disposal container **fails** due to normal evolution processes **after 10 000 years**.

Geosphere

- ✓ Geosphere represented by a **crystalline host rock** environment.
- ✓ Radionuclides reach the geospheres through the fractures and faults.

Geosphere – biosphere interface

- ✓ Interconnection between the geosphere and the biosphere is represented by an **aquifer**, from which the contaminated water flows through the surface flow into the water reservoir.

Reference biosphere

- ✓ The primary medium through which radionuclides come into the biosphere is water.
- ✓ Conservatively, it is assumed that all consumed environmental components are contaminated with radionuclides, with the primary exposure pathways (ingestion, inhalation and external exposure).
- ✓ On such land are cultivated cereals, vegetables, grassland and trees. Radionuclides are transported through the root or leaf system into the plants, hence either directly into the human organism, or into the animal organism from which the animal products enter the human body.

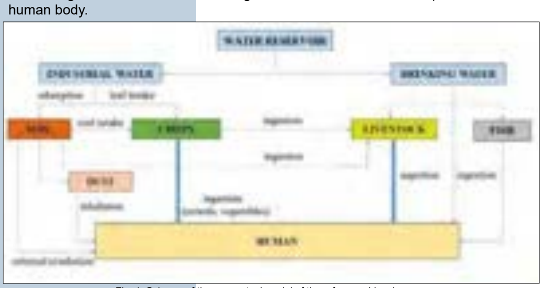

Fig. 1: Schema of the conceptual model of the reference biosphere

SAFETY ASSESSMENT OF DEEP GEOLOGICAL REPOSITORY – deterministic analysis

In order to evaluate the long-term safety of the disposal system of spent nuclear fuel, our aim was to determine the values of the annual effective doses for individuals from the critical exposure group.

Tab. 1: Food consumption, water intake and breathing rate of an individual

	INFANTS	(1-2 years)	(2-7 years)	(7-12 years)	(12-17 years)	ADULTS (> 17 years)
Milk and milk products [l/year]	150	120	222	237	206	173
Meat [kg/year]	11	26	42	58	65	60
Cereals [kg/year]	15	38	61	102	141	157
Vegetables [kg/year]	23	34	44	55	69	75
Fish [kg/year]	0.4	1	1.6	2.2	2.5	5
Water [l/year]	250	250	450	450	450	700
Breathing rate [m³/s]	3.17E-05	6.32E-05	1.27E-04	1.90E-04	2.57E-04	2.57E-04

Fig. 2: Maximum of annual effective doses

- The annual effective dose of an individual is mainly caused by **ingestion**.
- The values of the maximum annual effective dose for an individual of the critical exposure group are in all cases **lower** than the limit recommended by regulatory authority (**ICRP**) for waste disposal facilities - annual dose constraint for the population of **0,3 mSv/year**.
- Within the considered parameters deep geological repository is **satisfactory** from the safety requirements point of view.

PROBABILISTIC ANALYSIS

- Also probabilistic analysis was performed using the **Monte Carlo** method, which is directly implemented in the simulation tool GoldSim.
- Selected parameters were **transfer factors** for cereals. The transfer factor for the uptake of any radionuclide from soil to plant is defined as the ratio of the contaminant concentration in the plants and the contaminant concentration in the specified soil layer.
- By definition, concentration ratios and aggregated transfer factors assume that the activity concentration of the radionuclide in the organism is in equilibrium with that in the relevant environmental medium (soil, sediment or water).
- In the case of probabilistic simulations, **log normal distribution** was used and the evaluation of the impact of selected uncertainties on the long-term safety of the deep geological repository was performed.

Tab. 2: Values for selected transfer factors using log-normal distribution

ELEMENT	Minimum	Maximum	Geometric Mean	Geometric Standard Deviation	Reference Values
Ac	2.60E-05	2.60E-03	2.60E-04	3.2	2.20E-05
Am	1.60E-05	7.60E-02	4.90E-05	11.0	2.20E-05
C	1.00E-03	1.00E-01	1.00E-02	3.2	7.00E-01
Cl	4.50E+01	1.90E+02	8.00E+01	1.6	7.00E+01
Cm	3.10E-06	4.50E-04	5.10E-05	3.3	2.10E-05
Cs	4.50E-04	2.00E+00	6.50E-02	4.1	2.60E-02
I	2.20E-04	2.50E-02	1.40E-03	2.3	4.00E-02
Nb	8.20E-04	3.70E-02	1.40E-03	6.0	2.50E-02
Np	5.10E-05	1.60E-01	6.50E-03	5.0	2.70E-03
Pa	7.70E-04	7.70E-02	7.70E-03	3.2	2.20E-04
Pb	4.20E-03	1.10E-01	2.50E-02	3.6	4.70E-03
Pd	7.70E-03	7.70E-01	7.70E-02	3.2	4.00E-02
Pu	4.50E-07	2.50E-03	2.10E-05	6.7	8.60E-06
Ra	1.80E-04	1.50E+00	3.80E-02	12.0	1.20E-03
Se	3.10E-02	3.50E-01	3.10E-02	3.4	2.50E-01
Sm	2.60E-05	2.60E-03	2.60E-04	3.2	2.00E-03
Sn	2.60E-02	2.60E+00	2.60E-01	3.2	6.00E-02
Tc	4.00E-01	5.30E+00	2.90E+00	3.6	7.30E-01
Th	3.60E-04	4.90E-02	4.70E-03	3.4	3.40E-05
U	3.60E-04	1.80E+00	1.40E-02	7.7	1.30E-03
Zr	2.30E-04	2.30E-02	2.30E-03	3.2	1.00E-03

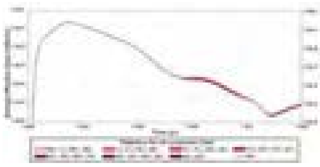

Fig. 3: Probabilistic analysis

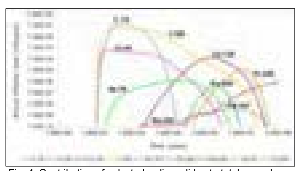

Fig. 4: Contribution of selected radionuclides to total annual effective dose for an adult

CONCLUSION

To evaluate **the long-term safety of the deep geological repository**, a model of the disposal system, geosphere and **the initial model of the reference biosphere** has been developed. Using the GoldSim simulation tool, **the annual effective dose** for individuals of different ages from critical exposure group was calculated. Based on the results, we can say that the maximum annual effective dose is obtained by an adult representative. Because the scenario considers, that the dominant pathway of intake of radionuclides is consumption of contaminated food and drinking of contaminated water from the well, it can be said that the annual effective dose of an individual is mainly caused by ingestion and the values of the dose are significantly dependent on the rate of intake of contaminated food and water. The values of the maximum annual effective dose for an individual of the critical exposure group are in all cases lower than the limit recommended by regulatory authority (ICRP) for waste disposal facilities and therefore we can say, that within the considered parameters deep geological repository is **satisfactory from the safety requirements point of view**. Also **probabilistic analysis** of selected **transfer factors** was performed. From the results can be seen that the dispersion of the values is significant in the last years of the analysis. It is caused by the contribution of radionuclides dominant in this period of time.

LONG-TERM PERFORMANCE OF VERTICAL SEALING SYSTEMS - IMPACT OF GAS MIGRATION

4-7 June 2019 Pitesti, Romania
EURADWASTE '19
9th European Commission Conference on EURATOM Research and Training in Radioactive Waste Management

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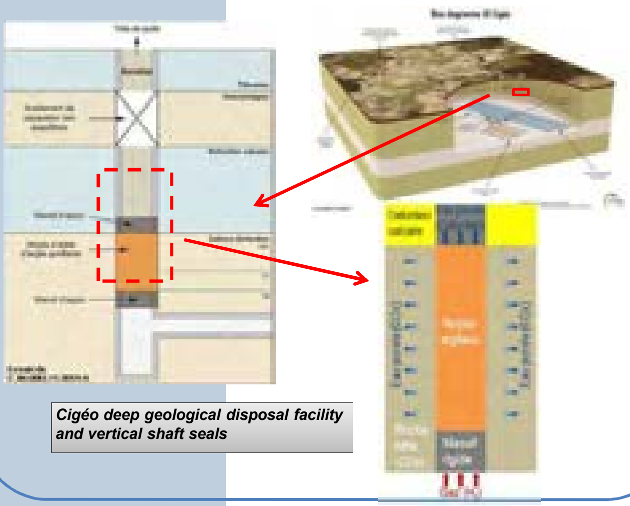
Institute for Radiation protection and Nuclear Safety, IRSN-France

Introduction

One of the key containment elements of a deep geological disposal facility is the vertical sealing system since it constitutes the main potential pathway between nuclear wastes and the biosphere. Within vertical sealing systems, the complex migration processes of gas produced by metallic corrosion, microbial degredation and radiolysis of water is of great importance for performance assessment and long-term evolution of deep geological disposals. Under geological disposal conditions, the vertical sealing will experience a particular saturation scenario :fast hydration from the upper surface by water coming from the calcareous Oxfordian leading to a rapid increase of water pressure in this zone, which should rapidly reach 3 to 4 MPa . Over time and depending on the rate of gas production, it is possible that gas reaches the vertical sealing system while the bentonite core is only partially saturated .



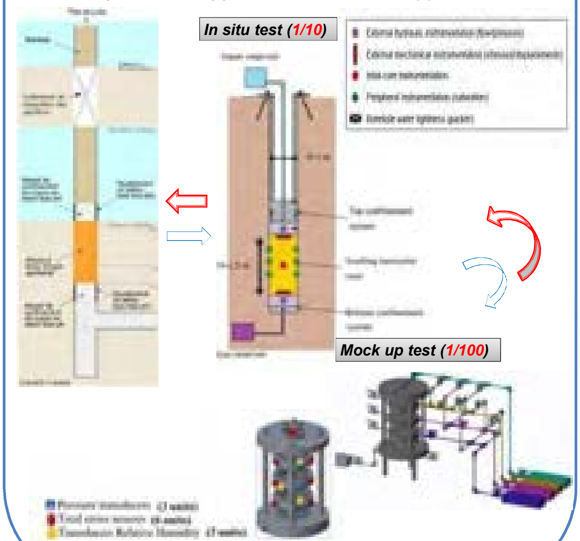
Cigéo deep geological disposal facility and vertical shaft seals

Objectives

As part of the overall IRSN R&D program that provides the scientific bases for expertise on disposal safety, the so-called VSEAL project is foreseen with specific focus on efficiency of shaft sealing systems. VSEAL is dedicated to investigate:

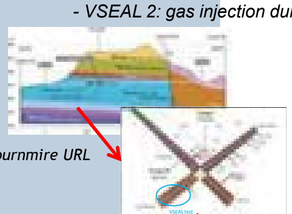
- The impact of gas during saturation of the bentonite seal.
- Gas migration processes through the saturated bentonite core (preferential flow paths, role of interfaces…).

VSEAL experimental approach : A multiscale approach

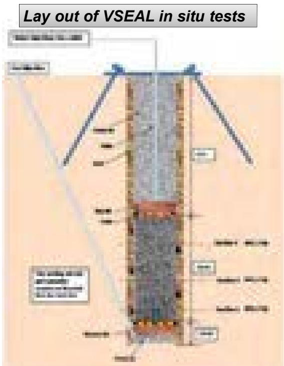


Vseal in situ tests

- *The bentonite core is composed of a mixture of MX80 bentonite Pellets and powder (1 m diameter, 3.5 m length)*
- *2 in situ tests will be installed in Tournemire URL:*
  - *VSEAL1: hydration, gas injection after saturation*
  - *VSEAL 2: gas injection during saturation*

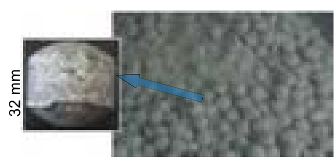


Tournmire URL



Lay out of VSEAL in situ tests

MX80 bentonite pellets and powder (80/20 in dry mass)

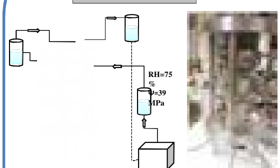


Drilling operations

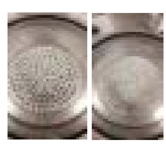
1 m in diameter, 10 m depth

Vseal Mock up test

View of the test



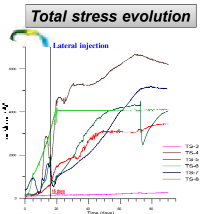
Preparation of the mixture



Powder
ρ_d=1.10 Mg/m³
w_o=10.47%

Pellets (D7mm)
ρ_d=1.98 Mg/m³
w_o=6.62%

Total stress evolution



4-7 June 2019 Pitești, Romania
EURADWASTE '19
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Model for granite fracture laboratory tracer test evaluation using the laser scanning data

TECHNICAL UNIVERSITY OF LIBEREC
Institute for Nanomaterials, Advanced Technologies and Innovation

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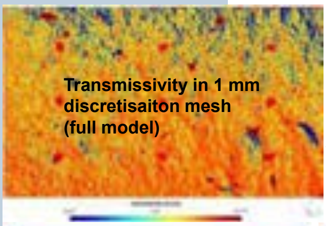
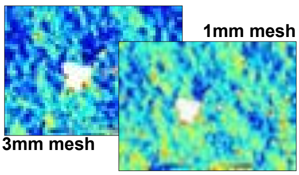
Laboratory experiment

Geometry settings

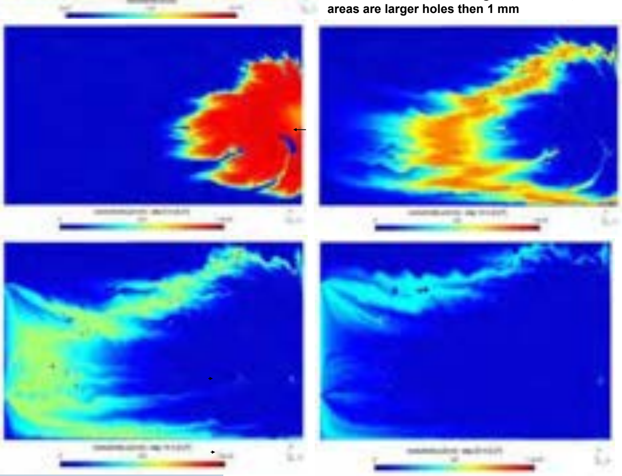
Granite block description

- granite block with dimensions of 80 x 50 x 40 cm
- artificial fracture is created by a large stone splitter
- edge of the fracture is sealed
- 8 outlets/inlets points (A-H): el. conductivity/concentration measurement
- 9 boreholes through upper part (1-9) for measurement of pressure/cond.





Aperture in a detail of 10 cm scale: comparison of discretization, the range of 0-1 mm, white areas are larger holes then 1 mm



The spatial distribution of model concentration in test "a" (inlet G, outlet A+C) in times of 150, 300, 450 and 650 s, ordered in rows (from upper left to lower right).

model name	in	out	flux [ml/min]	Pressure difference borehole 2 and 8 [mbar] exper.	model 3 mm	model 1 mm	tracer	Time of peak maximum [s] exp.	3 mm model alfa 1	3 mm model alfa10	1 mm model alfa 1	1 mm model alfa10
a	G	A, C	19.4	10.52	7.37	5.96	NaCl	361	270	280	275	395
		C					NaCl	327	380	385	435	290
c	C	F	19.2	8.99	7.39	5.93	NaCl	355	330	315	310	315
d	C	F, G, H	19.1	7	7.49	5.96	NaCl	480	320	315	315	320
		G					NaCl	391	420	385	490	445
		H					NaCl	332	>1000	>1000	1000	1000
e	F	C	18.6	13.61	7.18	5.76	NaCl	368	295	305	325	320
f	G	C	9.7	6.27	4.06	3.22	KCl	520	520	545	545	565
g	G	C	9.7	6.27	4.06	3.23	KCl	525	520	545	545	565
h	G	A	9.7	5.11	3.51	2.85	KCl	528	445	465	445	485
i	G	A	9.7	5.11	3.56	2.88	KCl	542	470	490	470	510
j	G	C	9.7	4.13	4.05	3.22	KCl	556	520	550	545	570
k	G	C	9.6	4.96	4.02	3.19	KI	503	490	515	520	535
l	G	C	9.6	5.17	4	3.18	KI	507	505	530	535	550
m	G	C	9.7	5.22	4.04	3.22	Pb	604	500	530	525	550
n	G	C	9.7	4.94	4.08	3.24	Pb	617	490	520	515	535

Acknowledgement: This work has been supported by the Czech Technology Agency under the project No. TH02030543.

Main points

A methodology is demonstrated for future host rock flow and transport analysis with site-specific rock data. The study verifies the general formulas if the variable fracture aperture is obtained by laser scanning.

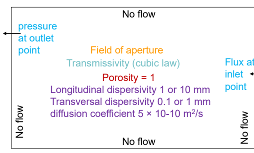
Point cloud data with 0.1mm resolution were converted to a regular grid, the two surfaces subtracted, and then interpolated to the numerical discretization mesh.

The primary fracture surface data needed to be corrected by a virtual block movement to get a correct hydraulic aperture. After this change, both the fracture transmissivity and the tracer breakthrough time were fitted with reasonable accuracy up to exceptions is certain cases.

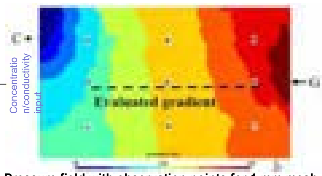
Variants of discretisation and hydrodynamic dispersion were tested.

Model settings

- Laser scanning from all sides with resolution 0.1 mm
- model range 772 x 470 mm
- fracture represented by a 2D planar model
- unstructured triangular mesh with spatially varying aperture for computation obtained by procedure in Surfer, MS Excel and GMSH.
- Resolution of 3 mm (51482 nodes, 102456 elements) and of 1 mm (459413 nodes, 917306 elements)
- computational time is 1000 seconds and time step is 5 seconds



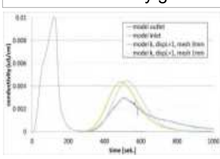
Boundary conditions and parameters



Pressure field with observation points for 1 mm mesh

Results

- Calibration of mutual block position - aperture is decreased by 0.1 mm, 0.2 mm, or 0.3 mm
- Hydraulics: results of 3 mm mesh are closer to measurements than the 1 mm mesh, results are reasonably good for both meshes using of unchanged of parameter of experiments
- Transport: results of the 1 mm mesh with dispersion coefficient of 10 mm have a very good fit of the rising part of the breakthrough curve



Peak of the breakthrough curve comparison model and experiment

Comparison of pressure gradient in model and experiment

Conclusion

- Most of the model versus experiment error comes from inaccurate data of the relative block positioning
- derived aperture fields must be considered with uncertainty, which can be eliminated by the hydraulic model calibration
- based on the peak position derived breakthrough time, the same aperture field can be used to calibrate both the flow and the transport model
- the tailing of the breakthrough curves was not captured, so there is a suspect on an additional phenomenon in the transport process
- model concentration field shows only very weak channelling, which is related to rather larger mean aperture of 0.2 mm, compared to natural fractures.

4-7 June 2019 Pitesti, Romania
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THERMOCHIMIE - a thermodynamic database to be used in radioactive waste management

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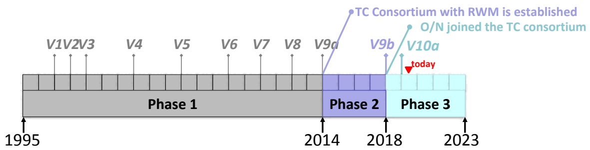
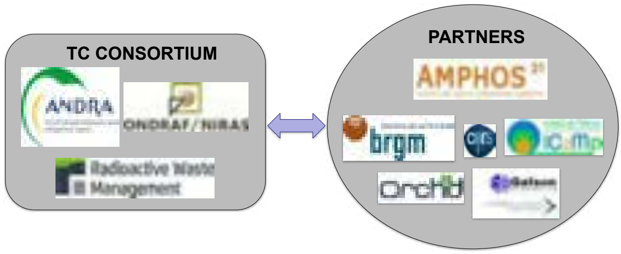
Introduction

ThermoChimie (TC) [1], is a thermodynamic database initially created and developed by Andra, since 1995. In October 2014, RWM and Andra formed a ThermoChimie project consortium to further develop the thermodynamic database. ONDRAF/NIRAS, joined the third phase of the project in March 2018. The ThermoChimie database is developed with the technical support of many scientific partners.



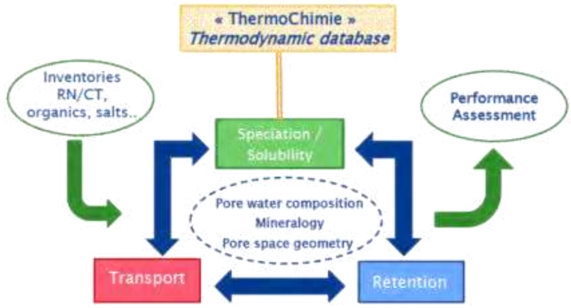


The latest release of ThermoChimie (V10a – status 2018) can be downloaded from the ThermoChimie website (https://www.thermochimie-tdb.com). ThermoChimie database is available in formats compatible with a variety of geochemical codes such as PhreeqC, Crunchflow, Toughreact, Chess, Spana and Geochemical Workbench (GWB).

Project objective

In radioactive waste management, **geochemical modelling** is used in different ways, to support the repository performance assessments, research activities or decisions about waste conditioning, reprocessing, and disposability. Specifically, when assessing the performance of a Disposal Facility, modelling allows to bound its chemical evolution in terms of the performance of the engineered and natural barriers as well as the fate of the contaminants.

As a matter of fact, such calculations are based on conceptual and numerical models fed by **reliable thermodynamic** (and kinetic) datasets. **Consistency and completeness** of the thermodynamic database for the given purpose are mandatory for the geochemical simulation results to be meaningful.

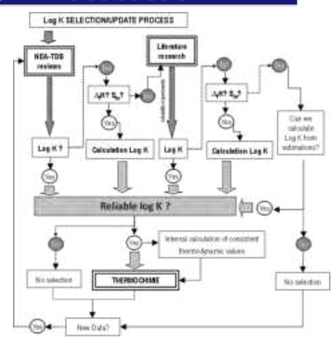


ThermoChimie has been designed to be applied over the 6 - 14 pH range at temperatures below 80°C and in systems with an Eh in the range -0.5V to +0.5V since these are the conditions generally expected to be representative of geochemical systems to be tackled in radioactive waste management [1] [2] [3] [4].

ThermoChimie includes datasets on major elements, radioelements and non-radiological pollutants for the most relevant phases in radioactive waste management.

Basic components	Free cations or anions Free oxycations or oxyanions H^+ and e^-	$\Delta_f G_m^0$, $\Delta_f H_m^0$, S_m^0 (25°C and I=0) SIT $\varepsilon(j, k)$ (25°C)
Aqueous species, solids, gases	$\mathrm{Log}_{10}K^0$, $\Delta_r G_m^0$, $\Delta_r H_m^0$, $\Delta_r S_m^0$ (25°C and I=0) $\Delta_f G_m^0$, $\Delta_f H_m^0$, S_m^0, ($C^o_{p,m}$) (25°C and I=0) SIT $\varepsilon(j, k)$ (25°C)	

Workflow



ThermoChimie III priorities:

- To benchmark TC-V10A against other high quality DBs developed for similar purposes based on a set of well-defined cases.
- To assess oxidation-reduction mechanisms in relevant geochemical systems and to define how to tackle these thermodynamically in the scope of ThermoChimie.
- To keep the TC DB up to date with the NEA TDB blue books to be published (*e.g.*, AC update, Ancillary data, Iron II, …).
- To enhance the TC DB with new datasets based on TC consortium members needs
    - *stability constants of organic complexants such as ISA, TBP/DBP, EDTA, Phtalic, Oxalic and their interactions with various elements,*
    - *cements phases, …*

The NEA TDB is the main data reference for the radioelements but this high-quality database is not fit for the purposes tackled in radioactive waste management due to the acknowledged data gaps. ThermoChimie aims at filling these gaps and complement the NEA TDB in order to comply with the range of defined applications.

[1] Giffaut, E. et al. (2014). "Andra thermodynamic database for performance assessment: ThermoChimie". Applied Geochemistry, 49, 225–236.

[2] Grivé, M., et al. (2015). "Thermodynamic data selection applied to radionuclides and chemotoxic elements: An overview of the ThermoChimie-TDB". Applied Geochemistry, 55, 85-94.

[3] Blanc, P., et al. (2015) "ThermoChimie database developments in the framework of cement/clay interactions". Applied Geochemistry, 55, 9-107.

[4] Marty, N. C., et al. (2015) "A database of dissolution and precipitation rates for clay-rocks minerals". Applied Geochemistry, 55, 108-118.

DEVELOPMENT AND IMPROVEMENT OF QUALITY ASSURED THERMODYNAMIC UNDERSTANDING FOR USE IN PERFORMANCE ASSESSMENT OF NUCLEAR WASTE DISPOSAL

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Motivation

Thermodynamic and geochemical model calculations are important tools used in the context of safety case development and safety analyses of repositories for nuclear waste. Understanding and properly quantifying the thermodynamic driving forces controlling the mobilization and retention of radionuclides, as well as the degradation of waste matrices and technical barriers, underpins the long-term performance assessment of such disposal systems and increases its credibility. Thermodynamic approaches can sometimes add time-independent boundary conditions into long-term predictions. Further developing thermodynamic databases (TDBs) and underlying scientific understanding of key processes has obtained the highest priority in the evaluation of the JOPRAD/EURAD strategic research agenda by TSO, WMO and research entities.

Thermodynamic long-term predictions

- *Driving forces controlling retention / mobilization of RN*
- *Integrity / degradation of waste matrices and technical barriers*
- *Very long time scales*

- *Thermodynamic approaches and calculations*
- *Thermodynamic databases*
- *Key activity: reviews within OECD NEA-TDB (release of update book on actinides + Tc in 2019)*

OECD NEA TAB

National and trans-national TDB initiatives

- *ThermoChimie (France, UK, Belgium)*
- *THEREDA (Germany)*
- *JAEA-TDB (Japan)*
- *WIPP-TDB (USA)*
- *…*

Fundamental constants as input for geochemical model calculations (!)

Research needs

- *Addressing key data gaps identified within NEA-TDB*
- *Data for other relevant systems not covered within NEA-TDB*
- *Decrease of uncertainties (conservatism) due to estimation approaches*
- *Radionuclide-organics complexation, including cement additives (beyond CORI), degradation products and small organic ligands*
- *TDB for elevated T conditions, including advanced methods for estimation of thermodynamic properties*
- *Solid solutions including relevant end-members for waste disposal*
- *Interplay of thermodynamic and kinetic effects → ill-defined solid phases and redox processes*
- *Link between local equilibrium at small scale and global disequilibrium*
- *…*

Development of a future working / discussion group on needs for setting up a long term initiative for improving available thermodynamic description

Topics discussed according to WMO, TSO, regulators and RE needs

Survival Of Indigenous Microorganisms In Bentonite Subjected To Gama Radiation And The Effect Of Anaerobic Conditions On The Microbial Ecosystem Evolution In Bentonite

4-7 June 2019
Pitesti, Romania

EURADWASTE '19
9th European Commission Conference on EURATOM Research and Training in Radioactive Waste Management

TECHNICAL UNIVERSITY OF LIBEREC
Institute for Nanomaterials, Advanced Technologies and Innovation

Centrum výzkumu Řež s.r.o.
Research Centre Řež

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INTRODUCTION:

Microorganisms are naturally present in deep underground waters, host rocks as well as in various kinds of bentonite [1,2]. Metabolic activity of microorganisms might negatively influence long term safety and performance of deep geological repositories (DGR) [3]. The key role of bentonite as a part of engineered barrier system surrounding the nuclear waste is to limit microbial activity. In the repository, several effects such as long time, high pressure, elevated temperature and low-level radiation on the bacteria can be expected [3,4]. Nowadays, we have reasonable good understanding about the effect of each particular variable separately, however their synergic effect and especially the effect of radiation and incredible long time frame remains rather unclear.

Swedish KBS-3 HLW repository concept relevant for the planned Czech DGR expects the maximum dose outside the canister to be less than 0,5 Gy/h [5]. The gamma and neutron radiation are expected to be significant during approximately 1,000 years past deposition [5] and it will take 100,000 years for the radioactivity to decrease to similar levels to those of natural uranium [6]. The radiation resistance of a microorganism is commonly measured by the decimal reduction dose (D10), which is defined as the radiation dose (kGy) required to reduce the number of that microorganism by one log (reducing 90 % of the total number). The average D10 dose for most vegetative microorganisms was calculated to be 0.420 kGy, although the variation between species and even strains is very high and some species can have D10 values higher that 10 kGy [7]. It is known, that microorganisms are able to survive in various radioactivity highly contaminated sites [8,9] and studies on soil ecosystems suggest that doses higher than 70 kGy might be necessary to sterilize the samples effectively [10]. More studies on bentonite irradiation and especially long-term studies under realistic repository conditions including radiation are thus highly needed. Our study aims to increase the knowledge about the effect of Gama radiation on the indigenous microbial community in the bentonite.

EXPERIMENTAL SET-UP:

Suspension: Czech candidate bentonite BaM + underground anoxic VITA water from Josef Undreground Laboratory (Czech Republic) rich in sulfate reducing bacteria (3:10 w/w), 260g of suspension.

Gama irradiation: 19,656 Gy total absorbed dose during 9 weeks of irradiation at 13 Gy/h dose rate, in aerobic conditions for technical reasons.

- Irradiated samples + aerobic controls
- Anaerobic controls with and without addition of nutrients (nitrate, sulfate, acetate) – to study evolution of indigenous microbial comunity in anaerobic conditions more relevant to the repository conditions

Analyses: relative quantification by qPCR, NGS of 16S ribosomal RNA gene amplicons – Mothur and DADA2 softwares for NGS data processing – detected OTUs metabolically characterized, PCoA was calculated in Phyloseq.

ACKNOWLEDGEMENT:

The research presented in this article was supported by the Euratom research and training programme 2014-2018 under grant agreement No. 661880 (Microbiology in Nuclear Waste Disposal - MIND), by the Research Infrastructure NanoEnviCz (LM2015073) and the Ministry of Education, Youth and Sports of the Czech Republic and the European Union - European Structural and Investment Funds in the frames of Operational Programme Research, Development and Education - project Hybrid Materials for Hierarchical Structures (HyHi, Reg. No. CZ.02.1.01/0.0/0.0/16_019/0000843)

REFERENCES:

[1] Svensson et al. (2011), TR-11-06, Swedish Nuclear Fuel and Waste Management Co.
[2] Pedersen et al. (2008), ISME J. 2, 760–775.
[3] Humphreys et al. (2010), QRS-1378Q-1, UK NDA.
[4] Stroes-Gascoyne et al. (1997), FEMS Microbiol. Rev. 20, 573–590.
[5] Svensk Kärnbränslehantering AB (2006), TR-06-18, Swedish Nuclear Fuel and Waste Management Co.
[6] Lopez-Fernandez et al. (2018), Appl. Clay Sci. 160, 206-2016.
[7] Van Gerwen et al. (1999), J. Food Prot. 62, 1024-1032.
[8] Chapon et al. (2012), Appl. Geochem. 27, 1375–1383.
[9] Theodorakopoulos et al. (2017), FEMS Microbiol. Ecol. 93, 1-12.
[10] McNamara et al. (2003), Appl. Soil Ecol. 24, 117–132.

OBJECTIVES:

- To study impact of Gama radiation on the survival and compositon of indigenous microbial ecosystems in bentonite suspension
- To study impact of anaerobic conditions on the survival and compositon of indigenous microbial ecosystems in bentonite suspension

RESULTS:

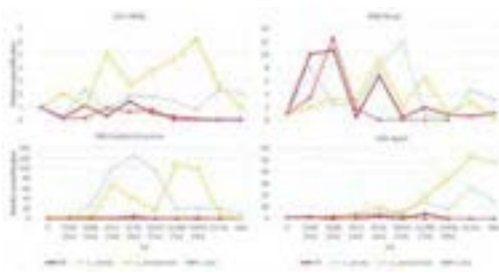

Fig 1: Relative quantification (qPCR) results showing the differences in microbial abundances in samples during experiment. Markers specific for total Eubacteria (16S rRNA), nitrate reducers (NRB), iron reducers (IRB) and sulfate reducers (SRB) were used to compare the changes in relative abundances of particular metabolic groups of bacteria in the samples during the experiment. IR – irradiated samples, c_anoxy – anaerobic controls, c_anoxy+nutr – anaerobic controls enriched in nutrients, c-oxy – aerobic controls. The values on x-axis show applied total radiation doses and corresponding weeks of sampling.

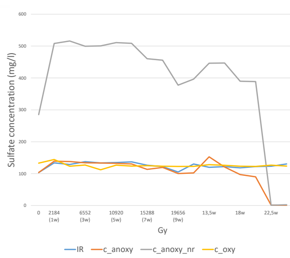

Fig. 2: Concentration of available soluble sulfate in the samples detected by ion chromatography. IR – irradiated samples, c_anoxy – anaerobic controls, c_anoxy+nr – anaerobic controls enriched in nutrients, c-oxy – aerobic controls. The values on x-axis show applied total radiation doses and corresponding weeks of sampling.

Key findings:

- **Application of 19,656 Gy absorbed dose of Gama radiation at the constant dose rate 13 Gy/h not sufficient to completely eradicate present bacteria.**
- No microbial recovery was detected in three months past the end of irradiation.
- Gradual changes in microbial community composition were observed corresponding to the prevailing conditions in the samples.
- Presence of oxygen was the most important factor responsible for functional structuring of the microbial community within the samples.

Aerobic conditions:

- In the aerobic samples (both IR samples and controls) the community changes depended on the available electron donors evolving from heterotrophs (chemorganotrophs) to autotrophs (chemolitotrophs) with the decrease of available organic material.
- Gram negative non-spore forming microorganisms dominated the aerobic samples

Anaerobic controls:

- In the anaerobic conditions, limitation by available electron acceptors and donors was detected.
- The anaerobic communities evolved from heterotrophic facultatively anaerobic nitrate reducers to autotrophic anaerobic iron or sulphur reducers or fermenting microorganisms.
- Iron and sulfate reduction key processes under anaerobic conditions in bentonite.
- Microorganisms consumed all available sulfate witin 22 weeks under anaerobic conditions.

Taxonomical composition:

- The microbial composition of anaerobic controls clearly differed from all the aerobic samples (IR + aerobic controls).
- Radiation caused significant shift in the microbial composition of the irradiated samples compared to non-irradiated aerobic controls.
- *Azohydromonas*, *Jathinobacterium* or *Herpetosiphon* belong to the genera frequent in the irradiated samples, but missing in aerobic controls.
- *Acidovorax*, *Polaromonas* or *Geobacillus* are present only in aerobic control samples, which indicates their potential higher sensitivity to radiation.

Irradiated samples	Aerobic controls
Massilia	*Noviherbaspirillum*
Paenibacillus	*Pseudomonas*
Pseudomonas	*Acidovorax*
Bacillus	*Paenibacillus*
Azohydromonas	*Bacillus*
Noviherbaspirillum	*Geobacter*
Janthinobacterium	*Hydrogenophaga*
Klebsiella	*Caulobacter*
Ammoniphilus	*Gallionella*
Herpetosiphon	*Polaromonas*

Tab. 1: The most frequent microbial genera in irradiated and control samples. genera present only in IR samples are in red, samples unique to aerobic controls are in blue.

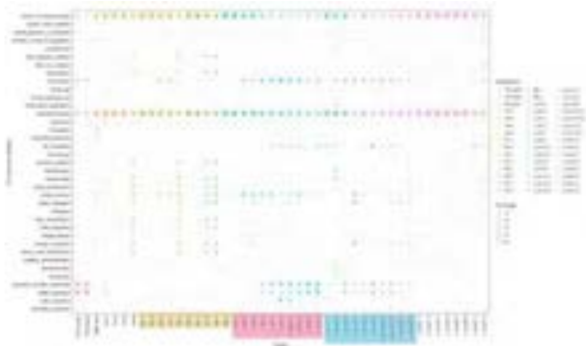

Fig. 3: FAPROTAX analysis enabled us to map detected OTUs to established metabolic or other ecologically relevant functions (on the y axis). The size of the circles in the graph corresponds to abundance of microorganisms possessing the particular metabolic function in the sample (x axis). Zero – zero point suspensions, IR – irradiated samples, c_an – anaerobic controls, c_an_nr – anaerobic controls enriched in nutrients, c-oxy – aerobic controls. First number in the sample description corresponds to the sampling week, second characterize sample in duplicates.

Fig. 4: PCoA analysis visualizing the differences in microbial composition between the samples. The closer the samples are, the more similar is their composition. Zero – zero point suspensions, IR – irradiated samples, c_an – anaerobic controls, c_an_nr – anaerobic controls enriched in nutrients, c-oxy – aerobic controls. First number in the sample description corresponds to the sampling week, second characterize sample in sampled duplicates.

CONCLUSION:

- The largest difference between aerobic and anaerobic samples – **anaerobic conditions generally very suitable for microbial activity** of indigenous microorganisms in BaM bentonite.
- Under aerobic conditions **application of 19,656 Gy total absorbed dose of Gama radiation at the constant dose rate 13 Gy/h did not manage to completely eradicate present bacteria**. The microbial abundances and general metabolic profiles remained rather similar as in aerobic control samples, but the microbial composition slightly changed.
- As anaerobic control samples were dominated by Gram-positive spore-forming bacteria generally more resistant to radiation, we can expect that even higher absorbed doses of ionizing radiation would be needed to eliminate microbial activity under anaerobic conditions – need for similar study under strictly anaerobic conditions.
- **Iron and sulfate reduction are important processes driven by indigenous microorganisms in the BaM bentonite under anaerobic conditions** - possible effect on performance and safety of the repository.

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An active microbial community in Boom Clay pore water collected from piezometers impedes validating predictive modelling of ongoing geochemical processes

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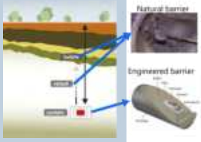
Introduction

Safe geological disposal of radioactive waste



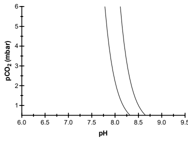
Analysis of pore water is essential for a detailed understanding of the geochemistry of the host formation, as its composition determines among others, the speciation and solubility of radionuclides.

Composition of Boom Clay pore water

Component	Concentration	Component	Concentration
HCO_3^-	880 mg/l	SO_4^{2-}	2.2 mg/l
Na^+	359 mg/l	Ca^{2+}	2 mg/l
Cl^-	26 mg/l	Mg^{2+}	1.6 mg/l
K^+	7.2 mg/l	Br	0.6 mg/l
Si	3.4 mg/l	Fe	0.2 mg/l
F^-	3 mg/l	Al	0.0006 mg/l

Although the elemental composition of Boom Clay pore water is relatively well known, the real mechanisms controlling the pCO2 (g) and the pH, the two most important parameters, are not completely understood.

Models need to be experimentally validated



Solid lines delineate lower and upper boundaries of pH-pCO_2 values calculated from measured Ca^{2+} and HCO_3^- values as input parameters for inverse modelling using the code Geochemist's workbench and the BRGM database.

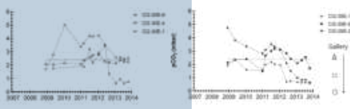
Methods & Results

7 years *in situ* monitoring campaign in HADES

Schematic view of the PRACLAY gallery within the HADES URF and the position of piezometers and filters around the PRACLAY gallery monitored in this study. Right: the *in situ* circulation system used for the sampling of pore water, the sampling of the dissolved gasses, and the measurement of the pH.

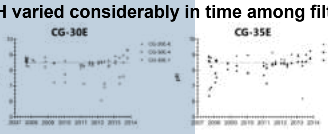
Partial pressure of CO_2 (pCO_2) varied in time

The sampling systems allows Henry's Law to calculate the pCO_2: $p_A = x_A{*}K_A$ where p_A is the pCO_2 in the gas phase, xA is the mole fraction of CO_2 in the liquid phase and K_A is Henry's law constant.



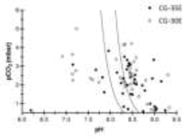
pCO_2 is lower in filters closest to the gallery lining

pH varied considerably in time among filters

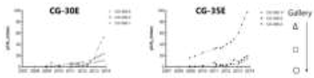


pH is higher in filters closest to the gallery lining

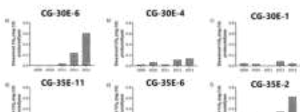
Experimental data do not fit the modeled data



pCH_4 increased in time in all filters

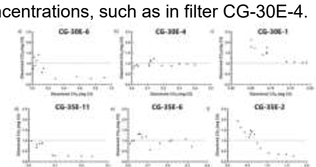


$CH_{4\,(g)}$ production rates increased in time



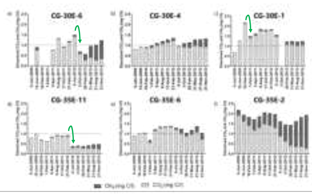
CH_4 (g) production affects the dissolved CO2 (g) – carbonate equilibrium

The dissolved CO_2 (g) should remain constant (dotted line) with increasing dissolved CH_4 (g) concentrations, such as in filter CG-30E-4.

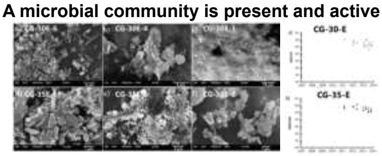


CH_4 (g) alone cannot explain discrepancies in CO_2 (g)

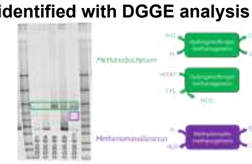
In some cases CO_2 (g) decreased tremendously without increasing dissolved CH_4 (g) concentrations.



A microbial community is present and active

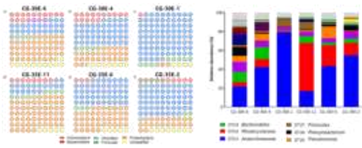


At least 2 different methanogenic archaea were identified with DGGE analysis



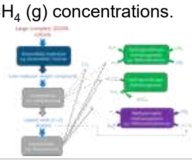
16S rRNA amplicon sequencing indicates a similar trend among filters in the bacterial community

Relative abundance of *Chloroflexi* increases with distance from gallery lining while the relative abundance of *Proteobacteria* decreases. OTU1 representing a species belonging to the *Anaerolineaceae* family increases with the distance from the gallery lining.



A complex methanogenic community is present in the Boom Clay porewater obtained via piezometers, affecting the geochemistry of the porewater.

The nature of the sampling equipment probably stimulated this microbial community, resulting in increased CH_4 (g) concentrations.



Conclusions

Results obtained during this 7 years monitoring campaign indicate a methanogenic microbial community is present in the Boom Clay porewater obtained via piezometers. This microbial community influences the geochemistry of the porewater, thereby hampering validation of current predictive models.

Acknowledgements: This work is partly performed in close cooperation with, and with the financial support of ONDRAF/NIRAS, the Belgian Agency for Radioactive Waste and Fissile Materials, as part of the programme on geological disposal/surface disposal that is carried out by ONDRAF/NIRAS.

Carbon release and speciation from JRT carbon steel and Zircaloy-4 corrosion in highly alkaline solutions

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Introduction

To improve understanding of the carbon and carbon-14 release, during corrosion of radioactive waste materials under disposal repository conditions, the gas release and speciation of carbon species from irradiated and unirradiated Zircaloy-4 samples (representative of the fuel cladding as used in Belgian nuclear power plants) and JRQ carbon steel samples (representative of the reactor pressure vessel (RPV) in Belgian nuclear power plants), were studied in a saturated $Ca(OH)_2$ solution in anaerobic conditions. To achieve this, we performed simple immersion corrosion tests. Carbon-based gas were analysed and quantified by gas chromatography. An estimation of the corrosion rate was also calculated using Co-60 release measurements for carbon steel samples, potentiostatic corrosion tests for Zircaloy-4 samples and simple immersion tests for both materials.

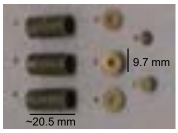
Materials

JRQ carbon steel

JRQ steel representative for end-of-life conditions of RPV steel in Belgium. The elemental composition is given in the table below. Samples used for simple immersion tests possessed a contact dose of ~350 µSv/h.

Element	C	Si	Mn	P	S	Cr	Mo	Ni	N	Fe
wt.%	0.10-0.17	0.60-0.90	0.50-0.80	0.025	0.035	0.50-0.75	0.15-0.25	<0.25	0.019	Bal.

Zircaloy-4 sample

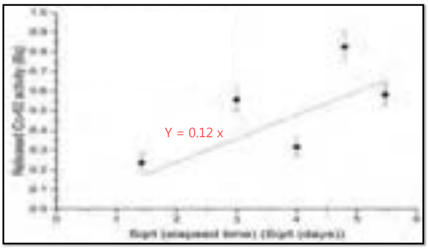


Fuel cladding from Belgium nuclear reactor cut in pieces. Samples A, B and C were used for simple immersion tests. Sample E was used for potentiostatic corrosion tests. The elemental composition is given in the table below. The contact dose rate were 270 µSv/h for sample E and 900, 450 and 400 µSv/h respectively for sample A, B and C.

Element	Sn	Cr	Fe	C	Hf	Si	W	O	N	Zr
wt.%	1.2-1.7	0.07-0.13	0.17-0.24	0.027	0.01	0.012	0.01	0.1-0.14	0.0025	Bal.

Corrosion rate calculation and carbon speciation

Co-60 release from JRQ carbon steel



Linear fit of the Co-60 release data in function of the square root of the corrosion time.

High scatter on the results due to precipitation of small size particles in the analysed solution. From this regression, the parabolic rate law of the Co-60 release can be obtained. It is given by:

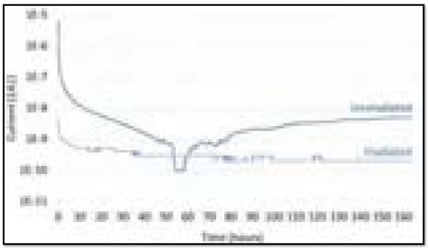
$$R_{Co\text{-}60} = (0.12 \pm 0.02)\sqrt{t}$$

This leads to a release of 2.3 Bq after one year.

Taking the sample size (2 x 2 x 35 mm) and its total Co-60 activity of 1.6 x 10^5 Bq, this leads to a corrosion rate of **7 nm/yr**.

Low corrosion rate compared to literature [1], but can be explained by the presence of the precipitates possibly catching some Co-60.

Potentiostatic measurement of Zircaloy-4



Current as a function of the time (recorded at a fixed potential of -0.7 V vs. Ag/AgCl).

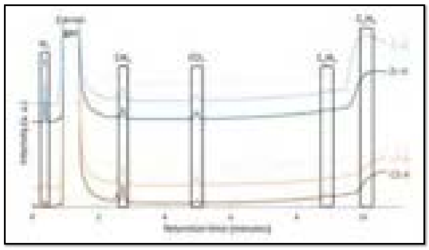
The potentiostatic tests were conducted for ~7 days. The current decreased up to nanoAmpère or less before to stay constant.

Considering that all the recorded current originated from the corrosion of the metal, an approximation of the corrosion rate could be calculated.

For the **unirradiated** Zircaloy-4: **~54 nm/yr**
For the **irradiated** Zircaloy-4: **~ 4 nm/yr**

Lower value for the irradiated samples due to the initial presence of the passive oxide layer at the beginning of the test. From the literature, a corrosion rate of 20 nm/yr was suggested [2] indicating the conservative nature of the rate obtained from the unirradiated sample.

Simple immersion tests: gas release (both samples)



Gas chromatographs of gas sampling from the headspaces of the simple immersion corrosion tests after ~6 months experiments.

Production of **hydrogen**, **methane**, **carbon dioxide** and **ethene** from both materials. Detection of **ethane** too from the corrosion of the carbon steel samples. Methane is the major contributing component.

Assuming that all the carbon present in the metal bulk and released during corrosion was transformed in carbon-based gas, an approximation of the corrosion rates could be calculated:

For the **irradiated Zircaloy-4**: **57-84 nm/yr** (depending if the CO_2 concentration was taken into account).

For the **irradiated carbon steel**: **68-117 nm/yr** (depending on the carbon concentration in the samples (0.10-0.17 wt.%)).

Conclusions

This work investigated the release of carbon from irradiated and unirradiated Zircaloy-4 and JRQ carbon steel samples, as well as their corrosion rate in a saturated $Ca(OH)_2$ solution in anaerobic conditions. After ~6 months duration of the simple immersion corrosion tests on irradiated samples, the analysis of the gas phase by GC revealed the production of hydrogen, methane, ethene and carbon dioxide from the corrosion of Zircaloy-4 samples, while, ethane is also detected from the corrosion of carbon steel. Based on the measured gas concentrations, an approximation of the calculated corrosion rate was 57–84 nm/yr and 68-117 nm/yr, respectively for Zircaloy-4 and JRQ carbon steel.
The corrosion rate of the JRQ carbon steel samples was also calculated by the release of Co-60 and led to a corrosion rate of 7 nm/yr. This is lower than the ~ 100 nm/yr, but this may be explained by the observation of precipitation in the analysed solution. Potentiostatic corrosion tests on unirradiated Zircaloy-4 provided a corrosion rate of ~54 nm/yr over a 7 day-experiment, if it is assumed that all the recorded current originates from the corrosion of the unirradiated Zircaloy-4, whilst a corrosion rate of only ~4 nm/yr was calculated for the irradiated samples. This lower value is maybe due to the presence of a passive film formed on this sample after the potentiodynamic test.

References

(1) Mihara M. et al. (2002). Estimation on gas generation and corrosion rate of carbon steel, stainless steel and zircaloy in alkaline solutions under low oxygen conditions. ZNC Technical Review, 15, 91-101.
(2) IAEA (2006). Understanding ang managing ageing of material in spent fuel storage facilities. IAEA Technical Reports serie 443.

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The beneficial role of microbes in nuclear waste disposal

EPFL nagra.

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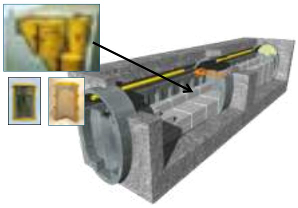
[2]National Cooperative for the Disposal of Radioactive Waste, NAGRA, Wettingen, Switzerland

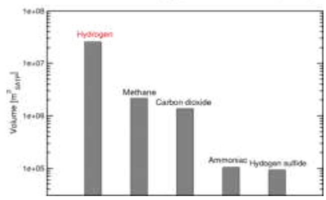
The Swiss design for a low and intermediate level waste repository

A deep geological repository in Opalinus Clay rock located at around 500 meters below the surface is proposed as place of safe storage for low and intermediate level waste (L/ILW). Currently, three sites in the North-West of Switzerland are under consideration. Large quantities of H_2 gas are expected to evolve from the anoxic corrosion of steel and the degradation of organic wastes. Engineered gas transport systems (EGTS) are proposed to decrease the pressure built-up within the repository but no gas sink is currently included in the design.

1. Main facility
2. Pilot facility
3. Test zones
4. Access tunnel
5. Ventilation and construction shafts



Prediction of evolving gases in L/ILW repository



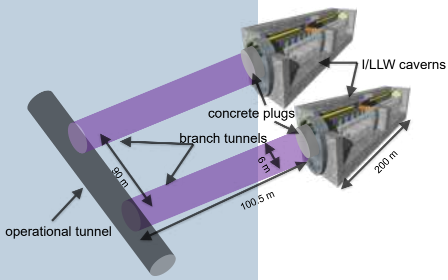
Diomidis, N. et al. Production, consumption and transport of gases in deep geological repositories according to the Swiss disposal concept - Technical Report 16-03. (**2016**).

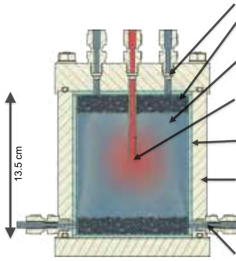
Taking microbial activity into account – How to asses the potential benefits of microbial activity?

Each of the 200 meter-long caverns holding L/ILW will give rise to 4,000m³ H_2 (SATP) per year. This represents 451'380.5 moles of H_2 per year (base case AG1). However, microbial oxidation of H_2 is a common microbial process. Hence, evolving gases may be consumed by microbial activity in backfilled branch tunnel (backfilled with a 80:20 weight-base sand to bentonite ratio and representing 19% of external porosity) and operational tunnels (backfilled with a mixture of sand and crushed Opalinus rock). EGTS provide H_2 from anoxic metal waste degradation, sulfate-rich porewater is provided from the host rock, leading to sulfate reduction as the most likely microbial metabolism to influence the gas balance in this concept. Considering a 19% porosity of the branch backfill material and a hypothetical **microbial community** capable of oxidizing 143 moles H_2 day^{-1} m^{-3}, then, 90% of the daily hydrogen evolving from the waste degradation would be **consumed in a ~100 meter-long branch tunnel**. The remaining 10% of gas would be consumed in the backfilled operational tunnel.
To test the ability of microbes to oxidize H_2 in backfill material, bioreactors were deployed at the Underground Rock Laboratory (URL) Project Mont Terri to investigate the *in situ* rates of sulfate reduction and to determine the geochemical conditions necessary to reach even lower redox states when the porewater is depleted in SO_4^{2-} which enable the evolving biofilms to produce CH_4 in terms of methanogenesis.

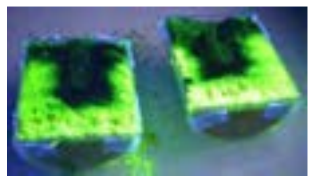
sulfate reduction $6H_2 + HCO_{3\,(aq.)}^- + SO_{4\,(aq.)}^{2-} + 2H^+ \rightarrow CH_2O_{(biomass)} + HS^-_{(aq.)} + 6H_2O$

methanogenesis $4H_2 + CO_{2\,(aq.)} \rightarrow CH_4 + 2H_2O$





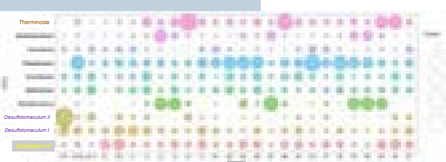
Water flows preferentially at the interface with plexiglas due to a lower flow resistance compared to the porous medium. This creates a gradient of bio-available SO_4^{2-}.

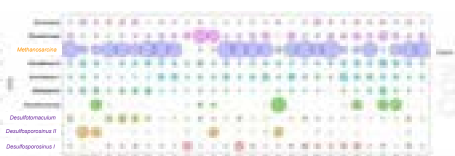


Results of two bioreactors in two different experimental set-ups showing a microbial community capable of sulfate reduction and methanogenesis

Bioreactors were retrieved from URL Mont Terri and disassembled under sterile conditions to obtain two halves. The spatial distribution of the microbial community was investigated. The microbial groups identified were assigned a putative metabolism (solely based on 16S rRNA gene identification). The top 5 functional groups for each of the sampled points are plotted as relative abundance (in %) in an overlay of the dissected bioreactors, bubble plots (below) representing an overview of the top 10 operational taxonomic units (OTUs) of all samples obtained.

The observed preferential flow path of porewater determines the location of activity for sulfate-reducing bacteria. The top coarse sand layer is assumed to hold a gas phase of H_2 from where H_2 can diffuse into the porewater. The hotspot of H_2 consumption is expected close to the gas phase (at the top) and close to the H_2 inlet tube (middle), dominated by SRB as long as the SO_4^{2-} is not depleted. Where no SO_4^{2-} is available, methanogens will use the H_2 and grow throughout the bioreactor. Fermenting bacteria occur everywhere, feeding on residual organic matter and biomass produced by SRB and methanogens.

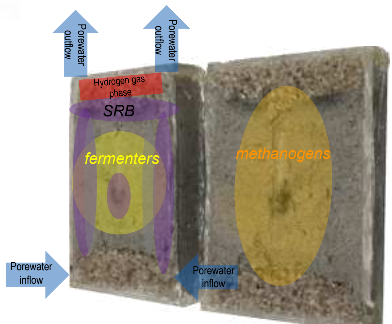




iron-reducing bacteria
sulfate-reducing bacteria (SRB)
methanogenic archaea
sulfur-oxidizing bacteria
nitrate-reducing bacteria
fermenting bacteria
syntrophic bacteria

A microbial community is fueled by hydrogen and has the potential for a) sulfate reduction, b) iron or sulfur reduction.

The biofilm has the potential for methanogenesis in absence of sulfate



This project has received funding from the Euratom research and training programme 2014 - 2018 under grant agreement No. 661880

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Study of impact of gamma radiation and LOCA environment on concrete structure behaviour

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Concrete gamma irradiation

Fine aggregate mixed-Portland cement concrete was exposed to the doses of 1.6 to 1.8 ×106 Gy (1.6 to 1.8 ×108 rad) with a rate of 0.5 to 4.5 kGy (Figures 1 and 2) per hour under the temperature 24±3°C in a gamma radiation cell with a gamma source of 172 TBq (60Co).

The composition of the concrete was selected according to the sample size and the requirements of the standards. Also to fit to the Czech NPPs composition taking into account their fine aggregate composition, i.e. siliceous sand 0 ÷ 4 mm.

Little prisms 40x40x160 mm made of standardized siliceous sand 0 ÷ 2 mm were tested after 21 days in the gamma radiation cell non-destructively by ultrasonic and resonance methods to check the change of the E-modulus of irradiated concrete (see Figures 4 and 5).

All samples were taken out of the cell after next 27 days and tested non-destructively and destructively.

Figure 1. Samples before inserting to irradiation cell with the cobalt 60 source

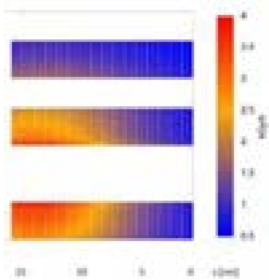

Figure 2. Distribution of the doses rates in irradiated samples

Concrete LOCA and post LOCA treatment

World nuclear power plants NPPs are designed for any case of exceptional state. LOCA, Lost of Coolant Accident is one of the severe accidents. There are three types of LOCA: LOCA inside the reactor when the core melts due to the loosing of the coolant; LOCA inside the containment and LOCA outside the containment vessel. Huge expansion of the temperature and air pressure follows after the loosing of the coolant. It is important to sustain the durability of all the NPP's components during severe accident as LOCA. Concrete components designed as pre-stressed reinforced concrete wall or reinforced concrete floor of the containment vessel must resist elevated temperatures, steam and air pressure.

The in-containment-vessel LOCA is presented in the contribution (Fig 3). Its parameters were selected such to be similar to Czech NPP Temelin which has nuclear reactor of WWER 1000. For this experiment the cumulative dose 1.6 to 1.8 MGy of gamma radiation was applied during 21 + 27 days of irradiation in the gamma irradiator. After consequent non-destructive tests the temperature was increased rapidly to +250°C and the pressure to +9 bars (Fig 4). It happened during several seconds.

Figure 3: Samples prepared for LOCA experiment in steel vessel

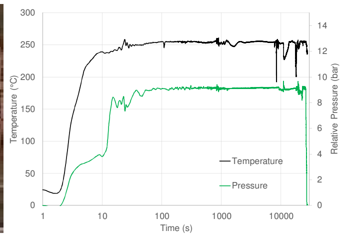

Figure 4. Record of expected and measured temperatures and pressures inside the pressure vessel during LOCA

Results of the experiments

Dynamic moduli of elasticity, compressive and tensile strenghts were compared before and after gamma irradiation, also after LOCA treatment.

The results are provided in Figures 5, 6 and 7. Deatail view of the samples is in Figure 7.

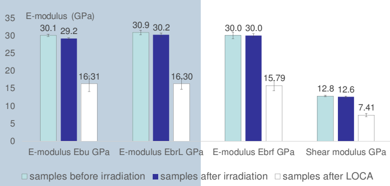

Figure 5. Moduli of elasticity determined by ultrasonic and resonance methods

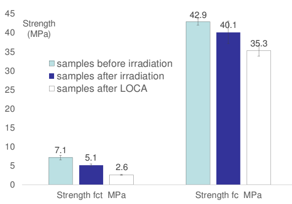

Figure 6. Tensile and compressive strenght of concrete samples

Figure 7. Details of concrete surface before irradiation a), after gamma irradiation b) and after LOCA c)

While gamma irradiation has no visible effect, the effect of LOCA and post-LOCA shower by boron acid solution is remarkable.

Conclusions

The high dose irradiation (more than 0.5 kGy per hour) had a significant effect solely on the flexural strength, which remained in 73 ± 9 % of the reference samples'. Deterioration of all other magnitudes, concrete physical or chemical properties, was not considerable. Although, lower compressive strength was found in 2 out of three tested samples after gamma irradiation. The third tested sample had higher value than the reference samples.

The damage caused by sudden increment of temperature and pressure while Lost of Coolant Accident (LOCA) simulation was much higher than in the case of pure gamma irradiation. Both observed strengths decreased considerably. Residual flexural and compressive strengths were 37 ± 9 % and 82 ± 4 % of the reference samples', respectively. All dynamic attributes of concrete samples investigated non-destructive testing decreased due to LOCA. Dynamic moduli of elasticity or shear modulus were lowered by 42 ± 2 %.

Acknoledgement

Concrete samples were designed, fabricated and pre-inspected by financial support of the Ministry of the Interior of the Czech Republic, by the project VI20152018016 Non-destructive testing of biological shielding concrete. Irradiation of concrete samples and post-irradiation examination was financially supported by the Ministry of Education, Youth and Sport Czech Republic - project LQ1603 Research for SUSEN.

4-7 June 2019 Pitesti, Romania

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Development and improvement Of NUmerical methods and Tools for modelling coupled processes: a R&D initiative within EURAD

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[1]BRGM, France, [2]GRS, Germany, [3]Andra, France, [4]INRIA, France, [5]UFZ, Germany, [6]PSI, Switzerland, [7]TS Enercon, Hungary, [8]Surao, Czech Republic

Context

Understanding of multi-physical Thermo-Hydro-Mechanical-Chemical coupled processes (THMC) occurring in radioactive waste disposal is a major and permanent issue to support optimization of design and safety case abstraction. Numerical simulations are necessary to make predictive multi-physical analyses for time periods and space scales larger than experiments can cover. These numerical simulations require integrating, in a consistent framework, an increasing scientific knowledge acquired for each of the individual components of a system for radioactive waste disposal. This implies to consider couplings of different and non-linear processes from a wide range of materials with different properties as a function of time and space in ever-larger systems.

The development of cutting-edge and efficient numerical methods is thus necessary, in the scope of having useful, powerful and relevant numerical tools for assessments. It is also necessary to manage the uncertainties associated to the input data feeding the models and the representation of the processes, to assess the range of variability of the results and to identify the main parameters and processes driving the behaviour of the systems of interest. Managing uncertainties in these complex systems require the improvement and the development of innovative, appropriate and efficient numerical methods.

WP Main Objectives

- Development of relevant, performant & cutting-edge **numerical methods that can easily be** implemented in existing or new tools, in order to carry out high-performance computing to study of **highly coupled processes** in large systems (reactive transport, 2-phase flow & THM modelling in porous and fractured media);
- Development of numerical **scale transition schemes** for coupled processes (meso to macro scale, or pore to Darcy scale) supporting the study of specific multi-scale couplings e.g. chemo-mechanics;
- Development of **innovating numerical methods** to carry out uncertainty and sensitivity analyses;
- **Benchmark exercises**, on representative test cases, to test the efficiency of developed methods (robustness, accuracy, time computational) on relevant tools.

WP Main Impacts

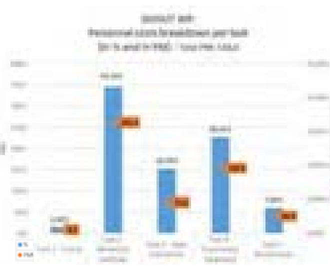
- **Improvement of multi-physical understanding of radioactive waste disposal**
- **Supporting design and abstraction for safety case**
- Bring together at European level diverse scientific communities to reinforce innovation through cross-fertilization
- Skills developments for young researchers through thesis or postdoc funding
- Interaction with civil society through strategic studies (e.g. UMAN)
- High scientific-technical impact (via open peer-publications, benchmark exercises, etc...)

Involved Organization

Organisations
✓ **Andra**, France (WMO) ▪ BRGM, France
✓ **CEA**, France (RE) ▪ EDF, France
✓ **CNRS**, France (RE) ▪ ULille, France ▪ Unice, France
✓ **COVRA,** Netherlands (WMO)
✓ **ENRESA**, Spain (WMO) ▪ UDC, Spain
✓ **FZJ**, Germany (RE) ▪ HZDR, Germany ▪ UFZ, Germany
✓ **GRS**, Germany (TSO)
✓ **IRSN**, France (TSO)
✓ **LEI,** Lithuania (RE)

Organisations
✓ **MTA EK**, Hungary (RE) ▪ SORC, Hungary
✓ **NRG**, Netherlands (TSO)
✓ **PSI,** Switzerland (RE)
✓ **SCK-CEN**, Belgium (RE)
✓ **SURAO**, Czech Republic (WMO) ▪ CTU, Czech Republic ▪ CU, Czech Republic ▪ IGN, Czech Republic ▪ TUL, Czech Republic ▪ UJV, Czech Republic
✓ **TS Enercon,** Hungary (TSO)
✓ **TUS,** Bulgaria (RE)
✓ **UHELSINKI**, Finland (RE) ▪ TUT, Finland

Planned resources



Naumov et al. (2018): OpenGeoSys-6. In: Thermo-Hydro-Mechanical-Chemical Processes in Fractured Porous Media (Eds Kolditz O, Nagel Th, Shao H, Wang W, Bauer S), Springer text book

Design and implement efficient numerical algorithms taking advantage of the latest research achievements for solving complex coupled problems

- numerical algorithms for parallel computing (e.g., linear solvers, domain decomposition,...)

- efficient multiscale numerical methods for coupled problem

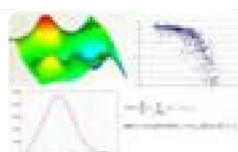
- adaptive grid generation and stopping criteria based on a posteriori error estimates

Churakov & Prasianakis *Am. J. Science, 318 (9)* 921-948.

Coupled processes are inherently multi-scale. Several numerical tools for individual processes at each scale are well established. However, coupling between processes and scales is missing.

- Provide numerical methods to bridge spatial scales (atomic scale not tackled in DONUT)

- Provide tools that enable the consideration of chemo-mechanical process couplings



Development of innovating numerical methods to treat uncertainty and sensitivity analysis on complex coupled representative cases with strong non-linearities (2 phase flow, THM, reactive transport)

- intrusive / non intrusive methods

- global/local sensitivity analysis

- variance decomposition with specific tools (surrogate models / metamodels)

Marty, N.C.M. et al.(2015) Comp. Geo. 19, 635-653.

Development of suitable benchmarks, mainly derived from 2-phase flow, THM, and reactive transport test-cases at large time and space scales (porous/fractured and free media)

- Implementation of numerical methods developed at task 2, 3 and 4 in existing tools used by each involved partner,

- Quantification of efficiency of each methods (speed, accuracy, improvement of knowledge, …)

4-7 June 2019
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EURAD: SFC WP
Spent Fuel Characterisation and Evolution Until Disposal

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Task 1 - S/T coordination, State-of-the-art and training material

Task objectives:

- To provide efficient management and administration of the work package, to identify potential problems at an early stage and provide timely and effective solutions.
- Developing/updating State-of-the-art, performing WP-specific gap analysis.
- Developing training materials as an input to KM.
- Collecting data from tasks 2-4.
- Collecting experience from the project to guide efforts in a possible future 2nd wave of the programme.

Subtask 1.1 – S/T coordination

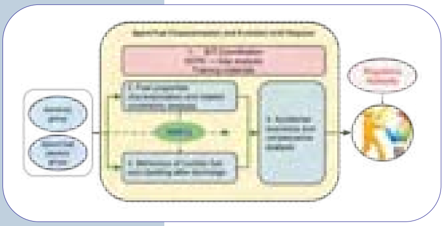
- WP operational management and performance monitoring
- WP information and communication management

Subtask 1.2 – State-of-the-art and Gap analysis

- Current state-of-the-art: The current state-of-the-art of nuclear fuel characterisation and evolution of its properties will be summarized in a state-of-the-art report
- Updated state-of-the-art: At the end of the project, the report describing state-of-the-art will be complemented with text on how state-of-the-art has been improved by contributions from the project

Subtask 1.3 – Training materials

- Training material, in the form of e.g. lecture materials, containing state-of-the-art of nuclear fuel modelling, characterisation and evolution of nuclear fuel until disposal, is to be developed during the project in close link with KM Training/Mobility WP.



Task 2 - Fuel properties characterisation and related uncertainty analysis

The main objective is to produce experimentally verified procedures to estimate reliable source terms of spent nuclear fuel (SNF), including realistic uncertainties. The main source terms of interest are gamma-ray and neutron emission rate spectra, decay heat and inventory of specific nuclides, i.e. activation products (e.g. ^{14}C and ^{36}Cl), long lived fission products (FP), fissile nuclides (^{235}U, ^{239}Pu) and minor actinides (^{241}Am, $^{242,244}Cm$). The inventory of fissile nuclides is needed for reactivity calculations to prevent criticality and nuclear safeguards requirements. The inventory of activation products and long-lived FP are important to study the impact to the biosphere. Some of the FP (e.g. ^{148}Nd) are used to for burnup determination.

Subtask 2.1 – Theoretical study of SNF source terms

Subtask 2.2 – Develop, improve and demonstrate NDA methods/systems for SNF characterisation

Subtask 2.3 – Determine the inventory of activation and fission products in cladding material

Subtask 2.4 – Define and verify procedures to determine the source terms of SNF assemblies with realistic confidence limits

Task 3 - Behaviour of nuclear fuel and cladding after discharge

The aim of the work is to understand and describe numerically the behaviour of spent nuclear fuel (SNF), irradiated cladding, fuel/cladding chemical interaction (FCCI) and ageing effect under conditions of extended interim storage, transportation and emplacement in a final disposal system. These objectives will be achieved by involving experimental works and modelling studies.

Subtask 3.1 – Thermo-mechanical-chemical properties of SNF rods and cladding

- Thermo-mechanical-chemical properties of unirradiated and irradiated samples of spent nuclear fuel rod segments and cladding (BAM leading institution with contributions of CIEMAT, JRC-KA, MTA-EK, NAGRA, UPM, VTT).

Subtask 3.2 – Behaviour of SNF pellets under interim storage conditions

- Influence of oxygen and fission products on microstructure of UO2 fuel and He within the UO2 matrix (HZDR leading institution with contributions of CIEMAT, CNRS-CEMHTI and CNRS-ICSM).

Subtask 3.3 – Pellet-cladding interaction under conditions of extended storage, transport and handling of SNF rods

- Chemical and structural / crystallographic properties of simulated fuel pellets and irradiated fuel pellets at the cladding/fuel interface (KIT leading institution with contributions of CIEMAT and PSI).

Task 4 - Accident scenario and consequence analysis

The main goal of this work package is to study SNF behaviour under accident conditions which may lead to a potential loss of confinement during storage, transport and pre-disposal activities. As a result, the task will be fed by the empirical formulations in conjunction with mathematical numerical models produced in task 2 and task 3 and building up synergetic activities, to the development of concepts for the mitigation of the consequences.

Subtask 4.1 – Accident scenario for fuel under dry interim storage conditions.

The subtask aims to provide a synthetic analysis of identified potential but credible accident scenarios related to the transport and long-term dry interim storage of SNF.

a) Accident conditions during transport, two main specific objectives are planned by establishment of a comprehensive methodology for assessing the postulated scenarios, based on analytical tools with 3D capabilities and development of an engineering methodology capable of assessing the scenarios with considerably less computational cost and without losing accuracy.

b) Regarding accident conditions in interim storage, two specific tasks are to be tackled by development of a vault model adapted to a lumped parameter code and establishing a methodology for determination of the potential source term.

Subtask 4.2 – Consequence analysis of accident scenarios.

Experimental investigations and analytical studies from previous tasks are considered to assess accident scenarios with loss of cladding integrity.
The experience gained from investigating the real consequences of beyond design basis accident at Chernobyl NPP would also support the assessment of simulation models for radiation release and environmental impact.

4-7 June 2019
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EURAD HITEC: INFLUENCE OF TEMPERATURE ON CLAY-BASED MATERIAL BEHAVIOUR

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[2]University of Lorraine, CNRS, GeoRessources, 2 rue du Doyen Marcel Roubault, 54518 Vandoeuvre-lès-Nancy - France
[3]CTU in Prague, Centre of Experimental Geotechnics, Thákurova 7, 166 29 Prague 6 – Czech Republic

General

Most of Deep Geological Repository Safety Cases limit maximum temperature to 100°C. Higher temperatures can have significant advantages such as higher enrichment/burn-up fuels, shorter interim storage requirements, easier (re)packaging of the waste, reduced footprint of the disposal. The overall aim of the HITEC Work package of EURAD project is to improve Thermo-Hydro-Mechanical (THM) description of clay based materials - host clay rock and bentonite buffer - at elevated temperatures. HITEC work programme aims to provide results that are applicable to a wide range of buffer materials and host clay rocks, which can be useful for different national programmes. For host clay rock temperatures under 120°C and for bentonite buffer temperatures under 150°C are considered.

The HITEC Work package will be carried out by 30 organisations from 12 countries. The HITEC will be led by VTT Technical Research Centre of Finland Ltd. The two technical tasks are:

1. Host clays formations - led by University of Lorraine
2. Buffer bentonite - led by CTU in Prague

Host clays formations

The characterization of in situ THM behaviour of the host clay rocks is significant for the design of the underground nuclear waste disposal facility and for the long-term safety. When temperature increases in a low permeable media, the pore water is compressed as a consequence of the difference between its thermal expansion coefficient and that of the solid skeleton of the rock, which leads to an over pressure.

In the near field, the excavation of galleries or micro tunnels induces a fractured zone around them. The evolution of the effective stress field due to the temperature rise can induce fracture opening or propagation of the excavation damaged zone (EDZ). The focus will be to assess, through lab experiments (fractures self-sealing tests at high temperatures), a possible extension of the EDZ and permeability evolution.

In far field, the pore pressure induced by the temperature increase leads to a decrease of the effective vertical stress, which can reach the tensile strength of the rock and induce damage. It could therefore reactivate fracture/fault. The focus will be to characterize, through lab experiments (triaxial tests at high temperatures), the THM behaviour of host clay rocks.

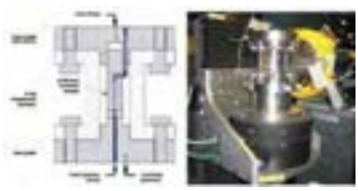

Figure 1: Left: schematic representation of a triaxial compression cell with a fractured sample for self-sealing tests. Right: the triaxial compression cell in a X-ray nano-Tomograph.

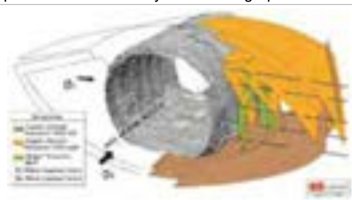

Figure 2: Vertical cross section of the EDZ with the different induced fractured zones.

Buffer bentonite

The investigation of buffer behavior at high temperatures is important for the design optimization of the underground nuclear waste disposal facility and for the long-term safety. The increase of temperature may result in strong evaporation near the heater and vapor movement towards the external part of the buffer. Therefore, part of the barrier, or all of it, depending on the particular disposal concept, will remain unsaturated and under high temperatures during period that can be very long. Moreover the high temperature gradient (and pore pressure) even crossing boiling point of water will lead to several adverse effects.

HITEC is investigating buffer material behaviour is divided into three areas:

- Assessment of the impact of having clay buffer subjected to high temperatures over long time periods on the clay buffer properties.
- Determination of bentonite hydro-mechanical properties for temperatures higher than 100°C, which will provide parameters for the modelling work.
- Identification of key processes at high temperature, particularly those affecting the saturation rate. Calibration and development of suitable THM models for clay buffer at higher temperatures.

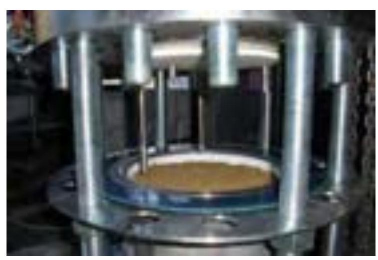

Figure 3: Inside view of high temperature bentonite experimental system (CTU).

HITEC is a Work package of EU project 847593 - EURAD

Uncertainty Management multi-Actor Network (UMAN)

Frank Lemy[1], Valéry Detilleux[1], Dirk-Alexander Becker[2], Daniela Diaconu[3], Astrid Göbel[4] and Julien Dewoghelaere[5]

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[2] GRS, Braunschweig, Germany
[3] RATEN, Pitesti, Romania
[4] BGE, Peine, Germany
[5] MUTADIS, Paris, France

1. Rationale

While the involvement of stakeholders is essential to the decision-making process at all stages of a radioactive waste management programme, decisions associated with each of these stages have to be made in the presence of both irreducible and reducible uncertainties. Some of these uncertainties decrease as new information becomes available (e.g. "as-built" properties, monitoring data, RD&D results,…) whereas activities associated with the programme (process modelling, safety assessment,…) can also lead to new viewpoints and sometimes new uncertainties.

At the end of the process, uncertainties will inevitably remain but it should be demonstrated that these uncertainties do not undermine safety arguments. Hence, the management of uncertainties represents a key part of successful programme planning and is central to the safety case of waste management facilities. Dealing with uncertainties associated with waste disposal facilities is particularly challenging due to the long timescales during which the radiotoxicity of the waste remains significant.

Uncertainty is a cross-cutting issue within the different themes and stages identified in the Roadmap and in the Strategic Research Agenda of the newly established European Joint Programme on Radioactive Waste Management (EURAD). Associated RD&D activities are expected to reduce uncertainties by improving the state-of-knowledge.

Comprehending the contribution of these activities to their management is important for the different actors involved in the decision-making process and for the identification of future priorities.

2. Objectives

The objectives of the Uncertainty Management multi-Actor Network (UMAN) are as follows:

- Develop a common understanding among the different categories of actors (WMOs, TSOs, Research Entities & Civil Society) on uncertainty management and how it relates to risk and safety;
- In cases where a common understanding is beyond reach, to achieve mutual understanding on why views on uncertainties and their management are different for various actors;
- Share knowledge/know-how and discuss common methodological-strategical challenging issues;
- Identify the contribution of past and on-going RD&D projects to the overall management of uncertainties;
- Identify remaining and emerging issues and needs that could be addressed in subsequent waves of EURAD.

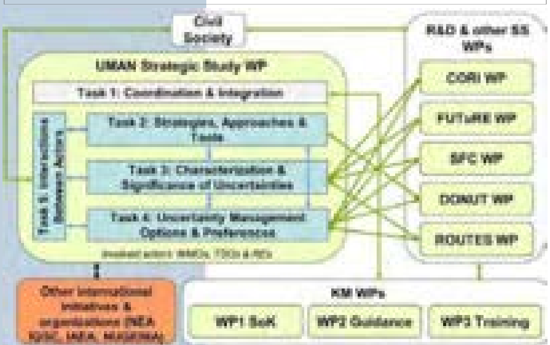


Figure 1. UMAN WP structure and interactions.

3. Work Programme

This Work Package (WP) of EURAD includes the following tasks (Figure 1):

- Task 1 - Coordination, interactions with Knowledge Management (KM) WP & integration
- Task 2 - Strategies, approaches and tools
- Task 3 - Characterization and significance of uncertainties for different categories of actors
- Task 4 - Uncertainty management options and preferences of different actors across the various programme phases
- Task 5 - Interactions between all categories of actors including Civil Society

A particular focus will be put in the first wave of the Programme on potentially safety-relevant uncertainties associated with the following topics in direct link with RD&D WPs of EURAD and/or for which exchanges have been identified as beneficial by the actors themselves:

- Waste inventory and impact of predisposal steps;
- Spent fuel (characteristics, release processes and ageing);
- Site and geosphere characteristics;
- Human aspects.

4. Interactions

Interactions between the different tasks and types of actors including civil society are central to this WP as illustrated in Figure 1. These interactions will take place notably through workshops and seminars (Task 5) where the significance of identified uncertainties (Task 3) as well as possible strategies and options to manage them (Tasks 2 and 4) will be discussed.

Interactions with the ROUTES and the RD&D WPs of EURAD are also foreseen on the identification, characterisation and potential significance of uncertainties associated the above mentioned topics. The knowledge consolidated or generated through knowledge/know-how sharing and discussions of common challenging issues constitutes also a valuable input to KM WPs. Furthermore, collaborations and synergies with other international initiatives and organizations (such as IAEA, NEA, NUGENIA) are planned.

5. Expected impacts

UMAN is expected to contribute to the vision statement of EURAD by:

- fostering mutual understanding and trust between actors;
- enhancing the understanding of the risks and uncertainties;
- ensuring societal visibility and transparency of RD&D.

The WP will contribute as well to targeting the scope of future programme activities onto uncertainties that are most significant in terms of their impact on the safety cases and the implementation of waste management programmes. UMAN is also expected to contribute to the fulfillment of implementation needs and safety case concerns by:

- compiling, reviewing, comparing and refining uncertainty management strategies, approaches and tools;
- identifying possible options for the management of specific safety-relevant uncertainties at different programme phases;
- addressing the identification and characterization of potentially safety-relevant uncertainties that need to be considered in safety cases;
- identifying methods for exchanging on uncertainties and their management during the development and review of the safety cases.

The EURAD EU Project Work Package FUTURE:

Fundamental UndersTanding of radionUclide REtention

PAUL SCHERRER INSTITUT PSI · ÚJV · JÜLICH Forschungszentrum · SCK•CEN · HZDR · brgm

EURADWASTE '19

Sergey V. Churakov[1], Vaclava Havlova[2], Dirk Bosbach[3], Norbert Maes[4], Martin Glaus[1], Cornelius Fischer[5], Bart Baeyens[1], Sylvain Grangeon[6], Maria Marques Fernandes[1]

[1]PSI, Switzerland; [2] Řež a.s, Czech Republic; [3] FZ-JUELICH, Germany; [4] SCK.CEN, Belgium; [5] HZDR, Germany, [6] BRGM, France.

The work package (WP) FUTURE is dealing with radionuclides retention and transport in repository systems in clay/clayrock and crystalline rocks. Twenty European Research Entities (RE), Waste Management Organisations (WMO) and Technical Support Organisations (TSO) are integrated. FUTURE is organized in two main tasks: (1) MOBILITY, comprising work on mobility of radionuclides in compacted clay, the mobility of radionuclides in crystalline rock and the reversibility of sorption as well as (2) REDOX, comprising work on redox reactivity of radionuclides on mineral surfaces.

Main Objectives

The main research objectives of the WP FUTURE comprise:

(i) Impact of chemical boundary conditions (pH, ionic strength) and the rock microstructures on radionuclide (RN) speciation, mobility and sorption reversibility in argillaceous and crystalline rocks.

(ii) Quantitative and mechanistic understanding of the impact of specific surface properties of materials (diffusive double layer, surface potential), the role of grain boundaries, and structural heterogeneity on the mobility of chemical species at pore scale.

(iii) Relationships between fracture/pore structures and transport as well as the feedback of mineral reactions on RN mobility/retention.

(iv) Fundamental understanding of surface induced (heterogeneous) redox processes relevant for uptake of redox-sensitive radionuclides at Fe^{II}/Fe^{III} bearing minerals surfaces.

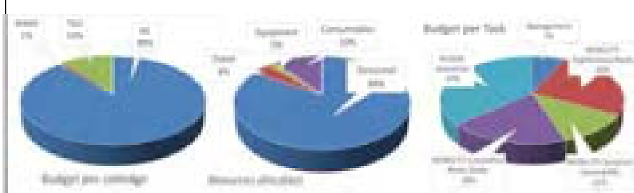
Impact: The WP will provide:

- Scientific basis needed to bound the applicability range and to estimate uncertainties in the simplistic concepts used in the current safety assessment (SA) studies.
- Mechanistic process description necessary to ensure that all relevant processes are sufficiently understood and are taken in to account in SA at an appropriate level, e.g. surface diffusion, sorption mechanisms, competition and reversibility in clay rocks.
- Unique experimental dataset for model based analysis of RN mobility/retention coupled to mineral reactivity, real rock heterogeneities and flow field condition.
- Improved scientific basis for the safety case for deep geological disposal in argillaceous and crystalline rock. Reduction of uncertainties and conservatisms in descriptions of repository system evolution.

Contributing organization

Organisation	Function	Country	Organisation	Function	Country
BRGM	RE	France	Andra	WMO	France
CEA	RE	France	RAWRA/SÚRAO	WMO	Czeck Republic
CNRS	RE	France	UJV	LTP/RE	Czeck Republic
UGrenoble	RE	France	TNO	RE	Netherland
UPoitiers	RE	France	MTA EK	RE	Hungary
FZJ	RE	Germany	RATEN/ICN	RE	Romania
HZDR	RE	Germany	SCK-CEN	RE	Belgium
KIT	RE	Germany	UHELSINKI	RE	Finland
JGU INC MAINZ	RE	Germany	CIEMAT	TSO	Spain
PSI	RE	Switzerland	GRS	TSO	Germany

Budget and resources



Task MOBILITY: Argillaceous rocks

Objectives:

- To relate the mobility of radionuclides with structural information from diffusion profiles and from batch interaction experiments

Systems:

- Weakly, moderately or strongly sorbing radionuclides (e.g. Se, Ni, Ra, Eu, U)
- Pure clay minerals (e.g. illite) or clay rocks (e.g. Opalinus or CallovoOxfordian Clay), both in dispersed and compacted state

Outcome:

To enable a better description of radionuclide mobility by identifying potential mobile surface species in relation to structural information.

Task REDOX: Redox reactivity of radionuclides on mineral surfaces

Objectives:

- Investigate the interaction between different redox–sensitive
- radionuclides and relevant Fe-bearing minerals.
- Correlate the mineral properties with respect to its redox reactive iron content (structural/adsorbed) (i.e. abundance, location in the crystal structure, and oxidation state(s)) to the degree of radionuclides retention (Kd) and molecular scale surface speciation..

Systems:

- U, Pu, Tc, Np, Se
- Fe^{II}/Fe^{III} bearing minerals: Pure clays and iron oxides

Outcome:

An enhanced understanding of the surface-induced redox processes that influences the retention of redox-sensitive elements of interest for radioactive waste storage.

Task MOBILITY: Crystalline rocks

Objectives:

- Study the impact of chemical boundary conditions on RN speciation.
- Identify the role of nano-/ microstructures on RN mobility in fractured crystalline rocks

Fluid flow propagation in a fracture (core scale) visualized using Positron emission tomography

Systems:

- Fractured crystalline rocks
- Porous fracture fillings, including sheet silicates, iron oxides, etc.
- Weakly, moderately, and strongly sorbing RNs

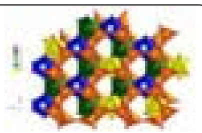
Outcome:

Fundamental understanding of

- Pore scale transport processes, impact of porosity and microstructures
- Variability of pore water chemistry on EDL characteristics
- Resulting mobility of sorbing RN

Task MOBILITY: Adsorption reversibility

Objectives



- Study the adsorption of moderately and strongly sorbing radionuclides on clay minerals and argillaceous rocks with the emphasis on reversibility.
- Address open questions with respect to adsorption reversibility and the nature of mechanism controlling the retention in the long-term, *e.g.*, adsorption versus incorporation (surface precipitation, neo-formation) and competitive adsorption.

Systems

- Ni/Zn/Se/Ra on purified clay minerals (illite/montmorillonite) and hematite.
- U/Ra on natural rocks (Opalinus Clay, Callovo-Oxfordian Clay).

Outcome

Obtain an improved fundamental understanding of adsorption mechanisms to elaborate the current state-of-the-art models and concepts for radionuclide behaviour in real systems.

FISA 2019
EURADWASTE '19

4-7 June, 2019
Pitesti, Romania

Annex IV. List of participants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Annex V. Acronyms and abbreviations

CS	Civil Society
E&T	Education anmd Training
EC	European Commission
EESC	European Economic and Social Committee
EJP	European Joint Programme
ENEN	European Nuclear Education Network
ENS - YG	European Nuclear Society – Young Generation
ENSRA	European Nuclear Security Regulators' Association
ENSREG	European Nuclear Safety Regulators Group
ERA	European Research Area
ERDO	European Repository Development Organisation Working Group
ESFRI	European Strategy Forum on Research Infrastructures
ESNII	European Sustainable Nuclear Industrial Initiative
ETKM	Education, Training and Knowledge Management
ETSON	European Technical Safety Organisations Network
EU	European Union
EURAD	European Joint Programme on Radioactive Waste Management
GD	Geological disposal
H2020	Horizon 2020 - The EU Framework Programme for Research and Innovation
HL&LL W	High Level Long Lived Waste
IAEA	International Atomic Energy Agency
IGD-TP	Implementing geological Disposal Technological Platform
LILW	Low and Intermediate Waste
MA	Minor Actinides
MS	Member State
NI2050	OECD/NEA Nuclear Innovation 2050 roadmap
NRA	Nuclear Regulatory Authority

OECD/NEA	Organisation for Economic Co-operation and Development/ Nuclear Energy Agency
R&D	Research and Development
R&D&I	Research Development and Innovation
R&T	Research and Training
RE	Reserach Entity
RI	Research Infrastructure
RTD	EC Research and Innovation Directorate General
RWM	Radioactive Waste managemnet
SF	Spent Fuel
SITEX-II	Sustainable network for Independent Technical EXpertise of radioactive waste disposal - Interactions and Implementation
SNETP	Sustainable Nuclear Energy Technology Platform
SNETP	Sustainable Nuclear Energy Technology Platform
SRIA	Strategic Research and Innovation Agenda
STC	Euratom Scientific and Technical Committee
TP	Technological Platform
TSO	Technical Support Organisation
URL	Underground Research Laboratory
WENRA	Western European Nuclear Regulators Association
WMO	Waste Management Organisation

FISA 2019
EURADWASTE '19

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EURADWASTE '19, the 9th European Commission (EC) conference on the management of radioactive waste and geological disposal was held under the auspices of the Romanian Presidency 2019 of the European Union (EU) in Pitesti, on 4-7 June 2019. It was organised concurrently with the 9th FISA 2019 conference on Euratom Research and Training in Safety of Reactor Systems.

The objective of EURADWASTE '19 was to present an overview of recent EC activities in the field of radioactive waste management with focus on geological disposal (GD) as the main challenge, including RD&D performed as part of the Horizon 2020 Euratom Framework Programme for research and training (2014-2020), policy at EU and national levels, strategic, legislative and socio-political aspects.

The programme included a common introduction and conclusion to the FISA conference to obtain a synthetic view of issues and policies regarding the status of research and implementation programmes in both reactor systems safety and high-level waste disposal in Europe.

The rest of the sessions were in parallel and cover specific FISA and Euradwaste themes.

The programme for EURADWASTE '19 was split in three sessions to present the results of 13 Euratom research and coordination projects and integration of the research communities and MS programmes. Session one was on predisposal and geological disposal technology developments. Session two covered radioactive waste source term and science for disposal safety and session three, on networking of the research communities, Joint Programming of national programmes, coordination with IAEA and OECD NEA programmes for efficient synergies and integration of radioactive waste producers. Each session included a keynote presentation and a general panel discussion.

The conference attracted some 416 participants from 27 countries (21 EU Member States and 6 third countries). The proceedings include written contributions from invited presentations and posters, session summaries and panel reports.

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