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FRENCH PRESIDENCY OF THE COUNCIL OF THE EUROPEAN UNION

# EURADWASTE'22

## CONFERENCE PROCEEDINGS
## Volume 1

10th European Commission Conferences
on EURATOM Research and Training in Safety of
Reactor Systems & Radioactive Waste Management

30 May – 3 June

Lyon, France

In cooperation with

NEA NUCLEAR ENERGY AGENCY
IAEA International Atomic Energy Agency
La Région Auvergne-Rhône-Alpes
Sfen
Nuclear Valley

With the support of

ANDRA
EPJ N Nuclear Sciences & Technologies
SNETP Sustainable Nuclear Energy Technology Platform
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**EURADWASTE '22 – Conference Proceedings**

European Commission
Directorate-General for Research and Innovation
Directorate C — Clean Planet
Unit C.4 — Euratom Research

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EUROPEAN COMMISSION

# EURADWASTE '22

## Conference Proceedings
## Volume 1

2024

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

EN

# FISA 2022
# EURADWASTE'22

# FOREWORD

It is our pleasure to introduce the proceedings of the 10th EU/Euratom conferences - FISA 2022 and EURADWASTE '22 – co-organised by the European Commission and the French Atomic and Alternative Energies Commission (CEA), under the scope of the French Presidency of the Council of the EU in 2022. Thank you also to the Région Auvergne-Rhône-Alpes to kindly host all events, from Monday 30 May till Friday 3 June, at the Hôtel de Région, in Lyon.

Gathering some 550+ stakeholders and policy makers, 49 nationalities, the FISA 2022 and EURADWASTE '22 conferences objectives were successfully achieved:

- To present progress and key achievements of some 80 Euratom research and training projects co-funded since its previous edition in June 2019, in Pitesti, in Romania, as part of the Horizon 2020 Euratom Research and Training Framework Programme (FP), all projects totalising EUR 300 million Euratom contribution for a total budget of around EUR 500 million during the last 4 years,

- To stimulate discussions on the state of play of Research and Innovations, key European, national and international challenges and opportunities, as well as exploring future perspectives in the framework of Horizon Europe, and

- To interact within dedicated parallel and poster sessions, exhibitions, business and Young Generation Nuclear researchers' matchmaking workshops (ENS YGN), and to reward relevance and excellence performed in nuclear research and innovation: ENEN PhD Event & Prize, calls for PhD and MSc posters, R&D topics and Euratom Nuclear Innovation Prizes.

With the incentive of Horizon 2020, Framework Programmes enhanced further integration towards a European Research Area together with better prioritisation at European level, with the capitalisation of European Technology platforms and in close cooperation with International Organisations or European Fora. Evolutions towards European Joint Research and Innovation Programmes, together with Member States programmes, successfully illustrated the added value of a concerted European approach in nuclear safety research and training consistently promoted by the European Commission together with EU Member States. Many fruitful discussions for future international cooperation and partnerships in research and innovation!

EURADWASTE '22 and FISA 2022 conferences addressed and engaged with all relevant stakeholders involved: research and training organisations, academia, industry, small and medium enterprises, spin-offs and start-ups, national and European policy makers, national government officials, European technology platforms, technical support organisations, European fora, European civil society and International Organisations e.g. IAEA, OECD/NEA or WNA.

A common introduction and closure to the two conferences provided a unique opportunity to set the scene at EU / national / international levels and to obtain a synthetic overview of issues and policies regarding the status of research on safety and implementation of programmes in existing and future reactor systems, radiation protection, radioactive waste management and geological disposal in Europe.

EURADWASTE’22 structure and its sessions’ objectives aimed at taking stock of what kind of research the Commission has funded during Horizon 2020 and open-up exchange and discussions on future collaborative research of EU added-value. The main focus of the 2022 edition of the conference was the first European Joint Programme on Radioactive Waste Management, EURAD and its sister project PREDIS. Joint programming has been a fundamental change of paradigm in the way research on RWM is performed and initiated by the European Commission.

Each one of the three sessions was introduced by a keynote lecture given on behalf of one of the three colleges of EURAD, the IGD-TP for the Waste Management Organisations (WMO), the SITEX Network for the Technical Support Organisations (TSO) and EURADSCIENCE for the Research Entities (RE). The keynote lectures were followed by a series of presentations from the different on-going projects and EURAD work packages and closed by a roundtable discussion between the speakers.

The first session was on the topic of “Collaborative research, development and demonstration in RWM”. A presentation of the work within IGD-TP was followed by presentations of the progress of the RD&D within EURAD and PREDIS as well as the results of some earlier EU-funded projects. The subjects covered were radioactive waste characterization, pre-disposal, radionuclide retention in the near field, evolution of engineered barriers, gas and heat transport in clay based materials and spent fuel characteristics.

The second session covered the topic of “Strategic research studies in RWM”. In addition to presenting the results from the two work packages dedicated to strategic issues, ROUTES and UMAN, presentations were also made in this session on the work within the SITEX Network and the collaboration between IAEA, OECD-NEA and EURAD and PREDIS.

The third session was dedicated to “Knowledge management in RWM”. In EURAD and PREDIS this work has a high priority. Three components of their KM work were presented and discussed: Training and mobility, State of knowledge documentation and Guidance based on information. As similar work is performed by IAEA and OECD/NEA a joint specific study should be initiated on how to preserve this valuable information and keep it up to date as new knowledge emerge.

There were many opportunities for interaction and dialogue among stakeholders, through dedicated parallel and poster sessions, Nuclear Valley’s exhibitors and an iOS/Android App Euratom4U which further facilitated communication, on-the-spot B2B meetings and 150+ online participants. Additionally, we benefitted from the great opportunity of organising, instead of the traditional FISA thematic workshops alongside the conferences, the 2022 edition of SNETP Forum. It covered: a) SMRs; b) Nuclear codes and standards and supply chain; c) Digital and robotics; d) R&D&I facilities; e) Waste minimization and fuel cycle; and f) The role of nuclear energy in mitigating climate change including non-electrical applications e.g. hydrogen, heat for energy-intensive industries and the potential of cogeneration.

MSc/PhD and R&D awards, Nuclear Innovation prizes and ENS Young Generation celebrated the 2022 European Year of Youth. 25 MSc/PhD/R&D, out of 100 invited in-person in Lyon to compete, for their excellent and innovative work on nuclear sciences and technologies' applications.

Technical visits of emblematic nuclear sites were foreseen to close the events on Friday 3 June. Unfortunately, since the COVID-19 pandemic measures were only lifted in March 2022, such visits were not possible. We are nevertheless very grateful that 150 participants were able to enjoy technical tours of nuclear and conventional research facilities or laboratories from members of

The Organising and Programme Committee sincerely appreciated its renewed cooperation with the European Physics Journal for Nuclear Sciences & Technologies (EPJ-N), an open access platform for the communication of original research, ideas and developments. Two dedicated peer-reviewed topical issues are published today, gathering 35+ peer-reviewed papers within a) 'Euratom Research and Training in 2022: challenges, achievements and future perspectives', and b) 'Euratom Research and Training in 2022: the Awards collection'.

The European Commission would like to thank the French Presidency, the French Atomic and Alternative Energies Commission (CEA), and the Région Auvergne-Rhône-Alpes to kindly host all events. We would also like to extend our gratitude to honourable guests and speakers, chairs and co-chairs, expert reviewers of all papers, posters and presentations, rapporteurs, projects coordinators, panel members, ENS YGN, SFEN, SNETP, IGDTP, Nuclear Europe, IAEA, OECD/NEA and WNA but also all staff involved at any time. Contributions ensured that the FISA 2022 – EURADWASTE '22 Conferences truly engaged with the audience in an enjoyable, dynamic and interactive way for the success of these conferences.

A Special Thank You to Gilles Moutiers, Anne Nicolas, Patrick Blaise, Cécile Ferry and Isabelle Auffret Babak, EPJ-N Editors in Chief and Guest editors, Valérie Vandenberghe, Danielle Gallo, Philippe Montarnal, Marie Fonteneau, Claudine Dubiau and Stéphanie Cornet from CEA, Roger Garbil, Seif Ben Hadj Hassine and Karolina Janatkova from the European Commission, DG RTD Euratom Research and Training, for their leadership and commitment which enabled this 10$^{th}$ successful edition of a High-Level Scientific and Policy event, a traditional key milestone of the Euratom Research and Training community striving future international cooperation and partnerships in nuclear research and innovation, education, training, mobility and knowledge sharing!

A great thank you to everyone participating in our events and please mark your agenda for the next edition, most probably in June 2025, under the Polish Presidency of the Council of the EU!

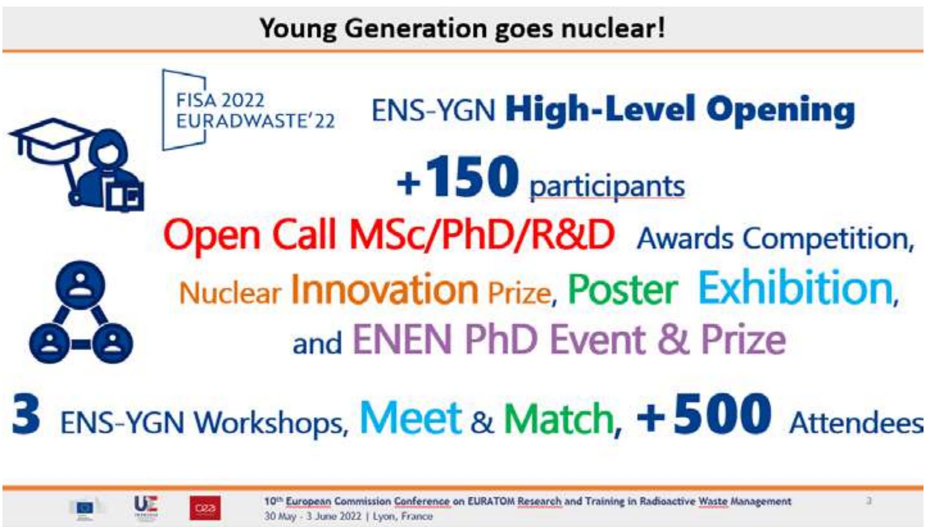
Yours sincerely,

On behalf of the Organising and Programme Committee

Roger Garbil and Seif Ben Hadj Hassine (EC DG RTD, FISA 2022 - EURADWASTE '22 Co-chairs)

Valérie Vandenberghe, Danielle Gallo and Philippe Montarnal (CEA and French Presidency, Co-chairs)

Karolina Janatkova, Marie Fonteneau, Claudine Dubiau and Isabelle Auffret Babak

# Table of Contents


FISA 2022
EURADWASTE'22

# PROGRAMME OVERVIEW

| | |
|---|---|
| **Tuesday 31 May 22** | |
| **Day 1 AM** | **Joint introduction FISA 2022 / EURADWASTE '22**<br>Co-chair: Bernard SALHA (FR, SNETP)<br>Co-chair: Rosalinde VAN DER VLIES (EC, DG RTD)<br>Rapporteur: Henri PAILLERE (FR, Expert) |
| 08:30 (15') | **Welcome** |
| 08:45 (15') | **Rosalinde VAN DER VLIES** (EC) on behalf of **Mariya GABRIEL** (EC) European Commissioner for Innovation, Research, Culture, Education and Youth<br>Keynote: Euratom Research and Training and Horizon Europe framework programmes: Opportunities and challenges in the EU Innovation landscape |
| 09:00 (15') | **Claire GIRY** (FR) Directrice Générale de la recherche et de l'innovation, Ministère de l'Enseignement Supérieur<br>Keynote: From Higher Education to Research and Innovation, a 'Team Europe and Global' approach / De l'enseignement supérieur à la recherche et à l'innovation : une approche globale et « équipe d'Europe » |
| 09:15 (15') | **Laurent MICHEL** (FR) Directeur Energie et Climat, Ministère de la Transition Ecologique<br>Keynote: Challenges and levers for the energy and climate transition - Evolutions of the energy mix and nuclear - Challenges of R&D and innovation for the ecological transition / Enjeux et leviers pour la transition énergétique et climatique. Évolutions du mix énergétique et place du nucléaire. Enjeux de R&D et d'innovation au service de la transition écologique |
| 09:30 (15') | **Rafael Mariano GROSSI** (IAEA), Director-General of the International Atomic Energy Agency<br>Keynote: IAEA Research and Innovation for safe, secure and safeguarded nuclear for every citizen, in support of the UN Sustainable Development Goals |

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| 09:45 (15’) | **William D. MAGWOOD IV** (OECD/NEA), Director-General of OECD Nuclear Energy Agency<br>Keynote: OECD/NEA Nuclear Research and Innovation Successes and Accomplishments, Looking to the future |
| 10:00 (15’) | **Sama BILBAO Y LEON** (WNA), Director-General of the World Nuclear Association<br>Keynote: WNA Promoting a wider understanding and streamlining international licensing and regulatory frameworks |
| 10:15 (15’) | **Pierre-Marie ABADIE** (ANDRA, FR), Director-General of Agence Nationale de Gestion des déchets radioactifs ANDRA<br>Keynote: European and international status of the management and disposal of radioactive waste, developments and challenges ahead / La gestion et le stockage des déchets radioactifs en Europe et à l‘international, situation et perspectives |
| 10:30 (15’) | **Rosalinde VAN DER VLIES** (EC) on behalf of **Mariya GABRIEL** (EC) European Commissioner for Innovation, Research, Culture, Education and Youth<br>Awards ceremony for the Euratom Nuclear Innovation Prize |
| *Coffee Break (30’)* | |
| 11:15 (15’) | **François JACQ** (CEA, FR), Administrateur Général, Commissariat à l’Energie Atomique et aux Energies alternatives<br>Keynote: Research and Innovation interdisciplinary opportunities and challenges to enable sustainable and decarbonised societies / Recherche et innovation : une approche interdisciplinaire pour relever les défis d'une société durable et décarbonée |
| 11:30 (15’) | **Cristian-Silviu BUŞOI** (ITRE, EP), Chair of the Committee for Industry, Research and Energy, European Parliament<br>Keynote: Let’s join Euratom Research and Training and Horizon Europe forces, investments and ideas for making research and innovation the driving force of our future |
| 11:45 (15’) | **Baiba MILTOVIČA** (EESC, EU), President of the section for Transport Energy, Infrastructure and Information Society, European Economic and Social Committee |

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| | Keynote: Research and Innovation missions and benefits from continuous and meaningful Civil Society's involvement to tackle today's Societal Challenges |
| 12:00 (15') | **Marta ZIAKOVA** (ENSREG), Chair of the European Nuclear Safety Regulators Group<br>Keynote: ENSREG commitment to continuous improvement of nuclear safety when new knowledge and experience are available: Progress, Lessons learned and Challenges |
| 12:15 (15') | **Yves DESBAZEILLE** (FORATOM), Director-General of the European Nuclear Industry Association FORATOM<br>Keynote: Research and Innovation benefits for a low-carbon and climate neutral economy, Industrial Competitiveness and sustainable development |
| 12:30 (15') | **Jadwiga NAJDER** (ENS YGN), Chair of the Young Nuclear Generation of the European Nuclear Society<br>Keynote: The future of Nuclear: Collaboration, Vision and Innovation – perspectives from YGN |
| *Lunch (75')* | |
| **Day 1 PM** | **FISA 2022 – Session 1: Safety of nuclear installations**<br>Co-chair: Myriam CALACICCO (FR, NUCLEAR VALLEY)<br>Co-chair: Stefano MONTI (IAEA)<br>Rapporteur: Ferry ROELOFS (NL, Expert) |
| 14:00 (20') | **Bernard SALHA** (EDF, FR) *SNETP*<br>Keynote: SNETP-NUGENIA-ESNII-NC2I Research and Innovation in Nuclear, a non-profit international organization to promote Research & Innovation |
| | **Reactor Performance, system reliability: Long-Term Operation** |
| 14:20 (20') | **Marta SERRANO** (CIEMAT, ES)<br>*ENTENTE – ATLASplus – NOMAD – STRUMAT-LTO*<br>Euratom projects supporting Long Term Operation of primary circuit components, including RPV |
| 14:40 (20') | **Tomasz BRYNK** (SCK-CEN, BE)<br>*FRACTESUS – MEACTOS – INCEFA-SCALE* |

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| | Increase of nuclear installations safety by better understanding of materials performance and new testing techniques development (MEACTOS, INCEFA-SCALE and FRACTESUS H2020 projects) |
| 15:00 (20’) | **Albannie CAGNAC** (EDF, FR)<br>*sCO2-4-NPP – APAL –* CAMIVVER<br>Codes and methods improvements for safety assessment and LTO: varied approaches |
| | **Reactor Performance, system reliability: Instrumentation and control** |
| 15:20 (20’) | **Morgane BROUDIN** (EDF, FR)<br>*TEAM-CABLES – EL-PEACETOLERO*<br>Methodologies for efficient and reliable NPP polymer ageing management |
| | **Advanced numerical simulation and modelling for reactor safety** |
| 15:40 (20’) | **Christophe DEMAZIERE** (CHALMERS, SE)<br>*CORTEX – McSAFER – METIS*<br>Advanced numerical simulation and modelling for reactor safety – contributions from the CORTEX, McSAFER and METIS projects |
| *Coffee Break (30’)* | |
| | **Innovative Gen-II -III and Research Reactors’ Fuels and Materials** |
| 16:30 (20’) | **Ville TULKKI** (VTT, FI)<br>*ELSMOR – PASTELS – NUCOBAM*<br>Ensuring safety with passive systems |
| 16:50 (20’) | **Jared WIGHT** (SCK-CEN, BE)<br>*EU-QUALIFY – LEU-FOREvER*<br>Innovation and qualification of LEU research reactor fuels and materials |
| | **Safety assessments and severe accidents, impact of external events on nuclear power plants and on mitigation strategies** |
| 17:10 (20’) | **Luis E. HERRANZ** (CIEMAT, ES)<br>*MUSA – PIACE – AMHYCO*<br>Towards an optimized management of accidents |

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| | **Probabilistic Safety Assessment for internal and external events on nuclear power plants and on mitigation strategies** |
| 17:30 (20’) | **Atte HELMINEN** (VTT, FI)<br>*BESEP – NARSIS – R2CA*<br>Probabilistic Safety Assessment for internal and external events on nuclear power plants and on mitigation strategies |
| 17:50 (40’) | **General discussion and research perspectives for the safety of nuclear installations, long term operation, reactor performance and systems reliability, and advanced modelling, safety assessments and severe accidents mitigation strategies** |
| 18:30 (90’) | ***YGN Cocktail Dating, Meet and Match Lounge*** |
| **Day 1 PM** | **EURADWASTE’22 – Session 1: Collaborative Research, Development and Demonstration in Radioactive Waste Management**<br>Co-chair: Daniela DIACONU (RO, RATEN ICN)<br>Co-chair: Seif BEN HADJ HASSINE (EC, DG RTD)<br>Rapporteur: Marie-Anne BRUNEAUX (FR, Expert) |
| 14:00 (30’) | **Tiina JALONEN** (POSIVA, FI) *IGD-TP*<br>Keynote: IGD-TP – Towards operating and optimization. |
| 14:30 (25’) | **Erica FRANCHINI** (CAEN, IT) on behalf of **Massimo MORICHI** (CAEN, IT)<br>*MICADO – CHANCE – PREDIS*<br>Radioactive Waste Characterization |
| 14:55 (25’) | **Erika HOLT** (VTT, FI)<br>*PREDIS – THERAMIN*<br>Predisposal conditioning, treatment, and performance assessment of radioactive waste streams |
| 15:20 (25’) | **Johan BERTRAND** (ANDRA, FR)<br>*CORI – CONCORD – FUTURE – MODATS*<br>Long-term radionuclide retention in the near field: collaborative R&D studies within EURAD focusing on container optimisation, mobility, mechanisms and monitoring |
| 15:45 (25’) | **Francis CLARET** (BRGM, FR)<br>*ACED – DONUT – MAGIC – BEACON* |

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| | Modelling of the long term evolution and performance of engineered barrier systems |
| *Coffee Break (20')* | |
| 16:30 (25') | **Séverine LEVASSEUR** (ONDRAF/NIRAS, BE)<br>*GAS – HITEC*<br>Mechanistic understanding of gas and heat transport in clay-based materials for radioactive waste geological disposal |
| 16:55 (25') | **Anders SJÖLAND** (SKB, SE)<br>*SFC – DISCO*<br>Spent fuel management, characterisation and dissolution behaviour: progress and achievement from SFC and DISCO |
| 17:20 (45') | **Roundtable and general discussion. The roundtable should focus on how collaborative research on crosscutting topics related to radioactive waste management made significant breakthroughs in the recent years. The speakers would be invited to describe and give concrete examples of collaborative research in their respective projects/programs, discuss the outcomes and the achievements and dwell on the lessons learned and the possible improvements in future collaborations.** |
| 18:30 (90') | ***YGN Cocktail Dating, Meet and Match Lounge*** |

# Wednesday 1 June 2022

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| **Day 2 AM** | **FISA 2022 – Session 2: Advanced nuclear systems and fuel cycles**<br>Co-chair: Hamid AIT ABDERRAHIM (BE, SCK-CEN)<br>Co-chair: Jan PANEK (EC, DG ENER)<br>Rapporteur: Teodora RETEGAN-VOLLMER (RO, Expert) |
| 08:45 (15’) | **Welcome** |
| 09:00 (20’) | **Stefano MONTI** (IAEA), Head of section Nuclear Power Technology Development<br>Keynote: Global trends in nuclear power: advanced reactors including SMR integrated in hybrid energy systems. Challenges and opportunities for increased sustainability |
| 09:20 (25’) | **Branislav HATALA** (VUJE, SK) on behalf of **Konstantin MIKITIUK** (PSI, CH)<br>*ESFR-SMART – SafeG – ECC-SMART – ACES – SAMOSAFER*<br>R&D in support to safety assessment, design and licensing of ESNII/Gen-IV |
| 09:45 (25’) | **Nathalie CHAUVIN** (CEA, FR)<br>*PUMMA*<br>Plutonium management in the whole fuel cycle |
| 10:10 (25’) | **Paul SCHUURMANS** (SCK-CEN, BE)<br>*PATRICIA - PASCAL*<br>Partitioning and Transmutation, contribution to an EU strategy for HLW management |
| *Coffee Break (25’)* | |
| 11:00 (25’) | **Lorenzo MALERBA** (CIEMAT, ES)<br>*ORIENT-NM – GEMMA – M4F*<br>Towards a single European strategic research and innovation agenda on nuclear materials for all reactor generations through dedicated projects |
| 11:25 (20’) | **Josef SOBOLEWSKI** (NCBJ, PL)<br>*GEMINI-PLUS*<br>Nuclear Cogeneration with High Temperature Reactors |

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| 11:45 (15’) | **Carola FRANZEN** (HZDR, DE)<br>*ARIEL – SANDA*<br>Nuclear data activities |
| 12:00 (30’) | **General discussion and research perspectives for the safety of advanced nuclear systems and fuels cycles, innovative designs, fuels and materials, partitioning and transmutation, and nuclear data** |
| *Lunch (90’)* | |
| **Day 2 AM** | **EURADWASTE’22 – Session 2: Strategic Research Studies in Radioactive Waste Management**<br>Co-chair: Irina GAUS (NAGRA, CH)<br>Co-chair: Zuzana Monika PETROVICOVA (EC, DG ENER)<br>Rapporteur: Piet ZUIDEMA (CH, Expert) |
| 08:45 (15’) | **Welcome** |
| 09:00 (30’) | **Valéry DETILLEUX** (Bel-V, BE) *SITEX Network*<br>Keynote: SITEX Network: key activities, lessons learned and upcoming challenges |
| 09:30 (25’) | **Daniela DIACONU** (RATEN ICN, RO)<br>*UMAN*<br>UMAN – A pluralistic view of uncertainties management |
| 09:55 (20’) | **Marja VUORIO** (COVRA, NL)<br>*ERDO*<br>ERDO – a road to sharing radioactive waste management solutions |
| 10:15 (20’) | **Zuzana Monika PETROVICOVA** (DG ENER, EC)<br>Radioactive Waste Management in the European Union - State of play and strategic prospects |
| *Coffee Break (25’)* | |
| 11:00 (25’) | **Liz Harvey** (Galson Science, UK)<br>*ROUTES* |

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| | ROUTES - Identified key issues and open questions about waste management routes in Europe, from cradle to grave |
| 11:25 (20’) | **Rebecca ROBBINS** (IAEA)<br>*IAEA*<br>Different Missions – Common Goals: the IAEA, PREDIS and EURAD Working Together to Strengthen Radioactive Waste Management World-wide |
| 11:45 (45’)<br><br>*Lunch (90’)* | **Roundtable and general discussion. The roundtable will focus on the strategic studies in support of the implementation of the national programmes that address scientific, technical and societal aspects of Radioactive Waste Management. The different speakers will be invited to give their views on how to tackle these issues, how the methodologies changed over time, the most important challenges in the process and the involvement of the Civil Society.** |
| **Day 2 PM** | **FISA 2022 – Session 3: Education and training, research infrastructures, low dose radiation protection, decommissioning and international cooperation**<br>Co-chair: Tatiana IVANOVA (FR, OECD/NEA)<br>Co-chair: Roger Garbil (EC, DG RTD)<br>Rapporteur: Said ABOUSAHL (FR, Expert) |
| 14:00 (20’) | **Marco UTILI** (ENEA, IT)<br>Keynote: Synergies between Fission and Fusion R&D towards demonstration plants |
| 14:20 (30’) | **Joerg STARFLINGER** (ENEN, DE)<br>*ENENplus – GREaT-PIONEeR – ENEEP – PIKNUS – A-CINCH*<br>Education, Training and mobility, knowledge management: towards a common effort to assure a future workforce in Europe and abroad |
| | **Radiation protection and medical applications, European challenges and opportunities** |
| 14:50 (20’) | **Isabelle THIERRY-CHEF** (ISGLOBAL, ES), **Christoph HOESCHEN** (OVGU, DE)<br>*MEDIRAD – HARMONIC – SINFONIA – EURAMED rocc-n-roll* |

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| | Medical applications of ionizing radiation and radiation protection for European patients, population and environment |
| 15:10 (20’) | **Ulrike KULKA** (BFS, DE)<br>*RADONORM* |
| 15:30 (20’) | **Hildegarde VANDENHOVE** (SCK-CEN, BE)<br>*MEENAS*<br>Challenges for European radiation protection research and innovation |
| *Coffee Break (30’)* | |
| | **Improved expertise and innovations in decommissioning** |
| 16:20 (20’) | **Robert WINKLER** (CEA, FR)<br>*SHARE* |
| 16:40 (20’) | **Philippe LEFEVRE** (EDF, FR) on behalf of **Nicolas MALLERON** (EDF, FR)<br>*INNO4GRAPH – PLEIADES – LD-SAFE – CLEANDEM - INSIDER* |
| | **Supporting Access to key pan-European research infrastructures and international cooperation** |
| 17:00 (20’) | **Petri KINNUNEN** (VTT, FI)<br>*JHOP2040 – TOURR – JHR ACCESS RIGHTS – OASIS JRC Open Access*<br>Key European research infrastructures at your service now and in future |
| 17:20 (20’) | **Tatiana IVANOVA** (OECD/NEA)<br>*OECD/NEA*<br>Keynote: NEA Seeking Excellence in Nuclear Education, Training, Knowledge Management and Supporting Research Infrastructure<br>Insights of the NEA Education initiatives and the Framework for Irradiation Experiments (FIDES) |

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| 17:40 (20’) | **General discussion and research perspectives for Education and training, research infrastructures, radiation protection, decommissioning and international cooperation** |
| 19:00 (4h) | ***Dinner reception, MSc/PhD/R&D Awards and ENEN PhD Prize Ceremony, and ENS High Scientific Council PhD Awards*** |
| **Day 2 PM** | **EURADWASTE’22 – Session 3: Knowledge Management in Radioactive Waste Management**<br>Co-chair: Rebecca ROBBINS (IAEA)<br>Co-chair: Manuel MARTIN RAMOS (EC, DG JRC)<br>Rapporteur: Christophe BRUGGEMAN (BE, Expert) |
| 14:00 (50’) | **Christophe BRUGGEMAN** (SCK-CEN, BE) and **Paul CARBOL** (JRC, EC)<br>Keynote: EURADSCIENCE, Knowledge Management aspects in the EJP EURAD and the PREDIS project |
| 14:50 (25’) | **Alexandru TATOMIR** (BGE, DE)<br>*SoK (EURAD)*<br>Capturing the state of knowledge in EURAD knowledge management |
| *Coffee Break (30’)* | |
| 15:50 (25’) | **Jiri FALTEJSEK** (SURAO, CZ)<br>*Guidance (EURAD) - PREDIS*<br>Development of guidance documents in EC projects EURAD and PREDIS |
| 16:15 (25’) | **Niels BELMANS** (SCK-CEN, BE)<br>*Training & Mobility (EURAD) - PREDIS*<br>Training and mobility in EU projects EURAD and PREDIS |
| 16:40 (20’) | **Rebecca TADESSE** (NEA/OECD)<br>*NEA/OECD*<br>NEA Activities  on information , data and knowledge management |

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| 17:00 (20’) | **Stefan MAYER** (IAEA)<br>*IAEA*<br>The IAEA approach to information and knowledge transfer on radioactive waste management – a brief review of synergies with the international cooperation conducted under EURAD and PREDIS projects |
| 17:20 (40’) | **Roundtable and general discussion. The focus of the third roundtable would be on the specificities and the challenges of an efficient and consistent Knowledge Management methodologies and systems applied to the radioactive waste management programmes.** |
| 19:00 (4h) | ***Dinner reception, Nuclear Innovation Prize, PhD Awards and ENEN PhD Prize, and ENS High Scientific Council PhD Awards*** |

## Thursday 2 June 22

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| **Day 3 AM** | **Joint conclusion FISA 2022 / EURADWASTE ’22**<br>Co-chair: Philippe STOHR (FR, CEA)<br>Co-chair: Bernard MAGENHANN (EC, DG JRC)<br>Rapporteur: Henri PAILLERE (FR, Expert) |
| 08:15 (15’) | **Welcome** |
| 08:30 (20’) | **Bernard MAGENHANN** (EC, DG JRC), Deputy Director-General of the Joint Research Centre<br>Keynote: JRC’s role in Euratom Research and Training and Horizon Europe |
| 08:50 (20’) | **Hans FORSSTROM** (SE, Expert), General Rapporteur<br>EURADWASTE ’22 - Key messages and future perspectives |
| 09:10 (20’) | **Henri PAILLERE** (FR, Expert), General Rapporteur<br>FISA 2022 - Key messages and future perspectives |
| 09:30 (20’) | **Jean-Louis GUYADER** (FR, AURA) on behalf of **Laurent WAUQUIEZ** (FR, AURA), President of the Region Auvergne-Rhône-Alpes |

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| 09:50 (20’) | Keynote: Région Auvergne-Rhône-Alpes, promoting Innovation Ecosystems and Strategic Clusters<br><br>**Philippe FRANTZ** (FR, NUCLEAR VALLEY), President of Nuclear Valley<br>Keynote: Nuclear Valley’s Pôle de competitivé, the Nuclear Industry Cluster in the Région Auvergne-Rhône-Alpes and GIFEN (Groupement des Industriels Français de l’Energie Nucléaire) |
| 10:10 (20’) | **Philippe STOHR** (FR, CEA) and **Bernard MAGENHANN** (EC, DG JRC)<br>Closing remarks from the French Presidency and the European Commission |
| *Coffee Break (30’)* | |
| **Day 3 AM-PM** | **SNETP Forum 2022** |
| 11:00 (1h30)<br><br>14:00 (4h) | SNETP annual FORUM in 2022 workshops to launch new project ideas:<br>• SMRs<br>• Nuclear codes and standards and supply chain<br>• Digital and robotics<br>• R&D&I facilities<br>• Waste minimization and fuel cycle<br>• The role of nuclear in mitigating climate change |

## Tuesday 30 May to Thursday 2 June 22

## SIDE EVENTS

**Day 1 to 3 AM-PM**

**Face-to-face networking opportunities and B2B matchmaking**

Poster (60 per day, Euratom projects, MSc/PhD/R&D, 120 in total)

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Exhibition (20 per day, 20 in total)
-
B2B Matchmaking (estimated 200 in total)

**At the conference, an iOS and Android App**
An iOS and Android App will be available to all confirmed registered participants at the conferences. The app will show the programme in an interactive manner and facilitates communication among the participants, sharing all information, also enabling scheduling B2B meetings, notifications and announcements.

## Wednesday 1 June 22

**Day 2**
**AM-PM**

**16th ENEN PhD Event & Prize 2022**

The 16th ENEN PhD Prize 2022 will be organized in the framework of the FISA 2022 and EURADWASTE ´22 Conferences in Lyon, France, on Monday 30 May to Friday 3 June, by the European Nuclear Education Network (ENEN) Association, in cooperation with the Joint Research Centre of the European Commission

## Monday 30 May to Wednesday 1 June 22

## SIDE EVENT

**European Nuclear Society Young Generation Network workshops (ENS YGN)**

**Monday**
**16:00-17:00**

ENS YGN will be organising three workshops, in the framework of the European Year of Youth 2022 and of FISA 2022 and EURADWASTE ´22 Conferences

**ENS YGN Young Generation Ice Breaker**

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| **Day 1 PM**<br>14:00 (2h) | A fun ice breaker connecting and encouraging ENS YGN team bonding! |
| **Day 2 AM-PM**<br>09:30 (2h) | **1. Kick-off of B2B sessions - Are you ready for the international job market?**<br>This workshop provides attendees with information and practical advice that they can use to understand and access the international job market |
| 15:30 (2h) | **2. Communicating science - Don't waste it!**<br>This workshop will teach how to provide facts in an understandable way, using simple comparisons and handy references. Come and learn how to lead an engaging conversation! |
| | **3. Nuclear for Climate - positive campaigning of nuclear topics**<br>Imagine the enormous impact you, as a single individual, has in the climate change conversation. Your voice is powerful, and when directed in the right places, highly impactful. And now imagine what would happen if we compounded all our efforts, sharing the same message across the globe, to communicate to leaders and decision makers that 'enough is enough: we need action now'. It would be immense.<br>Join the Nuclear for Climate team as they guide you through this engaging, action-focused workshop. Open to all backgrounds, viewpoints, experiences. #Togetherisbetter |

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| **Tuesday 30 May 22** | **SIDE EVENT** |
| **Day 1 PM**<br>**16:30 (2h)** | **AWARD and PRIZE pitches**<br><br>OPEN CALL – POSTER COMPETITION<br><br>➔ MSc/PhD awards, Student competition (10 in total) |

- R&D Topics Awards (4 in total)
- Euratom Projects (2 in total)

NUCLEAR INNOVATION PRIZES (7 in total)

ENS High Scientific Council PhD Awards (2 in total)

The Programme Committee will invite MSc/PhD/R&D Award, ENS High Scientific Council PhD and Nuclear Innovation Prize winners the opportunity to present a compelling 180 seconds spoken presentation of their research topic to the international Research Community during a dedicated Session of FISA 2022 – EURADWASTE ’22

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| **Friday 3 June 22** | |
| **Day 4 AM-PM** | **Technical visits**<br><br>JACOMEX<br>https://www.jacomex.com/<br>-<br>SILEANE<br>https://www.sileane.com/en/<br>-<br>VELAN<br>https://www.velan.com/<br>-<br>CEA Marcoule<br>https://www.cea.fr/Pages/le-cea/les-centres-cea/marcoule.aspx<br>-<br>ANDRA – Cigéo (cancelled)<br>https://international.andra.fr/ |

# FISA 2022
# EURADWASTE'22

# CONFERENCE SUMMARY

# SUMMARY REPORT OF THE EURADWASTE '22 CONFERENCE

**Hans Forsström**, International independant expert, Sweden- General Rapporteur

### Introduction

The EURADWASTE '22 conference, which was the 10th European Commission Conference on EURATOM Research and Training (R&T) in Radioactive Waste Management was organised jointly with FISA 2022 on Research and Innovation for Nuclear Reactors. The joint conference was attended by more than 500 participants from almost 50 countries. It was reassuring to see that more than 150 of the participants came from the young generation, which is very important as more than one third of the present nuclear staff is older than 55 years. Special workshops were organised for the young participants and also matching events with established researchers.

The conference took place at a time when a renewed interest in new nuclear energy is emerging, due to the climate change challenges in the world and the ongoing energy crisis. In particular, the recent increasing interest in new Small Modular Reactors (SMRs) was much discussed and played an important role in particular in the FISA part of the conference. This increasing enthusiasm for new nuclear power and the challenges connected to it was well described in several of the remarks made during the joint opening session of FISA and EURADWASTE. However, the waste challenges connected to new nuclear reactors were only mentioned en passant.

As some of the new types of reactors considered for SMRs will face new waste management challenges it will be very important to ensure a close cooperation between the reactor developers and the waste management organizations. The joint organisation of FISA and EURADWASTE provided an 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. At this meeting the contacts were only starting, but it was recognised that this will be of utmost importance for the future work.

### Recent developments

Since the last EURADWASTE conference in 2019 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.

As was mentioned by Mr Pierre-Marie Abadie, CEO for the French waste management organisation Andra, in his key note talk on the "European and international status on the management and disposal of radioactive waste and remaining challenges", the following positive developments can be noted:

- A disposal facility for spent nuclear fuel in crystalline rock is under construction in Finland.

- A similar facility has been approved by the Government in Sweden and final licensing steps are progressing in preparation for the start of construction.

- In France a licence application for a disposal facility in argillaceous rock for High Level vitrified waste and long-lived Intermediate Level Waste will be submitted shortly.

- Several other countries are following suite concerning disposal facilities for spent fuel and/or high level waste, e.g. :

    - One site has been chosen in Northern Switzerland, following an assessment of three possible sites.

    - Two sites are being investigated in Canada.

    - In the UK a consent based siting process is ongoing involving currently three possible areas.

    - Good progress in siting is seen also in Hungary and the Czech Republic.

    - In Germany a siting programme has been restarted including a nationwide geological study. About 90 potential zone have been identified.

- One repository for long lived ILW in salt rock is in operation since several years in the US, the WIPP facility.

- Low Level Waste is already adequately and safely disposed in many existing facilities throughout the world.

Mr Abadie also identified some common factors of importance for the success of a disposal projects. These included:

- *Governance and interaction between stakeholders*. It is important to have clear definitions of the roles and responsibilities of the different actors, e.g. the implementers, the regulators, the Government and the public. Further there should be a clear and transparent decision and licensing process, with adequate openness to the public.

- *Roadmap and milestones*. For the development of the repository project there should be a clear and stepwise roadmap. It should include important decision points (milestones) to identify that adequate progress has been made to take the next step in the development. If this has not been achieved a step backwards should be considered.

- *R&D programme* identifying the R&D needs at each step of development for the technical implementation of disposal and for ensuring the long-term safety. Especially the long-term aspects of the safety assessment will require an in depth scientific knowledge in many fields of science.

In particular, the R&D aspect and its long-term needs were discussed at EURADWASTE’22. 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. International cooperation also has an important role in increasing the trust of the public.

In earlier EU funded programmes (up to 2018) mainly several fairly small projects have been supported. This has been changed in the present ongoing Euratom programme for RT in radioactive waste management, where most of the EU funded activities now are performed within two projects, the European Joint Programming project EURAD and PREDIS. EURAD was selected in 2019 and the activities of EURAD was initiated in connection with EURADWASTE’19 in Pitesti, Romania. It mainly deals with R&D necessary for management and disposal of existing and future conditioned and packaged radioactive waste. To complement EURAD, the PREDIS project, dealing with pre-disposal activities for radioactive waste was started in 2020. The intention is that EURAD and PREDIS will be joined into one European Joint Programming project in the forthcoming calls for proposals and with a starting time of mid-2024.

During this EURADWASTE’22 conference, extensive reporting was given of the results achieved so far in EURAD and PREDIS. This is briefly discussed in the following and to a greater detail in the reports from the different sessions of EURAD.

In addition to the opening and closing session, which were organised jointly with FISA, three technical sessions were organised within EURADWASTE:

- Collaborative Research, Development and Demonstration in Radioactive Waste Management.

- Strategic Research Studies in Radioactive Waste Management.

- Knowledge Management in Radioactive Waste Management.

Each of the sessions represented the important components of EURAD and PREDIS.

In addition to the oral presentations, a large number of posters were presented. It was especially encouraging to see the many good quality PhD-posters, not least in view of the importance to ensure human capacity for the future.

**EURAD – European Joint Programme on Radioactive Waste Management**

Over the years, the EURATOM R&T programme has developed from supporting several small projects for coordinated R&D on specific issues to a large European Joint Programming of the R&D activities in radioactive waste management across Europe. To this end, European Joint Programme EURAD was selected for funding in 2019. EURAD is now fully functional and includes collaborative research on specific subjects and strategic research studies

The overall purpose of the joint programming is to identify topics and areas that will benefit from collaboration at a European level, and to ensure that the interests of all organisations involved in radioactive waste management are taken into account. This includes involving Waste Management Organisations (WMOs), Technical Support Organizations (TSOs), Research Entities (REs) and representatives from the civil society. It should also ensure inclusion both of representatives from the countries with important activities at the forefront of radioactive waste management and disposal in Europe, and representatives from countries with smaller or early-stage programmes.

The development of the EURAD joint programming started several years ago with the support of the European Commission. At first, the WMOs formed the IGD-TP in 2009. IGD-TP stands for Implementing Geological Disposal of radioactive waste Technology Platform. The original vision of IGD-TP was to cooperate towards a first GDR in operation Europe in 2025. This vision has now been broadened to ensure the industrialisation of radioactive waste disposal in Europe by 2040, via safe operation of the first geological disposal facilities in Europe, optimisation and industrialisation of the planning, construction and disposal operations; and development of tailored solutions for disposal of the diverse waste inventories in Europe.

The TSOs set up the SITEX project in 2012 and created the SITEX network. SITEX stands for Sustainable network of Independent Technical EXpertise for radioactive waste disposal. SITEX has the objectives:

- Enhance and foster cooperation at international level to achieve a high quality Expertise Function.
- Independent from Waste Management Organizations (Implementing Function).
- Aiming at supporting the Regulatory Function and the Society Function.
- In the field of radioactive waste management (including disposal).

In 2019, the Research Entities created the EuradScience network to provide the scientific basis underlying the responsible and safe management of radioactive waste. EuradScience carries the ambition to provide scientific and technical expertise and excellence in the light of the ever-advancing state of knowledge over the many tens of years of project operation until repository closure. EuradScience fosters innovation and novel solutions, in view of optimisation, improved durability and sustainability

In EURAD the IGD-TP, SITEX and EuradScience are called colleges. For the planning of the work of EURAD each of the three colleges are providing proposals for joint research based on their respective strategic research agendas. Detailed presentations of the work of the three colleges can be found later in these proceedings.

The EC also supported the preparation for the organisation of EURAD, through the JOPRAD project, which delivered a proposed organisation for the project, a joint strategic research agenda and a roadmap for implementing it. The organisation of EURAD is now fully functional with a General Assembly as the Governing Board and a Project Management Office as the coordinator for the implementation. The PMO is supporter by a Bureau with representatives from the three colleges. In addition, the modus operandi for selecting projects and for ensuring the good quality of the results has been established. The PMO is operated by Andra.

In total EURAD involves 51 mandated actors from 23 countries and 62 linked third parties and 3 international parties. Furthermore, civil society representatives and end-users are involved. It should be noted that regulators are not directly involved in order to ensure their independence. However, they can participate indirectly through SITEX.

The first period for EURAD goes from 2019 to 2024. For this period 10 work packages have been selected for pure R&D and 2 work packages for strategic studies. In addition, three work packages are devoted to Knowledge management, to ensure the availability and dissemination of the knowledge needed for a safe management and disposal and to provide training for young professionals. In particular, it will be of utmost importance to capture and transfer the knowledge and know-how over the generations, given the long time perspectives of radioactive waste disposal, both for the implementation and for the time scales to be considered in the safety assessment.

The work packages of EURAD are the following:

*Management*

1. PMO - Programme Management Office
14. Ethics requirements

*Research, Development and Demonstration*

2. ACED - Assessment of chemical evolution of ILW and HLW disposal cells
3. CORI - Cement-organic-radionuclide-interactions
4. DONUT - Development and Improvement of numerical methods and tools for modelling coupled processes
5. FUTURE - Fundamental understanding of radionuclide retention

6. GAS - Mechanistic understanding of gas transport in clay materials
7. HITEC - Influence of temperature on clay-based material behaviour
8. SFC - Spent fuel characterization and evolution until disposal
15. CONCORD - Container corrosion under disposal conditions
16. MAGIC - Chemo-mechanical aging of cementitious materials
17. MODATS - Monitoring equipment and data treatment for safe repository operation and staged closure

*Strategic studies*

9. ROUTES - Waste Management Routes in Europe from Cradle to Grave
10. UMAN - Uncertainty Management Multi-Actor Network

*Knowledge management*

11. State-of-Knowledge
12. Guidance
13. Training & Mobility

The intermediate results of the work packages were presented in the different sessions of EURADWASTE’22.

The start of EURAD has meant a step-change in the management of EC-funded research. EURAD provides a platform that ensures the structured and efficient interaction between key actors in RD&D that have a formal responsibility to support the implementation of radioactive waste management and disposal in their respective countries.

The research needs to be considered in EURAD have been developed through three important documents:

- A Roadmap, which provides a generic framework to organise typical scientific and technical domains/subdomains in a logical manner against different phases of a RWM programme.

- Themes overviews: The roadmap covers seven themes (Programme management, Pre-disposal, Engineered barrier systems, Geoscience, Design and optimization, Siting and licensing, and Safety case). For each of them the state of knowledge and the future needs are described in the themes overviews.

- Strategic Research Agenda identifying the research and development needs within the seven themes, which are of common interest for the EURAD participants and thus suitable for joint research and development.

The organisation of the European Joint Programming within EURAD provides a number of advantages to the earlier funding system for EC-funded projects, e.g.:

- An increased cooperation between all concerned parties in radioactive waste management and an enhanced information exchange between the different subprojects, and between the participating organisations.

- It is in line with EC ambitions to outsource the management of the R&T programme and make the decisions on the content closer to the users of the results.

- A better understanding of the role of a specific R&D project in the waste management system and in the safety assessment. It provides the specialists with a better understanding of how their R&D contributes to the overall implementation of waste management systems and their long-term safety.

- A good interaction between different disciplines also contributes to the better total understanding.

- It enhances the mutual understanding and trust between the partners involved in radioactive waste management.

- EURAD provides an excellent platform for early-stage programs to participate and learn from the more advanced countries. It provides possibilities of transfer of knowledge and know how from advanced programmes to less advanced programmes.

- There is a potential for synergies between countries with small inventories and those with large, in spite of difference in size of the projects.

- There is a strong ambition to involve many young researchers in the work of EURAD, thus ensuring a transfer of knowledge between generations and the availability in the future of qualified researchers in the different disciplines that will remain important for the implementation of radioactive waste management and disposal.

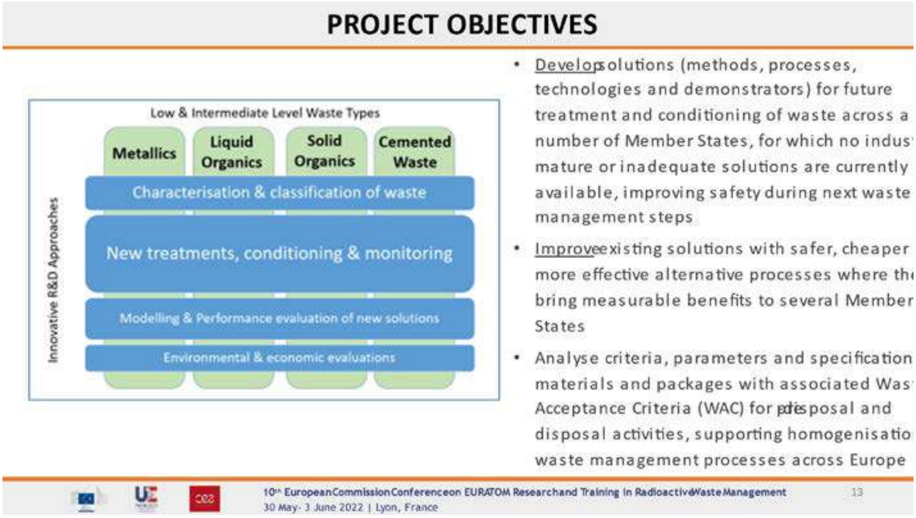
- And last but not least, EURAD is providing a more efficient management towards the European Commission, thus alleviating some of the burdens for the different work package leaders.

EURAD has become a strong platform for cooperation at European level of all aspects of management and disposal of radioactive waste. The structure built is functioning well and there is a great momentum in the work. It will thus be of utmost importance that funding can be ensured following the expiration of the present project in 2024 to build on the established activities and momentum.

**PREDIS - Pre-disposal management of radioactive waste streams-**

One of the themes identified in the Roadmap presented in EURAD is pre-disposal. As this theme was not included in the tasks of EURAD a special call for proposals for this area was launched by the Commission and the PREDIS project was selected and started late in 2020. The PREDIS project targets the development and implementation of activities for pre-disposal treatment of radioactive waste streams other than nuclear fuel and high-level radioactive waste.

The structure of PREDIS is similar to that of EURAD. PREDIS has 47 partners from 18 Member States. The objectives of PREDIS are given in the figure below.




In addition to a work package for Programme management, PREDIS has one work package on strategic implementation studies, one on knowledge management and four technical work packages. These are:

- Innovations in metallic material treatment and conditioning
- Innovations in liquid organic waste treatment and conditioning
- Innovations in solid organic waste treatment and conditioning
- Innovations in cemented waste handling and pre-disposal storage

Early results from these waste packages were presented at the conference.

The PREDIS project has been developed in close cooperation with EURAD and contains similar work packages, e.g. concerning strategic studies and knowledge management. The intention is that in the future PREDIS will be merged into the successor of EURAD.

**Some reflections from the presentations at the three technical sessions of EURADWASTE’22**

As mentioned above EURADWASTE’22 was organised in three technical sessions in addition to the opening and closing sessions organised jointly with FISA. Extensive summaries of the three sessions and more in-depth considerations are given in the separate reports by the session rapporteurs. Here I will only give a few personal reflections.

<u>Collaborative research, development and demonstration in Radioactive Waste Management</u>

In this session, a presentation of the work within IGD-TP was followed by presentations of the progress of the RD&D within EURAD and PREDIS as well as the results of some earlier EU-funded projects. The subjects covered were radioactive waste characterization, pre-disposal, radionuclide retention in the near field, evolution of engineered barriers, gas and heat transport in clay based materials and spent fuel characteristics. Given the short time available in the presentations, they were mainly appetizers for the details to be found in the many posters.

The presented results were interesting and useful. However, the connection to the needs of the safety assessment and design was not always obvious. This is an area where improvements can be made in the future work of EURAD as more crosscutting activities will be initiated. A good opportunity to bring this connection to the forefront will be in the preparation of the revised Strategic Research Agenda, which has been initiated.

Strategic research studies in radioactive waste management

In addition to presenting the results from the two work packages dedicated to strategic issues, ROUTES and UMAN, presentations were also made in this session on the work within the SITEX Network and the collaboration between IAEA, OECD-NEA and EURAD and PREDIS.

ROUTES deals with the cradle-to-grave management of odd wastes and management routes for countries with small inventories. It is well in line with the requirements in the Euratom Directive on the safe and responsible management of spent fuel and radioactive waste that each country should develop a plan for the management of its radioactive waste, however small quantities there are. In this connection, also a description was given of the ERDO project, in which several European countries with small quantities of radioactive waste are cooperating. The aim is to enable the establishment of one or more operational, shared multinational European waste management solutions as a complement to national programmes through jointly addressing the common challenges of safely managing the long-lived radioactive wastes in the countries.

UMAN tries to identify uncertainties at different stages of programme development and find methods to deal with them, including being prepared for the unknown. As many different uncertainties will exist it will be of utmost importance to also connect each uncertainty to the risk it implies.

The experiences, so far, from the strategic studies is that they work best if they are based on networking and addresses areas where common needs can be identified. An important component of the strategic studies is the involvement of the Civil Society, which can provide good and critical input. In this context it is, however, an issue to determine who are the Civil Society. Are they the local citizens concerned by the waste management activities or are they the vocal critics of the work. It is and will continue to be a challenge for EURAD to ensure that a broad enough cross section of the population is involved and are listened to.

There are several international organisations involved in studies of radioactive waste management and it was encouraging to see that good steps had been made towards close cooperation between EURAD/PREDIS and the IAEA and OECD/NEA, as there is a clear complementarity in their respective work activities.

Knowledge management

The time perspectives involved in developing and operating a GDR and for ensuring its safety are very long. It will often be more than 100 years between the start of the development of a repository project and the final closure of the repository. At all stages of this period there will be needs for recurrent safety assessments and for reanalyses of the bases for the design and operation. This work will thus be performed over several generations. Ensuring that knowledge is kept and transferred over this period is thus of paramount importance. Knowledge management (KM) is therefore an important component in both EURAD and PREDIS.

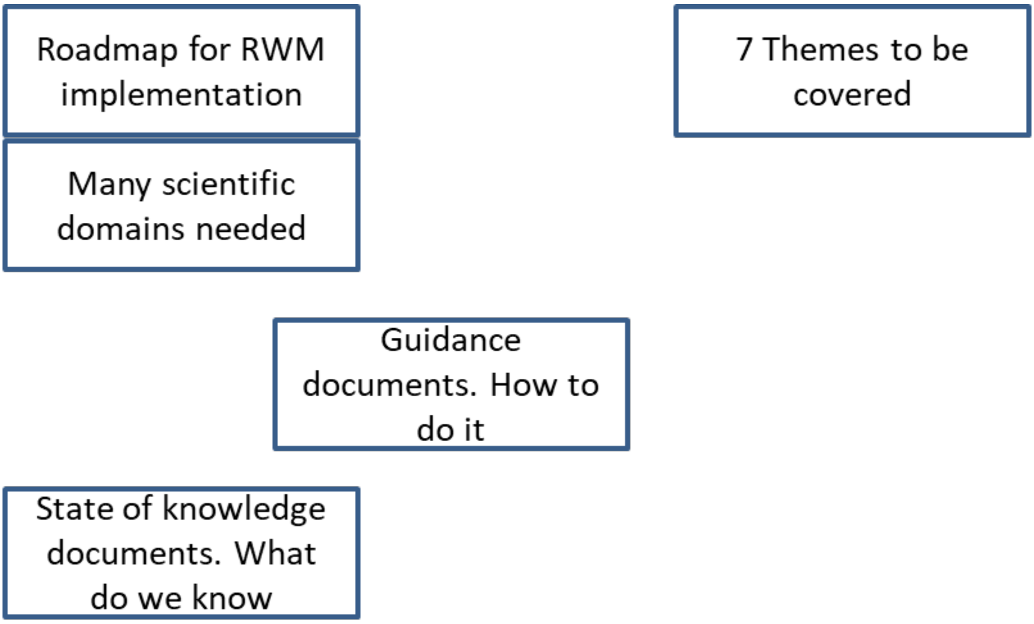
KM has two components, information and know how. Information can easily be documented. But it is important to have an efficient system to retrieve the relevant information necessary to understand what has been done earlier and to perform new and improved analyses. The know how will be more in the heads of those performing the work. To ensure that know how is kept, continuity will be needed through a system for successive transfer of knowledge. Here the requirements on the implementers to have recurrent safety assessments at regular intervals will be a good tool for both continuity and transfer to new generations.

Each Waste Management Organisation will surely develop its own KM system focused on the design, operation and long term safety of their specific disposal systems. Another challenge is to develop at an international level a broader KM available for other users. In EURAD and PREDIS this work has a high priority. Three components of their KM work were presented and discussed:

- Training and mobility
- State of knowledge documentation
- Guidance based on information

Within the Training and mobility work package, a School of Radioactive Waste Management has been established. It coordinates all training activities within EURAD and ensures that state of the art knowledge is provided. A variety of tools are utilised, e.g. training courses, webinars, PhD community support and lunch seminars. Through the mobility programme young researchers are provided the opportunity to participate in the different technical/Scientific work packages of EURAD and PREDIS.

To structure the development of the state of knowledge documentation and the guidance documents, the work on road map and themes described above is utilised. This is shown in a schematic way in the figure below.




An important question that still needs to be addressed is how to maintain the information base that will be generated within EURAD and PREDIS. As similar work is performed by IAEA and OECD/NEA a joint specific study should be initiated on how to preserve this valuable information and keep it up to date as new knowledge emerge.

**Main messages from EURADWASTE '22**

The main messages coming out of EURADWASTE'22 can be summarised as follows:

- Good progress can be seen in several Member States towards geological disposal of spent fuel and high level and long lived wastes. In Finland the first repository is under construction and Sweden and France are following suit, while other MSs are advancing their search for a suitable site.

- Although licenses have been approved future research will be needed to:

    - Improve and optimize design and operation and to find simplifications that reduces the costs, while keeping the safety level,

    - Adapt to the geological conditions of new facilities,

    - Adapt to new types of waste coming from new reactor systems

    - Take new and improved developments in other fields into account, e.g. digital twins,

    - Keep a watching brief on new scientific knowledge, and

    - Ensure availability of knowledgeable staff and availability of R&D capacity.

- In the future R&D some areas can be deemphasised, given the advanced state of knowledge or the lower importance for the safety. To this end it will be very useful to produce position papers or common opinions from EURAD based on the State of knowledge reports to be produced.

- Some new reactor systems, which are considered for Small Modular Reactors, will create new challenges for waste management. It is thus of utmost importance that these challenges are identified early through a close cooperation between reactor developers and those responsible for the management and disposal of radioactive waste.

- 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 establishment of EURAD and PREDIS has been an important change in the implementation of the EURATOM R&T programme. It has put the decision making on the details of the programme closer to those who actually will benefit from the R&D results. The process for developing the research programme based on input from the colleges, i.e. the WMOs, the TSOs, and the scientific society, ensures the usefulness of the programme.

- 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 administrative structure for EURAD, although at first sight quite complicated, is now well established and functional. It ensures a good balance of the work, an efficient administrative follow-up and an excellent scientific peer review process, while at the same time relieving some of the administrative burdens of the work package leaders.

- It is therefore very important that a continued funding can be ensured for a EURAD 2 after June 2024, which preferably also should include activities now funded within PREDIS.

- In preparation of EURAD 2 it will be important to continue ensuring the inclusiveness of all participants, to identify new areas, e.g. IT-based technologies for repository implementation and to close some areas based on common position papers of “how good is good enough for implementation”.

- The proposal for EURAD 2 should be based on an updated Strategic Research Agenda with input from different users through the three colleges, which is based on understanding the detailed needs of different Member States, including advanced and early/medium stage programmes and programmes with small inventories. An effort should be made to stimulate even more active engagement of advanced programmes, not least in developing KM and guidance and in becoming drivers within communities of practice.


FISA 2022
EURADWASTE'22

## JOINT INTRODUCTION FISA 2022 / EURADWASTE '22

Co-chair: Bernard SALHA (FR, SNETP)

Co-chair: Rosalinde VAN DER VLIES (EC, DG RTD)

Rapporteur: Henri PAILLERE (FR, Expert)

# OPENING SPEECHES

# KEYNOTE- EURATOM RESEARCH AND TRAINING AND HORIZON EUROPE FRAMEWORK PROGRAMMES: OPPORTUNITIES AND CHALLENGES IN THE EU INNOVATION LANDSCAPE

**Rosalinde VAN DER VLIES,** Director Clean Planet, DG Research and Innovation on behalf of **Mariya GABRIEL,** European Commissioner for Innovation, Research, Culture, Education and Youth

Ladies and Gentlemen,

[Introduction]

On behalf of Commissioner Mariya Gabriel, I am very happy to join you today at the 10$^{th}$ edition of the FISA-EURADWASTE conferences. It is a great honour to be here among the world's leading experts and stakeholders from industry, academia and policy-making.

I would first like to thank the French CEA, the Commissariat à l'Energie atomique et aux énergies alternatives that, together with the European Commission, has organised this important event for the nuclear community, under the scope of the French Presidency of the Council. A special thank you also to the Région Auvergne-Rhône-Alpes and his President Laurent Wauquiez who has kindly hosted this event throughout this week. Thank you also to SFEN, the Société française d'énergie nucléaire and to SNETP for the good collaboration.

I take this opportunity to pay tribute to ITER Organization Director-General, Dr Bernard Bigot, following his recent passing on 14 of May. I have a profound respect for his achievements, a life at the service of nuclear research and innovation, both fission and fusion. Bernard Bigot was also Administrateur général at CEA and former Director of École Normale Supérieure here in Lyon.

Ladies and Gentlemen,

We are all conscious of the challenging times we are living. These times require unity, and strong solidary action.

*[Euratom R&I support to the energy transition to 2050]*

Regarding the energy transition, I would like to underline that Research and Innovation (R&I) has growing relevance to accelerate the diversification of our energy sources and technologies. We need to reduce our dependency in particular from unreliable partners.

This is not only valid from a medium-term perspective but also for the very next future. And the Commission REPowerEU initiative is going in this direction.

The EU should accelerate its path in view of reducing by 55% its greenhouse gas emissions by 2030 and become the first carbon-neutral continent by 2050.

For this purpose, all technologies are needed and it is up to the Member States to choose their energy mix.

Last February, the Commission approved the complementary Delegated Act on the Taxonomy Regulation, which aims to guide private investments to achieve climate neutrality. Nuclear technologies are included in this Delegated Act with some conditions.

Today, half of the Member States[1] have opted either for large-scale nuclear facilities, or future Small Modular Reactors (SMRs). Because they are smaller in size and modular, SMRs promise to be safer, cheaper and easier to build and operate.

As a result, they could bring electricity and heat to regions where economic, geographical or grid-related constraints impede the economic viability of large conventional power plants. In several EU Member States, SMRs may be an option to switch from coal power plants to decarbonized electricity. This was explicitly mentioned in the recent High-level Commissioner Gabriel Nuclear Roundtable.

Innovative SMR designs are expected to display enhanced safety performance through passive and inherent safety features.

The Euratom Research and Training programme has been funding several activities on nuclear safety, advanced materials and licensing for new types of reactors, including SMRs.[2]

Within this context, our services (DG ENER, DG R&I and JRC) are looking at how to deploy SMRs in Europe, focusing on R&I issues that will promote industrial

[1] Currently, 13 Member States have operational nuclear power plants (Belgium, Bulgaria, Czech Republic, Finland, France, Germany, Hungary, the Netherlands, Romania, Slovakia, Slovenia, Spain and Sweden) of which 3 plan nuclear phase-outs by 2030 (Belgium, Germany, Spain). 8 Member States are building or planning new reactors (Bulgaria, Czechia, Finland, France, Hungary, Poland, Romania and Slovakia). In addition, companies from several Member States are developing SMR designs (Czech Republic, Denmark, France, Italy, Luxembourg, Poland and Sweden).

[2] Examples of current Euratom-funded projects focusing on SMRs nuclear safety are ELSMOR, McSAFER, CC-SMART, GEMINI+ with a total Euratom contribution of EUR 15 M. DG ENER established in December 2021 the Inter-Service Working Group (ISWG) to prepare and coordinate EC representation in view of launching a “European Small Modular Reactors (SMRs) Partnership” with EU stakeholders (industry, research organisation, European Regulators).

cooperation and build a stronger EU industry.[3] In our next Euratom work programme for 2023-25, we expect to invest EUR 20 M for SMRs research and innovation.

European industry is responding to this emerging demand with several EU SMR designs being already under development. The European Nuclear Safety Regulators Group (ENSREG) is working on possible licensing of SMRs.

Nuclear technologies could benefit from R&I developments in robotics and Artificial Intelligence (AI) combined with high-performance computing. AI in the nuclear sector has been expanding considerably in the last few years.

The know-how and expertise that is gained from applying AI-enabled digital tools to the nuclear industry have the potential to be fruitfully transferred to other sectors. We should therefore establish appropriate channels to facilitate those cross-sectorial synergies and the transfer of knowledge and expertise.

*[Euratom as a pan-European framework to work together]*

I am very pleased to share with you that the Euratom programme is and will fund to 2025, research and training activities in fission and fusion with EUR 1.4 billion. And funding should be further extended up to 2027 to align with Horizon Europe and the Multiannual Financial Framework of the EU. Political discussions will start next year with Member States on this extension.

Euratom provides a platform to work together on the common pan-European objectives of ensuring the safe and sustainable use of nuclear technologies. In few days, we will announce a Topic of EUR 10 M for diversifying the supply of nuclear fuel for VVER reactors currently coming from Russia.

For more than 65 years, Euratom has been the framework in which knowledge and competence in nuclear science and technology have been developed in Europe and through International Cooperation. Let me mention the excellent relations that we have with the OECD’s Nuclear Energy Agency (NEA) and the International Atomic Energy Agency (IAEA). Brussels, Paris and Vienna are today on the same *longueur d’onde*.

The EU has become the first major regional actor with a legally binding regulatory framework for nuclear safety following the implementation of the Euratom Directives on basic safety standards, on radiation protection and on radioactive waste management.

Euratom is supporting all EU Member States to meet equally high standards of safety, radiation protection, waste management and safeguards and continuously

[3] DG ENER established in December 2021 the Inter-Service Working Group (ISWG) to prepare and coordinate EC representation in view of launching a “European Small Modular Reactors (SMRs) Partnership” with EU stakeholders (industry, research organisation, European Regulators).

maintain high-level of competences, underpinned by sound and advanced research and innovation.

The Euratom Programme is mainly implemented through three co-funded European Partnerships involving EU Member States, with research funders and public authorities:

- the EURAD Partnership for Radioactive Waste Management;
- PIANOFORTE for Radiation Protection, placing a great emphasis on medical applications;
- And EUROfusion for Fusion energy research.

I am also pleased to announce that discussions are currently advancing with Member States on the Euratom support to a future European Partnership on Nuclear Materials.

In addition, the current Euratom Programme is funding several innovative cross-sectoral projects to promote synergies and new applications between nuclear and other sectors for EUR 10 Million including space and hydrogen. Hydrogen in particular, is emerging as a potential way to decarbonise hard-to-abate energy intensive sectors.

Nuclear technologies can support the industry needs for decarbonised heat and hydrogen by providing resilience to the electrical grid and complementing renewables in the supply of low-carbon electricity at affordable prices. They can support the decarbonisation of several applications that require heat, such as district heating and desalination.

With high and very high temperatures (above 1000 degrees Celsius), nuclear technologies can be used for industrial applications in the chemical sectors, for steel, cement, glass and paper production.

Another area that best exemplifies how important it is to build bridges between the nuclear sector and other sectors is the area of health. Rradiological and nuclear technologies play an important role in modern healthcare. In the EU alone, each year around 500 million medical procedures use ionising radiation. And 50% of cancer patients benefit from radiotherapy.

The EU is also the world’s leading supplier of medical radio-nuclides with a 60% market share of the global demand for some of the most widely used radio-isotopes used in diagnostics and therapeutics.

The current Euratom Programme puts a stronger emphasis on supporting research for the protection of patients benefiting from medical diagnoses and treatments using radiation sources. The programme is reinforcing the synergies between Euratom Research and the Health cluster of Horizon Europe by contributing to Europe’s Beating Cancer Plan and the EU Mission on Cancer. It also directly supports the Commission Strategic Agenda for Medical Ionising Radiation Applications (SAMIRA).

*[Euratom leveraging the Research & Innovation potential for training and the development of advanced skills]*

In the coming decades, various uses of nuclear science and technology will require highly educated personnel with very specific knowledge, skills and competences.

The profile of the coming generations of nuclear experts will be changing, as they will have to adapt to the digital transformation that will accompany these new technologies.

These aspects concern not only the energy sector but also medical and other applications making use of ionising radiations as well as fusion energy research.

The nuclear sector suffers from an ageing workforce. Some countries are faced by a declining interest by young researchers and students to enrol in the field. We need to act!

I take this opportunity to remind that 2022 has been declared the 'European Year of Youth'. Under this initiative, I am pleased to announce that today we are launching a new European social media campaign to attract younger generations to the nuclear field.

We have produced a short video including eight young nuclear talents. Let me show you this **2 minutes video** on *Young professionals in the nuclear field.* I hope that you will like it and if you do, please share it on your social media. The nuclear sector needs youth!

Ladies and gentlemen, young talents are crucial for Europe to maintain our world leadership in nuclear safety and waste management and the highest level of protection from radiation.

All stakeholders, including industry and regulators will need to play a vital role in ensuring that qualified and experienced staff continue to be available for the nuclear sector.

The Euratom Programme is going to support two new large initiatives on nuclear education and training:

- OFFERR, the 'European platform for accessing nuclear R&D facilities' will establish an operational scheme to facilitate access for researchers and industry to key nuclear science infrastructures in Europe.

- ENEN2plus means 'Building European Nuclear Competence through continuous Advanced and Structured Education and Training Actions'. ENEN2plus is the largest and most integrative nuclear Education and Training effort up to date. It supports cross-border and cross-disciplinary mobility within and beyond EU in cooperation with the Commission Joint Research Centre, with the Nuclear Energy Agency of the OECD, and with international partners including the United States, Korea and Japan.

[Conclusions]

FISA and EURADWASTE conferences have always been a major milestone on the Euratom agenda.

Their success lies in summarising the state of play of R&D on fission safety of reactor systems and radioactive waste management, highlighting major achievements and providing recommendations for the future.

The conferences are also fora to simulate discussions on the key needs in research and innovation policies addressed at national, European and international levels, promoting crosscutting synergies and partnerships within the nuclear sector and beyond.

I would therefore like to conclude by threes words, by three ‘R’ that I hope will remain in your mind for this conference:

- Research;
- Resilience, including for preparing the next generation of nuclear talents;
- Repower, for keeping our European strategic autonomy and decarbonizing our continent.

Thank you and enjoy the FISA-EURADWASTE conference.

# KEYNOTE- FROM HIGHER EDUCATION TO RESEARCH AND INNOVATION, A 'TEAM EUROPE AND GLOBAL' APPROACH / DE L'ENSEIGNEMENT SUPÉRIEUR À LA RECHERCHE ET À L'INNOVATION : UNE APPROCHE GLOBALE ET « ÉQUIPE D'EUROPE »

**Claire GIRY** (Ministry, FR), Directrice Générale de la recherche et de l'innovation, Ministère de l'Enseignement Supérieur

Madame la Commissaire européenne, chère Mariya GABRIEL,

Excellence, Monsieur le Directeur général de l'Agence internationale de l'énergie atomique, cher Rafael GROSSI,

Monsieur le Directeur général de l'énergie et du climat, cher Laurent MICHEL,

Monsieur l'Administrateur général du CEA, cher François JACQ,

Monsieur le Directeur général de l'Andra, cher Pierre-Marie ABADIE,

chers conférenciers et invités, Mesdames et Messieurs,

Au nom du ministère de l'enseignement supérieur et de la recherche, je tiens tout d'abord à remercier le CEA et la Commission européenne, coorganisateurs de cet évènement, pour leur invitation à cette prestigieuse session d'ouverture de la 10ème édition des conférences Euratom sur la recherche et la formation dans le domaine :

– de la sûreté des systèmes nucléaires de fission (FISA 2022)

– de la gestion des déchets radioactifs (EURADWASTE 2022),

qui se tient dans ce bel hôtel de région AURA[4] – merci à la Région pour son accueil.

[4] Mis à disposition gracieusement par la Région.

## Introduction

Il m'a été proposé de développer le sujet suivant « De l'enseignement supérieur à la recherche et à l'innovation : une approche globale et « équipe d'Europe » ».

Articuler la recherche, l'innovation et l'enseignement, souvent représentés comme le triangle de la connaissance, constitue le quotidien du ministère que je représente.

La double approche, globale et équipe d'Europe –Team Europe & global approach - a été introduite récemment par la Commission en vue d'intensifier la coopération internationale. J'en décrirai les principes appliqués à l'enseignement supérieur, la recherche et l'innovation.

De par la spécificité de la Communauté européenne de l'énergie atomique Euratom d'une part, l'exigence du partage des connaissances en matière de sûreté nucléaire et de gestion des déchets radioactifs d'autre part, le principe de cette approche est en quelque sorte déjà ancré au sein du programme de recherche et de formation Euratom. Il convient d'ajouter que le contexte de crise géopolitique et énergétique a amené à intensifier cette approche globale. J'y reviendrai.

**Principes généraux de coopération internationale et contexte du domaine nucléaire :**

- Si nous considérons tout d'abord le **programme de recherche et de formation Euratom**, il se rapporte au nucléaire et contribue donc à répondre aux défis planétaires posés par :

- Le changement climatique, avec la nécessité de développer des solutions de production sûre d'énergie décarbonée ;

- La crise énergétique exacerbée par le conflit en Ukraine ;

- La lutte contre le cancer, avec le développement d'une médecine nucléaire sur des méthodes de plus en plus évoluées et à ouvrir.

Sur l'approche globale ou « **Global Approach** », la Commission au travers de sa communication « L'approche mondiale de la recherche et de l'innovation » du 18 mai 2021[5] a présenté une nouvelle « stratégie de coopération internationale de l'Europe dans un mode en mutation »  réaffirmant l'engagement de l'Union européenne i) à promouvoir l'**ouverture** tout en réunissant des conditions de concurrence équitables et une réciprocité reposant sur des **valeurs fondamentales** d'une part, ii) à soutenir des **partenariats multilatéraux** afin

[5] Communication de la Commission au Parlement européen, au Conseil, au Comité économique et social européen et au Comité des régions, « L'approche mondiale de la recherche et de l'innovation - la stratégie de coopération internationale de l'Europe dans un monde en mutation », COM/2021/252 final, 18 mai 2021.

d’étendre les solutions aux défis planétaires, notamment écologiques, d’autre part.

Lors de la conférence ministérielle du 8 mars dernier à Marseille pour une approche globale de la recherche, de l'innovation et de l'enseignement supérieur, la ministre Frédérique Vidal a présenté, au nom de la présidence française du Conseil, la « **Déclaration de Marseille** »[6]. Cette déclaration propose neuf valeurs et principes communs aux États-membres et à l’Union européenne :

i) la liberté de la recherche scientifique,
ii) l’éthique et l’intégrité,
iii) l’excellence de la recherche,
iv) l’égalité entre les femmes et les hommes,
v) la science ouverte,
vi) le respect des droits de propriété intellectuelle et industrielle,
vii) la création de valeur et l’ambition de relever les défis sociétaux,
viii) la responsabilité sociétale et environnementale et la solidarité,
ix) la gestion des risques et la sécurité.

**Ces principes, croisés avec les thématiques de sûreté nucléaire et de gestion des déchets radioactifs, résonnent tout particulièrement.**

Sur le volet enseignement, la ministre a notamment évoqué le programme des actions Marie Sklodowska-Curie dont nous venons de fêter les 25 ans. Ce programme a été ouvert en 2021 aux jeunes chercheurs dans le domaine nucléaire ; j’aurai l’occasion d’y revenir.

Sur l’**approche « Equipe d’Europe » ou « Team Europe »**, celle-ci a été mise en place pour répondre aux situations d’urgence, telle la crise sanitaire en 2020. Le principe est de faire mieux ensemble, à savoir d’apporter des réponses à des pays partenaires, en particulier fragiles ou affectés par un conflit, grâce à une programmation et une mise en application conjointes. Ce point sera repris dans la suite, à propos du soutien apporté par le programme Euratom à l’Ukraine.

En définitive, ces deux approches structurent le **pacte de la Commission pour la recherche et l’innovation en Europe**[7] adopté récemment, dans l’ambition de créer un espace européen de la recherche **orienté vers l’avenir, notamment vers les transitions verte et numérique**.

[6] Déclaration de Marseille relative à la coopération internationale en matière de recherche et d’innovation, publiée à l’issue de la conférence sur une approche globale de la recherche et de l’enseignement supérieur organisée le 8 mars par la Présidence française du Conseil de l’Union européenne avec des représentants des États membres.

[7] « Recommandation du Conseil sur un pacte pour la recherche et l'innovation en Europe », 13669/21, 19 novembre 2021.

**L'approche globale et « équipe d'Europe » dans le programme Euratom de recherche et formation :**

**Qu'en est-il alors de la coopération internationale en matière de recherche, d'innovation et d'enseignement dans Euratom ?**

Depuis son entrée en application en 1958, « le Traité Euratom nourrit une triple ambition :

- **s'unir** afin de créer les conditions de développement de l'industrie nucléaire, à l'échelle européenne et mondiale,

- **établir les « conditions de sécurité** » pour protéger les travailleurs et les populations des effets néfastes des rayonnements ionisants,

- **coopérer avec les organisations internationales** attachées au développement pacifique de l'énergie atomique. ».

Ce traité décrit également les différents domaines du nucléaire relevant plus particulièrement du champ d'action de l'Union européenne, en premier lieu la recherche[8] et la diffusion des connaissances[9]. **L'approche « équipe d'Europe » s'avère ainsi être dans l'ADN du programme Euratom de recherche et de formation.**

Ce programme porte aussi cette ambition renouvelée d'intensification d'une **coopération fondée sur un socle commun, ouverte aux pays tiers**, particulièrement nécessaire dans le domaine du nucléaire civil, qui plus est dans la sûreté nucléaire et la gestion des déchets radioactifs. En lien étroit avec l'AIEA et l'Agence pour l'énergie nucléaire de l'OCDE, cette coopération est nourrie par divers groupements, plateformes, associations, réseaux européens, qui feront d'ailleurs part du bilan de leur action et de perspectives dans la suite de ces deux conférences.

**Illustrations antérieures :**

En revenant juste en arrière, la **précédente édition FISA/EURADWASTE en 2019 en Roumanie** a permis, au travers de la revue de l'ensemble des actions du programme de recherche et de formation Euratom, d'en illustrer les avancées, de la part non seulement des pays européens mais aussi de pays tiers, en pointe dans la recherche nucléaire civil ou s'y engageant. Au travers de ce bilan[10], il apparaît que, dans un esprit « équipe d'Europe » et plus global, des initiatives de programmation conjointes se sont concrétisées, préfigurant des partenariats durables.

[8] Partie 2 du traité, chapitre 1.
[9] Partie 2 du traité, chapitre 2.
[10] R. Garbil, C. Davies, D. Diaconu, "Euratom Research and Training in 2019: challenges, achievements and future perspectives", EPJ Nuclear Sci. Technol. 6, E2 (2020).

Ainsi, le **programme conjoint EURAD**, coordonné par l'Andra et dédié à la gestion des déchets radioactifs, permet aujourd'hui à plus d'une centaine d'organisations, soit 800 acteurs de 23 pays européens ou pays tiers, de coopérer. Ce partenariat associe notamment des chercheurs et experts du Japon, du Canada et d'Australie. Il est à noter qu'il est également **ouvert à la société civile**. En matière d'enseignement, ce partenariat dispose d'une école dédiée à la formation et la mobilité des chercheurs. Le bilan à mi-parcours d'EURAD a été discuté hier en vue de la prolongation de cette coopération exemplaire.

**Illustrations actuelles et nouvelles initiatives :**

La **10ème édition** qui nous concerne présente un programme qui augure d'un contenu au moins aussi riche que la précédente.
Toutes les parties prenantes sont représentées, rassemblant en quelque sorte cette **équipe d'Europe**[11] dans le domaine de la sûreté nucléaire et de gestion des déchets radioactifs.

L'impulsion de la Commission autour de la **double approche « globale » et « Equipe d'Europe », croisée avec le contenu du programme actuel de recherche et de formation Euratom**, amène à relever les principales inflexions suivantes:

❖ Tout d'abord dans le **règlement du programme actuel** (2021-2025):
- Les principes et valeurs partagées sont réaffirmés dans le règlement et un article est désormais dédié à la science ouverte[12].
- Les chercheurs au sein du programme sont désormais éligibles aux bourses postdoctorales des actions Marie Skłodowska Curie.
- Les synergies entre Euratom et Horizon Europe sont encouragées.
- Des actions d'innovation à finalités plus transverses au bénéfice de la société sont sollicitées, par exemple dans la santé.

❖ Considérons maintenant le **programme de travail actuel 2021-2022**:
- Lorsqu'il est question d'approche globale et d'équipe d'Europe, la **solidarité** en temps de crise est un élément fondamental. Ainsi, pour l'Ukraine, la Commission a proposé aux États-membres d'amender le programme de travail 2021-2022 avec des mesures adaptées aux équipes de recherche ukrainiennes et un budget supplémentaire.

- Sur l'importance des **partenariats**, EURAD a déjà été évoqué. Je souhaiterais souligner une autre illustration, avec le lancement, demain, de **PIANOFORTE** dédié à la recherche en radioprotection et à la détection des rayonnements

[11] Plateformes : SNETP (plateforme technologique pour une énergie nucléaire durable), plateforme technologique pour la mise en œuvre du stockage géologique (IGD-TP) ; Associations : ENSREG (European Nuclear Safety Regulators Group), WENRA (West European Nuclear Regulators' Association), ENEF (European Nuclear Energy Forum), ESARDA (European Safeguards Research and Development Association) ; Réseaux : ETSON (European Technical Safety Organisations Network), ENEN (European Nuclear Education Network), (ENS YGN (European Nuclear Society Young Generation Network), University Network of Excellence in Nuclear Engineering.
[12] Conformément aux dispositions du règlement (UE) 2021/695.

ionisants. Il convient de souligner que cette coopération large a pu se concrétiser grâce à:

- une mise en commun préalable de moyens au sein de six plateformes expérimentales européennes,
- l'établissement d'une stratégie de recherche partagés, au crédit du consortium précédent CONCERT[13].

PIANOFORTE coordonné par l'IRSN regroupe 59 partenaires de 24 pays, dont 2 pays tiers[14]. Il préfigure ce que cette approche, plus globale et en équipe, peut apporter en efficacité et visibilité. L'ouverture au domaine de la santé y est renforcée en synergie avec le plan SAMIRA[15] initié par la Commission.

- Sur la **question de l'enseignement et de la formation**, le constat partagé, tiré notamment d'un travail conséquent mené ces derniers mois en Groupe de recherche (questions atomiques)[16], est un besoin de renfort des compétences, avec la nécessité de rendre les métiers du nucléaire plus attractifs auprès des jeunes.

  Des actions dédiées sont entreprises au sein:

– du **Centre commun de recherche** (JRC) qui y consacre 11% de ses ressources, assurant la gestion des connaissances,

– des partenariats que je viens d'évoquer,

– des projets de recherche et d'innovation avec de l'ordre de 5% de leur budget fléché,

– de réseaux tel l'ENEN regroupant 87 membres de 27 pays ou encore le réseau de la jeune génération de la société nucléaire européenne bien mobilisée.

Deux prochaines actions de coordination et support illustrent aussi cette approche globale intensifiée en matière de formation :

– ENEN2Plus[17] avec 53 partenaires de 3 continents, dont le point fort sera de promouvoir la mobilité des jeunes chercheurs ;

– OFFERR[18] coordonné par EDF en lien avec la plateforme SNETP pour ouvrir aux jeunes chercheurs/ingénieurs des installations de R&D du nucléaire.

Enfin, l'ouverture à Euratom du programme des actions **Marie Sklodowska-Curie MSCA**, a porté ses premiers résultats avec 5 chercheurs post-doc soutenus

[13] European Joint Programme for the Integration of Radiation Protection Research.
[14] UK, NO.
[15] SAMIRA (Strategic Agenda for Medical Ionising Radiation Applications).
[16] Projet de Rapport de la présidence sur le soutien aux compétences européennes dans le domaine nucléaire dans le contexte du travail engagé au sein du groupe Recherche (Questions atomiques) au 1er semestre 2022, mai 2022.
[17] ENEN2PLUS (Building European Nuclear Competence through continuous Advanced and Structured Education and Training Actions).

[18] OFFER (eurOpean platForm For accEssing nucleaR R&d facilities).

dès le premier appel en 2021. Ce dispositif, à étendre, est essentiel pour ouvrir le secteur nucléaire à une communauté plus large.

**Conclusion et perspectives :**

Ainsi, pour conclure, la sûreté nucléaire et la gestion des déchets radioactifs reposent sur la connaissance et les compétences, deux exigences à porter sur des temps longs.
S’il s’agissait de l’illustrer, une coopération large et ouverte en matière de recherche et d’innovation, et d’enseignement, s’avère essentielle sur ces sujets complexes sous l’angle scientifique, technique ou sociétal.
En analysant comment le programme Euratom est structuré et évolue, il apparait que **son action bénéficie d’une approche, globale et « équipe d’Europe »** particulièrement mobilisatrice, sur les principes récemment réaffirmés par la Commission.

Le contexte actuel amène aussi à considérer les questions de souveraineté technologique et d’autonomie stratégique en matière d’énergie, voire de santé sur les radionucléides médicaux, ce qui devrait renforcer la mise en place de nouveaux partenariats « aussi ouverts que possible, aussi fermés que nécessaire », alimentés par une recherche d’excellence, une innovation dynamique et un enseignement ouvert aux meilleurs talents, le tout mutualisé à l’échelle de l’Europe et tourné vers l’international, sur des valeurs et principes partagés.

# KEYNOTE - CHALLENGES AND LEVERS FOR THE ENERGY AND CLIMATE TRANSITION - EVOLUTIONS OF THE ENERGY MIX AND NUCLEAR - CHALLENGES OF R&D AND INNOVATION FOR THE ECOLOGICAL TRANSITION

**Laurent MICHEL** (FR), Directeur Energie et Climat, Ministère de la Transition Ecologique

## Remerciements

- Je tiens à remercier les co-organisateurs, le CEA et la Commission européenne, de m'avoir invité à participer à cette séance introductive de la 10e édition de la conférence FISA – EURADWASTE.

- Je remercie également la région Auvergne-Rhône Alpes, région qui possède une forte activité économique dans le domaine du nucléaire avec de nombreuses entreprises du secteur, d'avoir permis de bénéficier de cet Hôtel de Région à Lyon pour sa tenue.

- Cette conférence est un événement majeur de la Présidence Française Européenne qui a commencé le 1er janvier et se terminera le 30 juin 2022.

## Enjeux et leviers pour la transition énergétique et climatique

- Le 12 décembre 2015 à la COP21, l'Accord de Paris, premier accord universel sur le climat, a été adopté.

- En signant cet accord, les pays se sont engagés à limiter l'augmentation de la température moyenne de la planète à 2°C d'ici 2100, et si possible 1,5°C.

- Pour cela, ils se sont engagés, conformément aux recommandations du GIEC, à atteindre la neutralité carbone au cours de la deuxième moitié du 21ème siècle au niveau mondial.

- La France s'est notamment engagée à atteindre la neutralité carbone en 2050. Il nous faut aussi réduire rapidement nos émissions de gaz à effet de serre car ceux-ci s'accumulent dans l'atmosphère, notre « budget carbone » résiduel est désormais compté. C'est pour cela que l'Union européenne se fixe comme objectif de réduire ses émissions de gaz à effet de serre de 55 % entre 1990 et 2030.

Concrètement, la neutralité carbone suppose une sortie des énergies fossiles d'ici à 2050. Or, malgré notre mix électrique largement décarboné, gaz, pétrole et charbon constituent encore 63% de notre consommation d'énergie finale.

Cet objectif va demander des efforts importants et une transformation profonde de nos modes de vie, de consommation et de production.

Pour réussir, la première priorité est la réduction des consommations d'énergie. Notre stratégie est claire : baisser de 40 % la consommation d'énergie en 2050 par rapport à notre consommation actuelle.

Ce défi est considérable mais nous sommes actuellement sur le bon chemin grâce aux politiques menées depuis 2017 sur la rénovation énergétique des logements, la modernisation automobile, la rénovation des bâtiments publics…

Cela ne sera cependant pas suffisant. Il faut développer toutes les énergies décarbonées, dont le biogaz et la chaleur renouvelable (biomasse, géothermie, solaire…) et en plus électrifier massivement l'économie : utilisation d'hydrogène décarboné dans l'industrie, développement de la mobilité électrique, remplacement des chaudières gaz ou fioul par des pompes à chaleur, etc. Ainsi, malgré la baisse de la consommation totale d'énergie, celle d'électricité décarbonée augmentera d'ici 2050, d'autant plus en cas de réindustrialisation forte du pays. Cette hausse sera donc forte et rapide.

Afin d'atteindre la neutralité carbone, la France a défini une stratégie française pour l'énergie et le climat

Les grands objectifs de cette stratégie sont déclinés dans la loi énergie-climat adoptée le 8 novembre 2019 qui porte sur quatre axes principaux :

- la sortie progressive des énergies fossiles et le développement des énergies renouvelables ;
- la lutte contre les passoires thermiques ;
- l'instauration de nouveaux outils de pilotage, de gouvernance et d'évaluation de la politique climatique ;
- la régulation du secteur de l'électricité et du gaz.

- La loi climat et résilience de 2021 a renforcé tant nos objectifs que nos outils pour les atteindre, dans des domaines très nombreux comme la rénovation des bâtiments, le verdissement des véhicules et des mobilités, l'incitation à une consommation plus durable, la lutte contre l'artificialisation des sols et bien d'autres.

- Pour mettre en œuvre cette stratégie, le Gouvernement s'appuie sur deux leviers : la Stratégie Nationale Bas-Carbone et la programmation pluriannuelle de l'énergie

- La SNBC fixe les orientations pour mettre en œuvre la transition vers une économie bas-carbone dans tous les secteurs d'activités.

- Concrètement, elle définit un chemin pour atteindre la neutralité carbone en 2050, élaboré en concertation avec les parties prenantes concernées, avec des orientations transversales et sectorielles qui visent à décarboner la production d'énergie, réduire la consommation d'énergie mais aussi les émissions non-énergétiques et également augmenter les puits de carbone.

- Elle vise également à identifier les verrous technologiques et à anticiper les besoins en innovation.

- S’agissant de la PPE, elle fixe les priorités d’actions des pouvoirs publics dans le domaine de l’énergie afin d’atteindre les objectifs fixés par la loi en cohérence avec la Stratégie nationale bas-carbone.

- La PPE fixe ainsi le cap pour toutes les filières énergétiques qui pourront constituer, de manière complémentaire, le mix-énergétique français de demain. Cela permet de construire une vision cohérente et complète de la place des énergies et de leur évolution souhaitable dans la société française.

- Au-delà de l’objectif d’atteinte de la neutralité carbone à l’horizon 2050, la question de l’indépendance et de la souveraineté énergétique de la France est en enjeu également décliné par la PPE.

- La situation actuelle en Ukraine et ses conséquences sur la sécurité d’approvisionnement mettent en lumière la nécessité de diversifier le mix énergétique français afin de le rendre plus résilient aux événements exogènes.

### Évolutions du mix énergétique et place du nucléaire

- En application de la PPE 2019-2023, le gestionnaire du réseau de transport d’électricité français, RTE, a publié en octobre 2021 le rapport « Futurs énergétiques 2050 » au terme d’un travail ayant largement associé toutes les parties prenantes concernées.

- Ce rapport présente six scénarios de mix électrique différents, trois d’entre eux comprenant une part de nucléaire, et les trois autres n’en comprenant pas.

- Cette étude comporte une évaluation économique globale des différents scénarios et conduit à considérer qu’une part d’énergie nucléaire dans le mix électrique français permet d’atteindre avec une plus grande robustesse les objectifs poursuivis, notamment en matière de neutralité carbone.

- Le Président de la République française a annoncé en novembre 2021 et février 2022, en complément de la poursuite du développement massif de sources d’énergie renouvelables, l’engagement d’un nouveau programme de construction de réacteurs nucléaires, pour garantir l’indépendance énergétique de la France et atteindre la neutralité carbone en 2050.

- Il est prévu qu’une loi de programmation en matière d’énergie et de climat soit discutée par le Parlement en 2023 pour traduire la stratégie française dans ces domaines pour la période 2024-2028, et que la PPE et la SNBC soient mises à jour en conséquence en 2024.

- De larges concertations ont été engagées depuis octobre 2021 pour préparer cette loi et la révision de la stratégie française pour l'énergie et le climat, et seront poursuivies prochainement au travers d'une concertation sur le mix énergétique.

**Enjeux de R&D et d'innovation au service de la transition écologique**

- La filière nucléaire va devoir faire face à de nombreux défis dans les prochaines décennies : prolongation du fonctionnement du parc existant, diversification des technologies nucléaires, gestion des combustibles usés et des déchets radioactifs, programme de construction de nouveaux réacteurs etc.

- Le Gouvernement a ainsi décidé de soutenir résolument la modernisation et l'innovation de la filière, et de lui allouer un soutien spécifique dans le cadre du plan France Relance, lancé en septembre 2020, à hauteur de 470 M€.

- Ce soutien vise le renforcement des compétences dans la filière et les projets de modernisation industrielle, de relocalisation et de recherche et développement.

- Le plan d'investissement France 2030, lancé en ce début d'année 2022, confirme le soutien du Gouvernement à une filière nucléaire innovante : un soutien public supplémentaire d'1Md€ est destiné aux réacteurs innovants, dont font partie les réacteurs modulaires.

- **Le projet français de petit réacteur modulaire (SMR) Nuward devrait ainsi bénéficier d'une part substantielle du soutien alloué (environ 450 M€)** pour accélérer son développement, dans l'objectif de démarrer la construction d'une première unité à l'horizon 2030.

- Les SMR pourraient présenter des avantages de par une conception plus simple et compacte et une modularité permettant des économies au stade de la construction, avec une part importante de préfabrication plus standardisée, ainsi que de par un recours accru à des systèmes de sauvegarde passifs pour garantir la sûreté nucléaire.

- La gamme de puissance des SMR est proche de celle des centrales à charbon, qui devront être déclassées pour atteindre les objectifs climatiques.

- De ce fait, les SMR constituent pour le réseau européen interconnecté une option complémentaire de l'offre nucléaire classique de grande puissance, en substitution des centrales thermiques fossiles ou en réponse aux besoins des pays pour lesquels les réacteurs de grande puissance ne sont pas adaptés.

- Le MTE soutient donc la démarche de partenariat européen sur les SMR initié par la Commission afin de faciliter le déploiement sûr et harmonisé d'un produit SMR à l'échelle de l'Union européenne.

- **L’autre partie de l’enveloppe de France 2030 (environ 550 M€) sera octroyée à des projets de réacteurs innovants,** sur la base d’un appel à projets (AAP) qui a été publié en mars 2022.

- La recherche et l’innovation autour de concepts de réacteurs nucléaires en rupture, portés par de nouveaux acteurs, doivent permettre d’apporter des réponses nouvelles aux enjeux propres à la filière nucléaire, par exemple en matière de compétitivité, de sûreté, de sécurité, de fermeture du cycle du combustible nucléaire ou de réduction du volume ou de l’activité des déchets radioactifs.

- Les candidats peuvent être un consortium de sociétés françaises ou européennes dont le chef de file est une société dédiée au projet déposé dans le cadre de cet AAP et immatriculée en France. Les associations et les organismes de recherche, français ou européens, peuvent également faire parties d’un consortium.

- Qu’il s’agisse de modernisation au bénéfice de l’outil industriel comme du développement de nouveaux réacteurs ou d’options de gestion des déchets radioactifs, le Gouvernement français soutient donc ainsi la filière nucléaire dans son exploration de nouveaux concepts au service de l’innovation industrielle.

- A l’occasion de cette conférence Fisa-Euradwaste, je voudrais aussi rappeler l’importance du programme-cadre de la Communauté européenne de l'énergie atomique pour des activités de recherche et de formation en matière nucléaire (PCRD Euratom) qui coordonne les programmes de recherche des États membres pour l'utilisation civile pacifique de l'énergie nucléaire.

- Le budget de ce programme pour la période 2021-2025 s’élève à 1,382 milliards d’euros réparti comme suit :

  - 583 millions d’euros pour les actions indirectes en matière de recherche et développement sur la fusion ;
  - 266 millions d’euros pour les actions indirectes en matières de fission nucléaire, de sûreté et de radioprotection ;
  - 532 millions d’euros pour les actions directes menées par le Centre commun de recherche.

- Ce programme permet le soutien de nombreux projets collaboratifs nécessaires aux besoins d’innovation de l’énergie nucléaire.

- C’est le cas par exemple du projet EURAD, coordonné par l’ANDRA avec l’implication de 23 pays européens, qui vise à mettre en œuvre un programme stratégique commun d'activités de recherche et de gestion des connaissances au niveau européen, en rassemblant et en complétant les programmes des États membres de l'UE afin d'assurer la création et la préservation de connaissances de pointe en vue de fournir des solutions sûres, durables et acceptables par le public pour la gestion des déchets radioactifs en Europe, aujourd'hui et demain.

- C’est aussi le cas de différents projets en cours ou à venir autour de la sûreté des SMR, avec comme par exemple le nouveau projet TANDEM, coordonné par le CEA avec l’implication de 14 partenaires européens et de l’Ukraine, qui vise à fournir des évaluations et des outils pour faciliter l'intégration sûre, sécurisée et efficace des SMR dans les systèmes énergétiques hybrides à faible émission de carbone.

- La France soutient également le lancement à venir d’un appel à projet qui vise à soutenir un projet permettant la réalisation des analyses et des tests de sécurité nécessaires afin d’établir les procédures requises pour l'octroi de licences pour un combustible VVER fabriqué par des fournisseurs extérieurs à la Russie. Cette action répond au besoin essentiel de sécuriser l'approvisionnement en combustible pour les réacteurs VVER de conception russe dans l'UE et en Ukraine.

**Conclusion**

- Pour terminer, je souhaiterais saluer la place donnée à l’éducation, à la formation et à la jeunesse dans les sessions et événements organisés dans le cadre de cette conférence.

- Une véritable dynamique européenne des compétences dans le domaine du nucléaire est en effet nécessaire pour préserver le haut niveau d’expertise de toutes celles et ceux qui contribuent à la R&D et à l’innovation.

- En conclusion, je vous souhaite une très bonne conférence qui sera l’occasion de discussions fructueuses sur les avancées et les défis de la recherche, de l’innovation et de la formation.

# KEYNOTE - KNOWLEDGE SHARING: A KEY TO ADDRESSING THE WORLD'S BIGGEST NEEDS

**Rafael Mariano GROSSI** (IAEA), Director-General of the International Atomic Energy Agency

Excellences, ladies and gentlemen, it's a pleasure to address you today. I thank rance for hosting this important gathering and for inviting me to be part of it.

As nuclear technology advances, safety and waste are two critically important areas to get right.

Clear and substantial progress has been made in safety, in new reactor designs, fuel cycle options, and in Small Modular Reactors. Clear and substantial progress has also been made in Radioactive Waste Management. From Finland, Sweden, and France, to Switzerland and Canada, projects at their various stages are moving in the right direction. Some are already very close to becoming real solutions to one of the biggest issues raised every time nuclear acceptance is debated.

Today you have the chance to share your experiences, the lessons you have learned, the progress you have made and the future you envision. It's on this topic of knowledge-sharing that I would like to focus my remarks. Let me give you three different examples.

Let me start with sharing our work with the wider public. While nuclear waste and safety lurk in the shadows of ordinary people's minds, they will remain things to fear and barriers to acceptance. I urge you to take what you do out into the wider world. Making it more visible to the public is how we demystify nuclear and allow people to make decisions based on science, rather than fear or ideology. It's also a way to reach students and young professionals who may otherwise not know what an exciting and important sector they could join.

Secondly, let me speak about sharing our experiences and progress with those who have less and need more. You of course know the IAEA's important work in formulating safety standards and security guidance. Another core part of the IAEA's mandate is to help Member States gain access to the many benefits of nuclear science and technology, and to assit them in the essential areas of safety, security and safeguards. Knowledge-sharing is a big part of how we do it.

ARTEMIS, for example, is a key collaboration between the IAEA and the European Commission, offering an integrated expert peer review service for national radioactive waste and spent fuel management, decommissioning and remediation programmes.

As you make progress in your areas and share your experiences through the IAEA and in other ways, you allow emerging programmes to become safer and more effective. That not only makes the world a better place, but also secures your own investment in nuclear. As we have experienced in the past, when nuclear energy programmes work well across the world, everyone benefits; and when accidents happen, the entire sector is affected.

As my final example, let me raise something else that you are doing this week: sharing knowledge and experience across the sector. FISA will present advances in technology that need to consider not only safety, but also radioactive waste management solutions before they are needed. Working across different parts of the sector, we all learn from the past and get better at anticipating the future.

For an IAEA example, there is our Nuclear Harmonization and Standardization Initiative. It brings together policy makers, regulators, designers, vendors and operators from around the world to develop common regulatory and industrial approaches that I am confident will facilitate the safe and efficient deployment of SMRs and other technology.

Ladies and gentlemen,

The better and the more we share our knowledeg and experience, the better and more nuclear can help address some of the world‵s biggest challenges.

For the past weeks, I have seen it up close. Safety, security and safeguards experts from across the world have been part of the IAEA‵s intense efforts to assist Ukraine‵s operators and regulators.

The conflict in Ukraine has had a big impact well beyond its borders. Today we face not only the disastrous consequences of climate change, but also the first global energy crisis. Together these twin emergencies have turned the spotlight firmly back on nuclear energy. We are at a crossroads and I am hopeful that these disasters – they are disasters, especially for developing countries - will push us towards a more sustainable energy path that includes nuclear.

From France, Belgium and the UK, to Brazil, South Korea and Japan, leaders are looking to nuclear. They are working on extending the lives of existing nuclear power plants; building new ones; and investing in research and technology.

Economists broadly agree that, if countries are to meet their economic and climate goals, global nuclear capacity will need to double. That growth will only be possible because it is able to build off the important work you have been doing on reactor safety, waste management and in preparing the next generation that will lead these sectors into the future.

In closing, let me again acknowledge our host. France has long played a leading and very visible role in nuclear. Last year I had the chance to discuss the agenda with President Emmanuel Macron. A highlight of my visit was the time I spent at the Saclay Plateau, seeing the cutting-edge collaboration between educators, researchers, start-ups and industry.

The investments and decisions France and countries with established nuclear power programmes make, not only affect their own journeys, but also the journeys other countries take.

The world needs more technological progress; more advances in safety; a bigger and more diverse workforce; and more ways to minimize and manage the waste that will be created before it is created.

What you do here and how you share what you do, is an integral part of meeting that need. Therefore, I thank you and wish you successful FISA and EURADWASTE conferences.

# KEYNOTE - OECD / NEA NUCLEAR RESEARCH AND INNOVATION SUCCESSES AND ACCOMPLISHMENTS, LOOKING TO THE FUTURE

**William D. MAGWOOD IV** (OECD/NEA), Director-General of OECD Nuclear Energy Agency

- Thanks to the French Presidency and the European Commission for the invitation to appear today and for their work in assembling this important conference.
- Thanks to all of you for surviving the pandemic and returning to the business of saving the planet. That is, after all, why we are here.
- The world faces many challenges today. Political, environmental, economic. Our world is rife with conflicts and uncertainties, the likes of which we have not seen in nearly a century. Nations face the challenge of reducing carbon emissions to "net zero" in less than 30 years. Humanity faces the challenge of a billion people seeking to rise from poverty and a generation in OECD countries who fear that the quality of their lives may not be as high as that of their parents.
- As in decades past, certainly since the industrial revolution, the availability of affordable, reliable supplies of energy lay at the core of many of these challenges.
- Energy, even more than in the past, will be the greatest determiner of economic and social success in the decades to come. Countries that are able to provide clean, economic, and reliable energy to their people and their industries will be more successful and more prosperous than those that cannot.
- Recent events have retaught the lessons that leaders should not have forgotten – that assuring reliable energy is one of the most important missions of any government. Hope and mysticism, ideology and sloganeering work best when there is a lot of energy available. When supply is constrained, controlled by others, or simply too expensive, real energy policy takes the center stage.
- Today, because of the challenge to reach net zero, energy policy is no longer simply the game of thrones played with reserves of oil and gas, but a race to innovate and create prosperity based on new concepts and new technologies.

And, as more and more countries around the world are finding, the nuclear sector is running hard in that innovation race.

- We here today are part of a sector that has been the sleeping giant in global energy for too many decades. Nuclear energy provides most of the non-emitting electric capacity in OECD countries, is reliable and available 24 hours a day and 365 days a year, but until very recently, was not included in many discussions about the future of energy. In part, we are to blame for this. For many years, the nuclear sector was happy to stay in the background, quiet and profitable.

- We were collectively too satisfied with the status quo, too willing to rest on the long success of proven technologies when other industries innovated and pushed new boundaries. Eventually, leaves and moss covered the comatose giant and it slipped out of sight and out of mind.

- In the minds of the public and many policymakers, the most advanced form of energy production on the planet was viewed as a relic of the dim past. Old outside cities with aging staff, pen charts and vacuum tubes.

- Finally, the giant has stirred.

- With some 70 projects around the world seeking the early deployment of SMRs and Generation IV systems, we are in a new era of nuclear technology innovation. One would have to look to the 1950s and 1960s to see a period of exciting and far-sighted research and development comparable to what we are seeing today. And it comes not a moment too soon.

- Countries around the world have set an ambitious target to reach net zero by mid-century in order to avoid reaching the much-discussed 1.5-degree C threshold that climate scientists believe is necessary to avoid a tipping point in climate change. In the aftermath of Glasgow, some analysts found heroic assumptions to point to progress—insufficient progress, but progress. Others, including the NGO Climate Action, say we are on path for 2.7 degrees C by the end of the century.

- Whatever your assumptions about the future, it is clear that we are not on track. Recent evaluations show that rather than slowing, global CO2 emissions reached their highest level in history in 2021, after two years of lower emissions in the midst of the pandemic.

- Governments are coming to realise that the approaches and strategies that have been most popular in recent years are falling short. This is why many of them are turning to nuclear energy.

- The work of the IPCC itself shows us why. In its 2018 special report, the IPCC reviewed 90 pathways with emissions reductions sufficient to limit average global warming to less than 1.5°C. When we reviewed these pathways, we found that on average, the scenarios reflect the need for global nuclear capacity to triple by 2050 to 1160 gigawatts, up from 394 gigawatts in 2020.

- The NEA's own analysis verifies this. Taking into account not simply electricity but also difficult-to-abate energy needs such as process heat, our recent publication released in May 2022 on The Role of Nuclear Power in Meeting Climate Targets, finds that nuclear capacity needs reach around 1200 GW by 2050.

- Doing so will require long-term operation of the existing fleet, the construction of new large Generation III reactors, as well as the success of SMRs and Gen IV technologies.

- And innovation is important in all of these areas. With many lessons learnt and the advent of digital technologies that hold the potential to enhance both efficiency and safety, long term operation of existing plants—for 60 or 80 years—is both practical and desirable. Construction of Gen III LWRs can be as successful in Western Europe as it has been in UAE. These existing, well-understood technologies can underpin the future.

- But the opportunity for the game to truly change rests with entirely new technologies.

- We must see Generation IV systems shift from concept to reality. After 20 years of work, the extensive of research and accumulated knowledge of the Generation IV International Forum could help industry to accelerate deployment with first demonstration projects. This is the objective of the GIF Industry 2022 conference that will be held in Canada in October.

- SMRs, which encompass a wide range of technologies, have captured the attention of capitals around the world, in both OECD and non-OECD countries. Based on our analyses, about a third of the nuclear capacity that is required by 2050 to meet global Net Zero will be new SMR designs, providing electricity, heat, clean water, and hydrogen.

- These technologies will be on-grid and off-grid. They will be light water and Generation IV. They will be mid-sized and microreactors. They will be land-based and marine-based. They will be mobile and multi-module configurations.

- And that is both the challenge and the potential of SMRs – they can fit in a wide range of applications and provide many services that are not possible for conventional reactors.

- These possibilities lay before us. The Generation IV International Forum and other activities can support the technology development and regulatory verification required of new technologies. But increasingly in our framework, we are concerned about whether our technical infrastructure can still meet our needs.

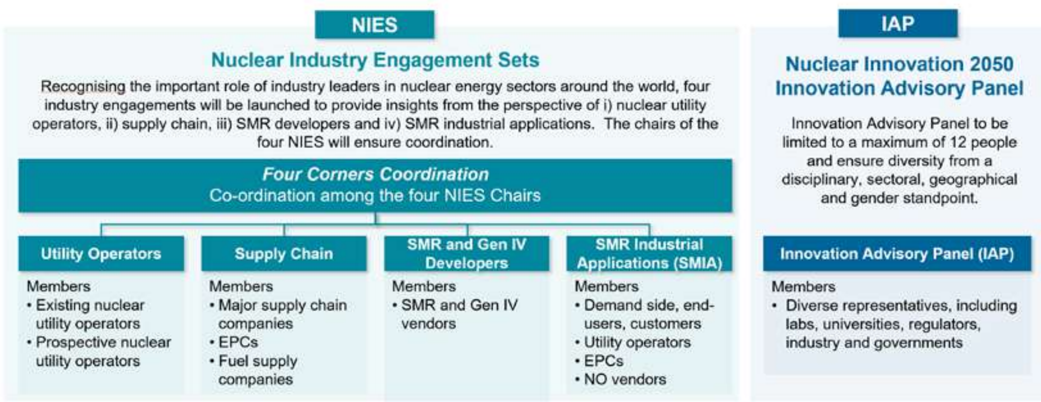
- In this context, the NEA launched a multinational framework for in-pile fuels and material testing: The Framework for Irradiation Experiments (FIDES). The main objective of FIDES is to strengthen our collective nuclear fuel and material experimental expertise and capabilities. Most of the countries represented here today are participating in this vital international platform.

- FIDES includes the study of the current nuclear fuel technology in extended conditions as well as the study of innovative nuclear fuel technology. But FIDES is not just generating key data to characterise these fuel materials, it is also designed with a holistic perspective of sustainability and continuous improvement.

- FIDES carries a commitment to compiling and retaining research data in a centralised manner. With the development of a central and systematic process for capturing research results, we can also obtain a clear picture of where gaps remain. Research efficiency is improved when we are truly clear about what we already know.

- Beyond the R&D of new technologies and systems, it is clear that the complexities of development, financing, licencing, and deployment of many diverse designs will present us with tremendous challenges. The public and private sectors will need to come together in a practical and focused manner to achieve success.

- For this reason, the NEA is launching its SMR Strategy, to coordinated the actions underway and identify the gaps related to the successful deployment of SMRs. With this strategy and the engagement of the thousands of member countries experts with who we work, we will set a path to assure that as many of these new technologies as possible are ready to help us meet the net zero challenge.




- Because the centre of gravity of nuclear innovation has shifted towards the private sector, the NEA is now launching a new engagement mechanism, the NEA Nuclear Industry Engagement Sets (NIES) to engage with industry leaders and practitioners from utility operators, supply chain, fuel cycle, SMR and Generation IV developers, and SMR end-users including heavy industry users.

- Invitations will be sent out soon. But I warn you – this is not an exercise in press releases and high-minded statements. This is a practical effort to identify and address barriers and to bring the attention of our member governments to the hard task of clearing away decades of underbrush. The giant is stirring, but he is not yet on his feet!

- Staying focused on what needs to be done and working with countries that will be part of this advanced technology future will help us all to accelerate the deployment of nuclear innovation – in support of LTO, Generation III new builds, SMRs, Generation IV concepts, and non-power applications such as heat and hydrogen – we need to work together to assure that these innovations are brought to deployment as soon as practical.

- Finally, we are the NEA are placing significant attention on the development of attention on the development of the next generation of nuclear technologists. Saving the planet will take longer than one career, so it is vital that our countries foster new scientists and engineers to design and develop further innovations, address legacy wastes and sites, and guide the nuclear sector into its second century.

- The NEA created the Nuclear Education, Science and Technology (NEST) Framework to build the capacity, skills, and knowledge of the nuclear leaders of tomorrow and additionally accelerate the deployment of nuclear innovations. NEST is a multi-national framework focused on developing the skills of the young generation through hands-on training activities while working on challenging, real-world research projects. I'm pleased to note today that Romania will join the Framework in the next few weeks and others are soon to follow.

- We have also launched the Global Forum on Nuclear Education, Science, Technology and Policy, giving the world's academic institutions their first standing international platform for cooperation and fostering fresh thinking on challenging issues confronting the nuclear sector, particularly with regard to the development of human capital.

- In addition to its programme of work, the Global Forum is supporting discussions within member countries about strengthening nuclear education and will also hold a Global Commencement for the world's graduating nuclear technologists on 29 June. Former Microsoft Chairman Bill Gates will provide the keynote address. Please join us for this online event.

- I will end my remarks today with three closing thoughts:

    1. The future for which we strive cannot be a future of scarcity and low ambition. People in OECD countries and in emerging economies expect and deserve better. We must provide both a prosperous future for all our people and a healthy environment for the generations to come. Nuclear energy in combination with renewables and other technologies provides the world with a clear and walkable path to achieve this.

2. As such, we in the nuclear sector hold one of the keys to the future in our hands. Our success is the world's success. The failure of our sector to achieve all of which we are capable will quite likely see net zero recede from society's reach.
3. The window to act is short and there is an urgency to act now or the window will close. We have slumbered. We have waited. But the sun has risen and is lighting the path ahead. It is morning and the time is now.

# KEYNOTE - WNA PROMOTING A WIDER UNDERSTANDING AND STREAMLINING INTERNATIONAL LICENSING AND REGULATORY FRAMEWORKS

**Sama BILBAO Y LEON** (WNA), Director-General of the World Nuclear Association

I want to start by thanking the European Commission for the invitation to join all of you today at FISA 2022 - EURADWASTE '22. I also want to apologise for not being there in person. I had absolutely planned to be this morning in person in Lyon with all of you. But unfortunately, planes, trains and automobiles have conspired against me, and I have not been able to make it in time.

There are about 500 of you this week in Lyon, and you are all going to be taking part in discussions and conversations on the state-of-the--art in research and development of efficient safety for reactor systems, and radioactive waste management. You are going to be looking at key challenges that need to be addressed at the national level, at the European level, and at the international and global levels. And you will also be looking at synergies and opportunities for partnership. You will be scanning the horizon together and looking at what are the challenges and the opportunities that are coming our way, and you will think about many ways to tackle them.

As you are doing all this very exciting work, remember that it is important to begin with the end in mind. The end that you should have in mind is that all this new technology, this innovation and this disruption, are ultimately intended to be used in the nuclear industry, and therefore will ultimately need to be licenced and regulated by our national regulatory agencies. This is why it is absolutely essential that from the very beginning the research and development community engages and collaborates with industry and with the regulators to make sure that we accelerate incorporation of all this disruption into the everyday nuclear industry.

Because nuclear energy is absolutely essential to address the climate change challenge at the speed and scale that is required. Nuclear energy can not only produce low carbon electricity, but also low carbon heat. And this is going to be a game changer to decarbonize the entire economy, including sectors that are very hard to abate, such as heating and cooling for buildings, such as many industrial sectors, such as shipping, transportation, the generation of hydrogen and other synthetic fuels, the production of fresh water... And this means that we are going to need much more nuclear energy. Some of the most robust scenarios indicate that by 2050, we are going to need to have about 1200 gigawatts electric of nuclear capacity in order to provide 25% of the global electricity needs. And this doesn't even include all the other applications beyond electricity generation that I just mentioned.

This is good news, right? This means that there is going to be a huge market, huge opportunities for the global nuclear industry to deploy nuclear technologies, including proven technologies that exist right now and also small modular reactors, advanced reactors and perhaps other future technologies in which some of you are already working.

However, there are challenges also… In order to have 1200 megawatts of nuclear by 2050 we need to build more than 30 new nuclear reactors every year from today to 2050, and then continue…. That is quite a few nuclear reactors. It is not impossible. It has been done before: in the 70s and 80s in France and in Sweden we actually achieved those speeds of deployment. So clearly, we can do it again.

However, there are a few things that need to happen for nuclear energy deployment to accelerate. These are the essential enabling conditions. First, we need the thought leadership and pragmatism of governments to put in place technology-neutral policies and markets, which recognise and appropriately price the attributes of all low-carbon technologies, including nuclear energy, of course.We also are going to need affordable financing for nuclear projects, thus to include nuclear energy among the eligible technologies for climate finance and ESG. We also need to attract and retain the best talent into the nuclear profession. And we need to ensure the generational exchange of knowledge among the experts of today and the future experts. Finally, to ensure the economic competitiveness of nuclear technology, we need to put in place the means for the emergence of a global market that capitalises on standardization and the consolidation of the global supply chain. This global market necessitates streamlined international licensing and regulatory frameworks that facilitate the deployment of nuclear technology in various countries. All these enabling conditions are needed if we are serious about deploying nuclear energy at the speed and the scale that is needed to achieve global decarbonisation and sustainable development goals by 2050.

Since 2007, when World Nuclear Association created the working group on Cooperation in Reactor Design Evaluation and Licencing (CORDEL), we have spearheaded industry efforts on standardisation and harmonisation in the reactor design and licencing spheres. Our efforts have been supported by the collective work of our members, vendors, reactor designers, utilities, energy end users. We have also worked very closely with many nuclear regulators and international organisations, and these efforts have resulted in a very large number of studies, from the more conceptual and strategic - looking at new paradigms that are going to enable international harmonisation, to the very technical - including detailed comparisons among codes and standards for instrumentation or mechanical components. Throughout this time, we have acted as the industry counterpart to other initiatives, such as the Multinational Design Evaluation Panel (MDEP) or the SMR Regulators Forum. More recently, CORDEL has also become the Secretariat to the Convergence Board for the various Standard Development Organisations. Our experience has allowed us to extract as many lessons learned as possible, map all these initiatives, assess where we are today and put together a path forward that can truly accelerate new nuclear projects.

So for the last year or so, we have embarked in a very intense effort to refocus the work that CORDEL is doing. We have put together a new sequential framework that proposes starting small with pilot projects, and that involves collaboration between the regulators and the industry. The idea is to work together in this sequential approach, going from an initial phase in which we will be focusing on simply aligning activities and developing a common understanding, and then moving forward to more advanced phases in which there will be more emphasis on achieving harmonisation, on having greater collaboration between the various regulatory bodies, and on defining areas that can be easily accepted from one regulator to another, and developing approaches to mitigate the gaps in the other areas in which that may not be so easy. We have put together this framework, we have shared it with many stakeholders, we have gathered comments and suggestions, and we are now hoping to move it forward.

Because, the long story short is, that we are at an inflection point for new nuclear and for the deployment of new nuclear reactor designs. The reality is that many regulators recognise the need for greater collaboration in order to realise this idea of a global nuclear market. There is an absolutely urgent need to move forward together. CORDEL is working to provide the thought leadership to realise this new licencing paradigm, working to support the regulators and working together with the rest of the industry.

This is why there is urgent need for leadership by national governments for the development of suitable legal frameworks and policies, which are going to give regulators the mandate and the resources to move forward in this direction. We also are going to need effective collaboration among international organisations, regulators and industry to streamline all these different international licencing and regulatory frameworks. All this work is also going to help newcomer countries looking to use nuclear energy to optimise their approach, by taking advantage of all the lessons learnt from existing nuclear countries. These efforts will also be essential as we move forward to licence and regulate new advanced technologies, some of which many of you are working today.

We of course need to continue to maintain safety and to improve the cost competitiveness of existing technologies. The work of the research community will be game changing, because the innovation and the disruptive technology you are working on will help see leaps in performance. But as I said at the beginning, it is important for you to begin with the end in mind. First of all, to bring these new technologies to deployment, it is essential to do this at a global level because they will most likely not be cost effective if they are to be limited to the home market. Thus, when you look at how to deploy these new technologies, think about how to standardise them and how to collaborate with others to bring them forward at a global level. The second recommendation, is to make sure that as you move forward, you engage from the beginning with industry and with regulators to make sure that we really transform the way these innovations are evaluated so that we accelerate the incorporation of disruptive technologies in nuclear.

Thank you very much for the opportunity to address you today. I wish you all a fantastic week of conferences, and I look forward to seeing many of you soon in person.

**Pierre-Marie ABADIE** (ANDRA, FR), Director-General of Agence Nationale de Gestion des déchets radioactifs

# EUROPEAN AND INTERNATIONAL STATUS ON THE MANAGEMENT AND DISPOSAL OF RADIOACTIVE WASTE, DEVELOPMENT AND CHALLENGES AHEAD

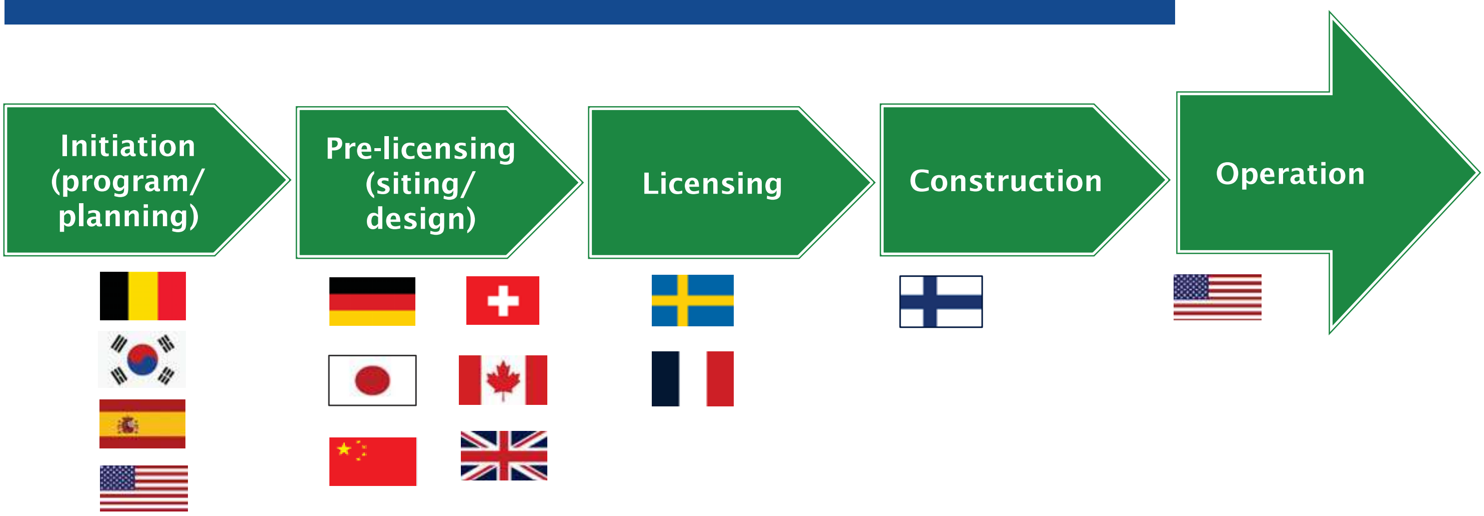
*Focus on Deep Geological Repositories*

 DDP/RI/22-0043

ANDRA

DDP/RI/22-0043
2

## Geological disposal for HLW : Situation at a glance




and Slovenia, South Africa, The Netherlands, Ukraine,…

and Czech Republic, Hungary, India, Romania, Russia, Slovakia, …



ANDRA

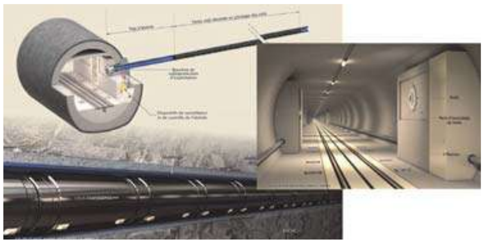
DDP/RI/22-0043 3

# Focus on some projects…

**Onkalo**
Under construction

**Forsmark**
Licence application

**Cigéo**
Licence application



2 potential locations Ignace and South Bruce (Ontario) – investigations for decision in 2023

3 potential locations North Switzerland : Decision expected in 2022

Inshore project : near to coast
Consent-based : 3 localities to investigate (near Sellafield or SE England)

DDP/RI/22-0043 4

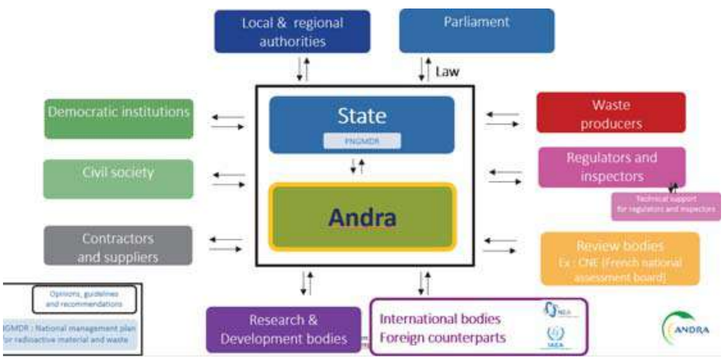
# Success factors in a DGR program

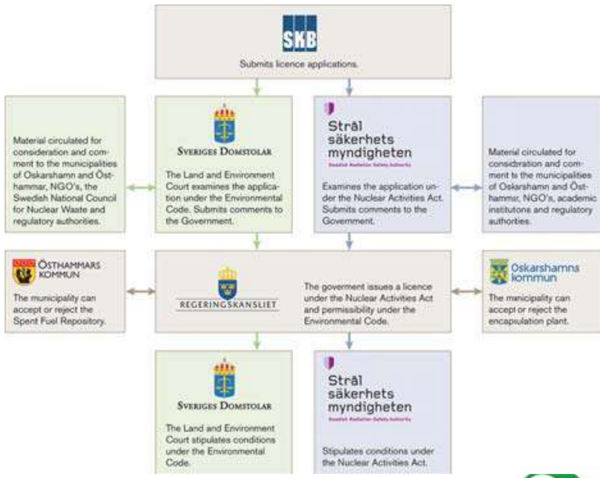
| | |
|---|---|
| Governance and interactions between stakeholders | Why ? Who? How ? … |
| Roadmap and milestones | Clear decisional process, What and When |
| R&D programme | Research and Development Programme to follow the roadmap |

# Key success factors

Governance and interactions between stakeholders

*Example of France and Sweden*



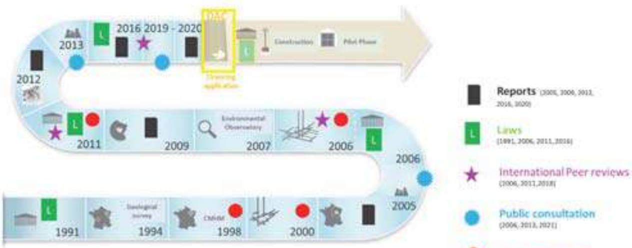







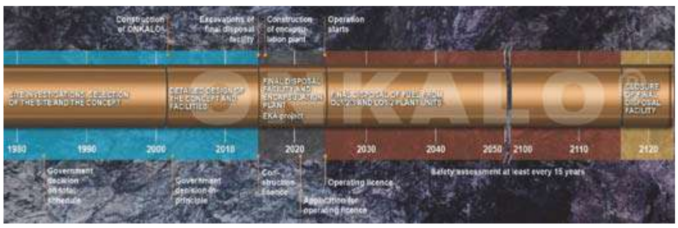

# Key success factors

Roadmap and milestones

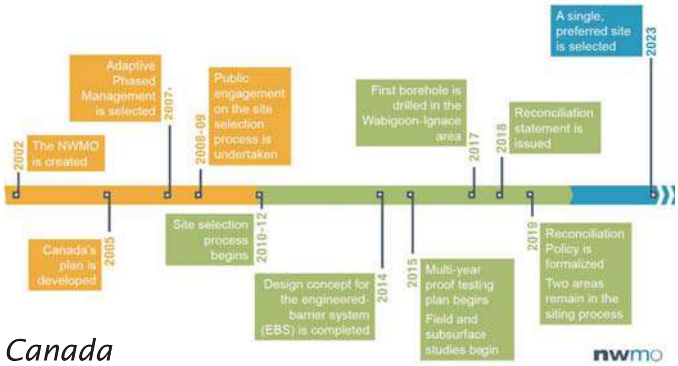



*France*


*Sweden*



*Finland*

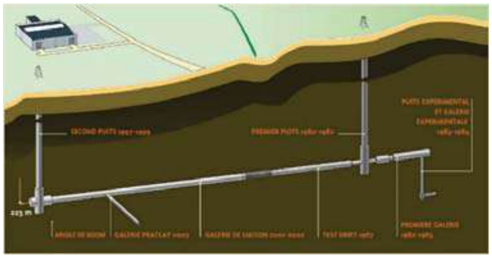



*Canada*

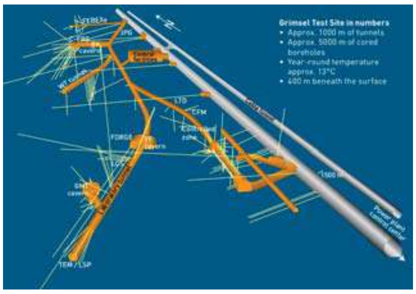
# Key success factors

**R&D programme** Underground research laboratory, research, technical innovation...

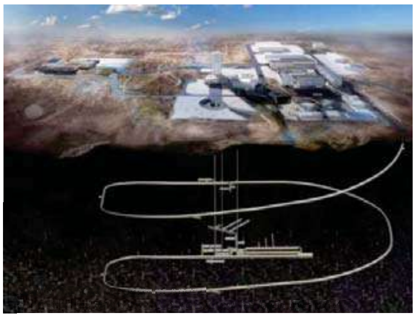
*Andra URL (France)*



*HADES laboratory (Belgium)*



*Grimsel laboratory (Switzerland)*



*Beishan URL (China)*

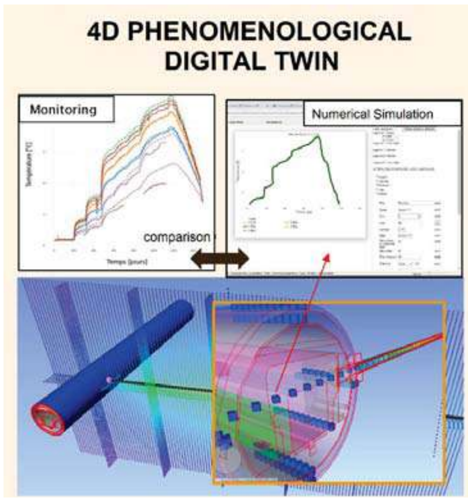


# Key success factors

**R&D programme** Underground research laboratory, research, technical innovation...

*Copper canister for spent nuclear fuel (Finland)*

*Automated transfer system to disposal tunnel (France)*




*France*

*Fire resistance test (France)*

DDP/RI/22-0043 9

# Challenges ahead

| | |
|---|---|
| Licencing and construction of DGR | Licencing – Permitting : numerous procedures to follow (safety and environmental assessment) before getting autorisation) |
| Commissioning and starting operation of DGR | Numerous steps before a first package can be disposed of |
| Dialogue and stakeholders involvement | Civil society awarness, interest and participation - Get in touch and involve young generations, |
| Knowledge Management | KM methodology, importance to keep the right knowledge and transmission |



10

# Challenges : licencing, construction and starting operations

Licencing and construction of DGR

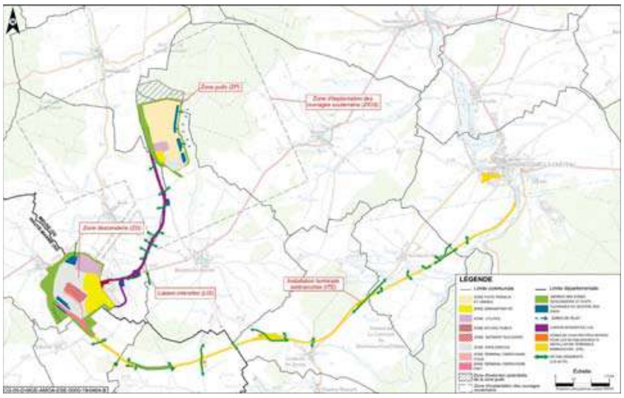
Commissioning and starting operation of DGR

- Safety assessment
- Environmental assessment
- connecting infrastructures to anticipate : train route, roads, water supply, power supply etc…

→ Unique type of project due to their

- Sizes (and depths) and costs
- Timeframes (from preparatory works to closure)…

➔ Long licensing procedures / challenging longlife project management

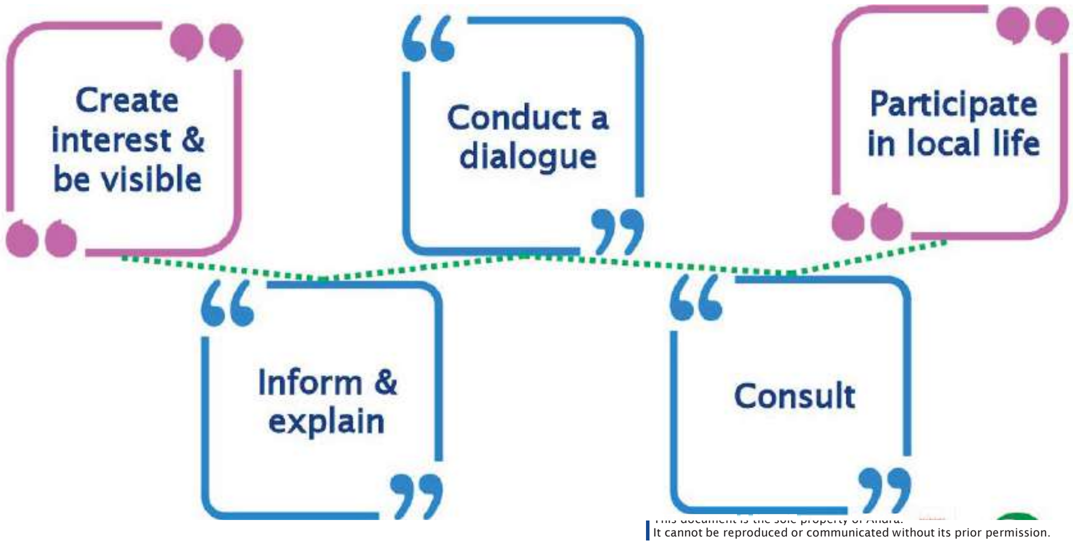


Ex : France, railway connection to Cigéo

DDP/RI/22-0043 11

## Challenges : Dialogue & stakeholder involvement

Informing, communicating, involving public on RWM's activities and projects :
**Numerous actions, interactions and innovations**







DDP/RI/22-0043 12

## Challenges : Young generation

**Innovations to get in touch** : Street art, conferences, podcasts, games, webinars, partnerships with youth associations and social media influencers, …

*Cartoon characters UK*


*Street art France*


*Escape Game Spain*

*Conference Belgium*

*video production contest Japan*

DDP/RI/22-0043 13

# International Cooperation : EURAD

*European Joint Programme on Radioactive Waste Management*

**23 European countries**
**116 organisations**

- Waste Management Organisations
- Technical Support Organisations
- Research Entities
- 51 Mandated Actors, 62 linked third parties & 3 international partners

5 years
2019-2024

59,9 M€
50 %EC contribution

**Objectives :**

- Implement a robust and sustained state-of-the-art **Science and Technology Programme**

- Identify and elaborate upon complex issues by bringing together interested actors to jointly conduct **Strategic Studies**

- Consolidate efforts across Member-States, organisations and generations on **Knowledge Management**

- Foster mutual **understanding and trust** between participants (incl. from Civil Society) and other stakeholders

**Looking ahead:**

2 remaining years in the current programme
Preparation of the next EJP started yesterday (workshop)



DDP/RI/22-0043 14

# Conclusions

- Deep geological disposal is the reference solution for HLW management
- DGR programs are lasting a few decades from initiation to commissioning : several generations concerned
- Earlier stakeholder involvement in recent programs
- 10 years from now DGR should be in operation

# AWARDS CEREMONY FOR THE EURATOM NUCLEAR INNOVATION PRIZE

**Rosalinde VAN DER VLIES** (EC) on behalf of **Mariya GABRIEL** (EC) European Commissioner for Innovation, Research, Culture, Education and Youth

## STEERING BRIEF

### Scene Setter

You will be awarding the winners of the Nuclear Innovation Prize. The European Commission is the organizer of the Nuclear Innovation Prize.

The Nuclear Innovation Prize is being offered to highlight and reward the excellence in nuclear innovation that can be found in this field of research as well as the quality of the talented researchers and companies involved. This is the first edition of the Prize. We have received 28 proposals and will be awarding 7 winners.

### Objective(s)

– Award the Nuclear Innovation Prize winners

### Line to take

– EU supports and encourages cutting-edge innovation to maintain a high level of competences, underpinned by sound and advanced research. Nuclear researchers and engineers are constantly challenging state-of-the-art in the field and improving evolving technologies towards a more dynamic and competitive European industry for the benefit of every citizen and the whole of society.

## SPEAKING POINTS

Award of the Prize

Introduction

- I am delighted to open the award ceremony for the Nuclear Innovation Prize.

- Before announcing the winners, I would like to share a few thoughts on the prize.

- This prize rewards outstanding researchers or industries who try to find innovative ideas or new solutions, possibly with wider applications.

- Nuclear research has pushed advances in disciplines ranging from medical technology, environment to astrophysics and material sciences.

- Today, we are not only rewarding the best candidates and their work, but we are also rewarding the institutions, which they are representing.

- We are giving seven Prizes to particularly successful projects in the field safety of reactor systems or radioactive waste management. I can assure you that the selection process was not an easy task.

- We have received 28 proposals that were all assessed based on originality and replicability, technical excellence, and economic impact and exploitation of the innovation

- The decision was made by an independent jury composed of experts in the nuclear area from business and academia.

- Finally, I would like to thank all those who participated in the first edition of the Nuclear Innovation Prize, and I would like to strongly encourage others to participate in the second edition that will be launched in 2024.

- On that note, I would like to proceed with awarding of the Nuclear Innovation Prizes.

Awards

- Let’s start with the category of safety of reactor systems. In this category, the experts have decided that the Third Prize will be shared between two excellent proposals.

- I am pleased to announce that the Third Prize in safety of reactor systems is awarded to Professor Jaakko Leppänen from VTT Technical Research Centre of Finland. Congratulations (give diploma & Karolina give out the trophy).

- Dr. David Legrady from Budapest University of Technology and Economics is also receiving the Third Prize in safety of reactor systems. Congratulations (give diploma & Karolina will be giving out the trophy).

- The Second Prize goes to Mr. Luis Lopez from Iberdola, he will receive the Prize on behalf of the two research teams: Iberdola and Innomerics. Congratulations (give 2 diplomas & Karolina will give out the trophy).

- I am pleased to announce that the First Prize goes to Dr. Martin Sevecek from the Czech technical university in Prague. Congratulations (give diploma & Karolina will give out the trophy).

Now let’s continue with the category of radioactive waste management.

- The Third Prize goes to Mrs. Gabriele Strehalu from RWE and Mr. Pedro Santos from Fraunhofer. Congratulations (give 2 diplomas & Karolina will give out the trophy).

- I am pleased to award the Second Prize to Dr. Laurent Coquard and Mr. Alexandre Felt from Framatome who will be receiving the Prize on behalf of the research teams including among others Aachen Institut for Nuclear Training. Congratulations (give 3 diploma & Karolina give out the trophy).

- The First Prize goes to Prof. Bo Wilhelm Cederwall from KTH Royal Institute of Technology in Stockholm. Congratulations (give 2 diplomas & Karolina give out the trophy).

- I would like to invite all of you to join me in participating to the Nuclear Innovation Prizes pitches today at 16:30.

- To close this ceremony, I would like to wish all seven Nuclear Innovation Prize winners success in their careers and further development of their innovations.

## ABSTRACTS OF THE PRIZES:

### Nuclear Innovation Prize in safety of reactor systems

### First Prize – MultiProtectFuel

Accident Tolerant or Advanced Technology Fuels (ATF) are one of the hottest research topics in the nuclear engineering research and development area since the Fukushima-Daiichi events with the first concepts inserted into commercial nuclear power plants in 2019. The most advanced ATF concept is Cr-coated Zr-based alloy, which was chosen as the near-term ATF solution by fuel vendors operating on the EU nuclear fuel market - Framatome, Westinghouse Electric Company, and TVEL. The research group at CTU in Prague identified several new degradation phenomena linked to this concept such as material interdiffusion, Cr enhanced embrittlement, and Zr-Cr eutectic formation. The optimization of advanced coating techniques and fuel cladding design led the team to develop and qualify innovative multicomponent Cr/CrN coated Zr alloy cladding that limits the degradation effects such as Cr enhanced embrittlement and delays the eutectic reaction to much higher temperature making the cladding more resistant and accident tolerant in comparison with both traditional Zr-based alloys as well as pure Cr coated Zr alloys. This innovative solution was qualified out-of-pile and is now under in-pile investigation in the LVR-15 reactor. In the next phase, this innovative nuclear fuel cladding will be inserted into a commercial reactor as a non-fueled material, the fabrication process will be qualified for industrial production, and the complete solution will be offered to fuel vendors as an advanced near-term nuclear fuel cladding for the current generation of light water reactors. Currently, there are ongoing discussions about future joint ventures or license transfers from CTU to one of the commercial fuel vendors operating on the EU market.

### Second Prize – MitMAT

Targeting ultimate fidelity coupled reactor physics and thermal-hydraulics calculations has recently entered the forefronts of reactor safety analysis research enabled by the vast forward leap of High Performance Computing (HPC). Our project has achieved a breakthrough by introducing Graphics Processing Units (GPU's) to the prodigiously progressive Dynamic Monte Carlo (DMC) method where time dependence is handled explicitly rather than by a series of static calculations, achieving simulations very faithful to nature. Algorithms were devised such that they both optimally fulfill DMC requirements and adapt to GPU specificities, moreover attention was paid to keeping statistical variance of the population low. In 2016 the GUARDYAN (GPU Assisted Reactor Dynamic Analysis) code development started and recently reached the capabilities to accomplish full core VVER-440/V213 calculations with meaningful detector reading simulation results. This indicates that with the inventions conceived and implemented into GUARDYAN, the DMC method was promoted from proof-of-concept to real application to power plants. The code has been verified and validated against 30 ICSBEP benchmark scenarios by comparison to MCNP6.1 for approximately 440 000 data points; further by performing experiments using the Budapest University of Technology and Economics (BME) Training Reactor of a Cd sample insertion and rod drop experiments, and even further by replicating a recent safety rod drop experiment results of the Paks Nuclear Power Plant for a VVER-440/V213 unit with realistic burnup values, each comparison was concluded with complete success. The code GUARDYAN fused existing and novel Monte Carlo techniques with GPU based high performance computing advocating DMC to be the gold standard of reactor physics, a calculation tool devoid of obscure approximations. A high fidelity simulation tool enables a more optimal use of design safety margins and creates room for efficiency improvement of NPPs.

### Third Prize – GUARDYAN

Targeting ultimate fidelity coupled reactor physics and thermal-hydraulics calculations has recently entered the forefronts of reactor safety analysis research enabled by the vast forward leap of High Performance Computing (HPC). Our project has achieved a breakthrough by introducing Graphics Processing Units (GPU's) to the prodigiously progressive Dynamic Monte Carlo (DMC) method where time dependence is handled explicitly rather than by a series of static calculations, achieving simulations very faithful to nature. Algorithms were devised such that they both optimally fulfill DMC requirements and adapt to GPU specificities, moreover attention was paid to keeping statistical variance of the population low. In 2016 the GUARDYAN (GPU Assisted Reactor Dynamic Analysis) code development started and recently reached the capabilities to accomplish full core VVER-440/V213 calculations with meaningful detector reading simulation results. This indicates that with the inventions conceived and implemented into GUARDYAN, the DMC method was promoted from proof-of-concept to real application to power plants. The code has been verified and validated against 30 ICSBEP benchmark scenarios by comparison to MCNP6.1 for approximately 440 000 data points; further by performing experiments using the Budapest University of Technology and Economics (BME) Training Reactor of a Cd sample

insertion and rod drop experiments, and even further by replicating a recent safety rod drop experiment results of the Paks Nuclear Power Plant for a VVER-440/V213 unit with realistic burnup values, each comparison was concluded with complete success. The code GUARDYAN fused existing and novel Monte Carlo techniques with GPU based high performance computing advocating DMC to be the gold standard of reactor physics, a calculation tool devoid of obscure approximations. A high fidelity simulation tool enables a more optimal use of design safety margins and creates room for efficiency improvement of NPPs.

**Third Prize – DH-LDR**

This invention is related to the passive decay heat removal function of the LDR-50 low-temperature decay heat reactor developed at VTT Technical Research Centre of Finland. The invention enables passive cooling of the reactor core without any mechanical moving parts. The application describes the technology and operating principle behind the invention, and presents results of computational simulations demonstrating its applicability. The economical and environmental impact of the invention results from the fact that inherent safety is considered a necessary requirement for district heating reactors, since the heating plant must be constructed close to urban areas. The background on heating reactors and the significance of decarbonization of heating systems is discussed, and the market potential of the LDR-50 reactor briefly evaluated.

**Nuclear Innovation Prize in radioactive waste management**

**First Prize – ARCTERIX**

The proposal concerns a newly developed technology for non-destructive assay (NDA) of radioactive waste that we call ARCTERIX. ARCTERIX stands for AdvancThe proposal concerns a newly developed technology for non-destructive assay (NDA) of radioactive waste that we call ARCTERIX. ARCTERIX stands for Advanced radwaste characterization based on tomographically enhanced radiation imaging without X-rays. The concept is based on the novel 3D radiation imaging modality for special nuclear materials (SNM) - neutron-gamma emission tomography (NGET) - invented by the PI. The purpose of the present application is to demonstrate how the invention establishes a new ground-breaking modality for passive NDA interrogation of mixed long-lived radioactive waste, so called legacy waste, with special security and safeguards concerns due to the presence of SNM. A detection system featuring the NGET imaging modality can also be applied to radioactive waste characterization in general, including verification of spent nuclear fuel and other high-level waste. ARCTERIX provides rapid imaging of nuclear materials and characterization of radioactive waste with a high degree of automation. In the future, we believe the technique can also be adapted for use with active interrogation measures based on pulsed and continuous neutron sources and high-energy photon sources. The ARCTERIX prototype system has demonstrated a high technological readiness to implement the technique in a commercial stand-alone system for rapid assessment of radioactive waste drums or in a system operating in conjunction with established techniques. By enabling rapid, high-spatial-resolution imaging of SNM the ARCTERIX concept has the potential to take routine radioactive waste characterization to an entirely new technological performance level. Its high throughput capabilities make it possible to quickly scan large radioactive waste inventories for the presence of special nuclear materials with minimal manual intervention.

## Second Prize – QUANTOM

During the last decades, the nuclear and non-nuclear industry has produced a considerable amount of low (LLW) and intermediate level (ILW) radioactive waste. Though the waste form and streams might be different, such radioactive waste must be safely disposed in a final repository under the same strict waste acceptance requirements (e.g. the radiological and material characterization) defined by national licensing and supervisory authorities. Material characterization remains an indispensable criterion to prevent pollution of the ground water with toxic materials. Nowadays material description stays very challenging for waste producers, especially for legacy waste. It can be performed on the basis of existing documentation or, if the documentation is insufficient (e.g. legacy waste), on further destructive or non-destructive analysis. Destructive analysis is not favored as operating personal is exposed to radiation, the waste volume is increased, it is very time-consuming and generates high costs. Therefore non-destructive methods are to be preferred. This R&D project presents an innovative non-destructive technology called QUANTOM® based on Prompt and Delayed Gamma Neutron Activation Analysis (P&DGNAA). This technology is able to identify, verify and quantify the amount of hazardous and non-hazardous substances in waste packages such as 200-l radioactive drums. The QUANTOM® measurement device will be integrated in a transportable container in order to perform measurement campaigns directly on site. The main benefits of QUANTOM® are summarized below:

- Non-destructive multi-element analysis with high sensitivity (ppm-range) of the entire matrix
- Fast measurement process (2h-4h per waste drum) with high measurement precision
- No repackaging and no increase of waste volume
- Reduction of costs (min. 50% per waste drum) compared to destructive analysis processes
- Minimizing the transportation of radioactive waste packages and radiation exposure

## Third Prize – ROBBE

For a successful dismantling of a nuclear power plant, correct and controlled processing of all components is necessary, whereby a large part of the work relates to coated (mainly painted) steel components, which make up a significant proportion of the total inventory of the power plant to be processed. The contamination of these components will be reduced by removing the surface coating using the UHD water jet technology in such a way that the decontaminated material will be released after it has been released in accordance with Chap. 3 StrlSchV (German Federal Law Gazette 2018 No. 41: StrlSchV, 2018) can be recycled conventionally. The manual processing of these individual parts is cost-intensive, so that an autonomous, automated solution is more economical when increasing throughput and ensuring consistently high quality. In addition, almost all processes, especially UHD water jet technology, require personal protective equipment and the work is very physically demanding for employees and poses a potential risk. The aspects of radiation protection should not be neglected either. In the case of manual processing, the staff is exposed to radiation that is not applicable to the autonomous variant. This corresponds to the ALARA principle. The aim of the project is to implement, for the first time, an automated and autonomous removal of the coating from component groups using UHD water jet technology when dismantling core technical systems and to use it in the German Biblis NPP on an industrial, productive scale. The acronym "ROBBE" (ROBOT-assisted processing of assemblies during the dismantling of nuclear power plants) is derived from this project objective. The core of the technology to be developed is the autonomous real-time acquisition of the 3D geometry of various components with multiple coatings, as well as the path planning derived from this for robot-assisted stripping using UHD water jet technology.

# KEYNOTE - RESEARCH AND INNOVATION INTERDISCIPLINARY OPPORTUNITIES AND CHALLENGES TO ENABLE SUSTAINABLE AND DECARBONISED SOCIETIES / RECHERCHE ET INNOVATION : UNE APPROCHE INTERDISCIPLINAIRE POUR RELEVER LES DEFIS D'UNE SOCIETE DURABLE ET DECARBONEE

**François JACQ** (CEA, FR), Administrateur Général, Commissariat à l'Energie Atomique et aux Energies alternatives

**Remerciements :**

- En tant qu'Administrateur général du Commissariat à l'énergie atomique et aux énergies alternatives, je suis très heureux de prononcer quelques mots aujourd'hui en ouverture de cette semaine de conférences et d'ateliers.

- Je tiens tout d'abord à adresser mes remerciements à la Commission européenne ainsi qu'à l'Etat français pour avoir fait confiance au CEA pour l'organisation de cette 10ème édition conjointe aux programmes FISA et EURADWASTE, investie du label de la Présidence française du Conseil de l'UE.

- Je tiens également à remercier la Région Auvergne-Rhône-Alpes et son Président, pour nous avoir permis de tenir cette conférence ici à Lyon, au sein de l'Hôtel de Région.

- Je voudrais aussi rendre un hommage à Bernard Bigot. Il forçait l'admiration par son abnégation et son don de soi au service de l'intérêt général. Par ses différents postes à l'université, aux ministères et à la tête successivement du CEA et d'ITER, Bernard Bigot a été un acteur majeur pour le développement des énergies nucléaires tant du point de vue de la fission que la fusion. Il a aussi contribué fortement au pôle d'excellence scientifique Lyonnais en particulier au sein de l'Ecole Normale supérieure de Lyon.

- Comme l'ont rappelé Madame la Directrice générale à la recherche et l'innovation Claire Giry et Monsieur le Directeur général à l'énergie et au climat Laurent Michel, **le défi sociétal que constitue la lutte contre le réchauffement climatique est de plus en plus manifeste, et de plus en**

**plus pressant**. Pour y répondre, nous aurons besoin de tirer parti de tous les moyens et ressources disponibles, en particulier pour mettre en oeuvre la transition vers un mix énergétique mondial et européen entièrement décarboné.

- La vision du CEA est celle d'un **système multi-vecteurs énergétiques** (soit tirant parti de l'électricité, la chaleur, et du gaz dont l'hydrogène), **multi-échelles et multi-agents** (de la boucle locale à l'échelle européenne), dans le cadre de réseaux énergétiques très fortement interconnectés. Ce mix énergétique du futur doit également pouvoir s'appuyer sur des réseaux rendus de plus en plus « intelligents » *(« smart grids »)* via la digitalisation et l'instrumentation, et, le pilotage de la demande par incitations économiques. Il doit en outre s'inscrire dans une logique d'économie circulaire de façon à réduire l'empreinte environnementale associée à la production et aux usages d'énergie et de réduire notre dépendance à l'importation de matériaux critiques.

- Dans ce contexte, le nucléaire a une place clé dans ce mix énergétique du futur, pour la réussite de la transition énergétique, en tant que source d'énergie pilotage, à faibles émissions de carbone, et contribuant à la sécurité d'approvisionnement.

- La technologie et l'innovation sont des leviers pour atteindre ces objectifs. Cela passe par le développement de nouvelles technologies, mais aussi par une analyse globale des systèmes énergétiques associant la compréhension et la maitrise des usages, l'optimisation des systèmes de production et de stockage et la limitation de l'empreinte environnementale.

- Les grands défis du nucléaire sont à ce jour :

– Sûreté et sécurité
– SMR : SMR à eau légère pour demain et SMR de Gen 4 pour « après-demain»;
– Flexibilité avec la pénétration croissante des énergies intermittentes ;
– Cogénération et couplage avec la chaleur ;
– Source d'électricité bas carbone pour la production d'hydrogène et au-delà pour la production de molécules plus élaborées (e-fuel ou e-carburant en associant de l'hydrogène bas carbone à de la capture de C02→ vers la « raffinerie nucléaire ») ;
– Mettre en oeuvre l'assainissement et le démantèlement.

- Au-delà de ces enjeux spécifiques, le secteur nucléaire est également concerné par des tendances communes à l'ensemble des filières industrielles nécessaires à la transition énergétique. La recherche nucléaire doit ainsi être décloisonnée et multidisplinaire, en intégrant des compétences plus larges que celles de ses disciplines traditionnelles. En particulier :

    - o La place du numérique est majeure : usine du futur / digitalisation / jumeau numérique. Ces outils numériques seront également utiles pour la formation aux métiers du nucléaire.

  - o L'évolution des systèmes énergétiques - en particulier le passage de systèmes centralisés à des systèmes distribués et le rôle désormais actif du consommateur et parfois producteur d'électricité - impose de prendre en compte l'apport des sciences humaines et sociales et de renforcer les relations entre chercheurs et parties prenantes sociétales lors des développements technologiques pour concevoir des technologies utiles, comprises, acceptées et dont l'utilisation permettra d'en optimiser l'apport.
  - o Tenir les objectifs de l'agenda net zero 2050 supposera une collaboration étroite entre chercheurs et industriels pour accélérer le déploiement des technologies.

- La collaboration et le partage des bonnes pratiques au niveau européen et à l'international seront aussi des facteurs clefs pour la réussite de cette transition écologique.

- **Nous avons besoin de l'Union européenne pour définir de grandes lignes directrices pour la recherche, pour assurer la continuité du lien entre recherche et capacité industrielle,** et pour accompagner la formation initiale et continue au service du secteur nucléaire. Dans cette perspective, le CEA identifie en particulier trois priorités :

- le soutien au financement des infrastructures nucléaires, qui sont indispensables pour maintenir et développer l'excellence de la R&D européenne dans ce domaine, et attirer et former de nouveaux talents.

- le maintien d'un niveau élevé de connaissance, de compétences et d'expertise est un défi qui concerne à la fois tout le cycle de vie nucléaire, et toutes ses applications (énergie, santé) – ce qui le rend hautement stratégique, et partagé par tous les Etats membres.

- le soutien à la mise en place d'une filière du démantèlement à l'échelle européenne,

- **Le programme EURATOM, reste un outil essentiel pour contribuer à ces objectifs ,** et se maintenir ainsi comme une plateforme incontournable de la transition énergétique. Les projets du programme EURATOM forment un ensemble cohérent et valorisant les synergies :

– dans le domaine de la science des matériaux, un projet comme INNUMAT adresse à la fois les problématiques de la fusion et de la fission ;
– Il est aussi intéressant de noter la continuité et les synergies entre les projets liés aux réacteurs et ceux liés à la gestion des déchets et du démantèlement;
– L'amélioration des standards de sûreté et d'exploitation est au coeur de nombreux projets à la fois pour le nucléaire de générations II et III [comme ELSMOR et PASTELS] et pour le nucléaire du futur pour les réacteurs de génération IV [ESFR-SMART, SafeG, ou encore SAMOSAFER].

- Pour l'avenir, permettez-moi de signaler deux enjeux d'évolution qui me semblent devoir être pris en compte pour ce programme, en complément des grands axes actuel de la sûreté, de la gestion des déchets et du démantèlement. En cohérence avec les tendances que je viens de décrire, le programme Euratom pourrait notamment s'intéresser à :

La recherche nucléaire ne peut plus être envisagée et programmée de manière totalement indépendante de la problématique globale des nouveaux systèmes énergétiques. Les projets Euratom peuvent être élargis à de nouveaux designs, à de nouvelles problématiques liées à la convergence à entre nucléaire et renouvelable. Par ailleurs, des ponts entre le programme Euratom et le programme Horizon Europe pourraient être utilement recherchés sur des sujets tels que le recours aux outils numériques, aux nouveaux procédés industriels, à la place du nucléaire dans les systèmes de production décentralisés…qui ne sont pas spécifiques à la filière nucléaire. Ainsi, les travaux et recherches pouvant conduire à développer des technologies utilisées dans un cas d'usage nucléaire, pourraient peut-être bénéficier de financement dans un cadre Horizon Europe.

- Le CEA plaide par ailleurs pour la définition d'un partenariat européen public-privé de R&D sur les SMR, pour lesquels un grand nombre d'Etats membres a manifesté son intérêt, qui permettrait de fixer une feuille de route commune aux acteurs et pays intéressés, combinant les financements européens et nationaux, publics et privés, en vue du développement d'un SMR européen, à la fois pour la production d'électricité, mais également pour ses autres usages potentiels, tels que la production de chaleur ou d'hydrogène.

- Porteur d'une expertise et d'un retour d'expérience de plus de 75 ans, le CEA veillera à poursuivre son action pour permettre à la France et à l'Europe de s'appuyer sur une filière nucléaire compétitive et répondant aux meilleurs standards de sûreté et de sécurité.

**Conclusions et voeux de succès de la conférence :**

En conclusion, je tiens à remercier tous les intervenants et participants, et j'espère que les échanges seront fructueux et contribueront à créer les conditions de coopération, d'échange et de mutualisation nécessaires à nos ambitions énergétiques et climatiques.

# KEYNOTE - RESEARCH AND INNOVATION MISSIONS AND BENEFITS FROM CONTINUOUS AND MEANINGFUL CIVIL SOCIETY'S INVOLVEMENT TO TACKLE TODAY'S SOCIETAL CHALLENGES

**Baiba MILTOVIČA** (EESC, EU), President of the section for Transport Energy, Infrastructure and Information Society, European Economic and Social Committee

Ladies and Gentlemen,

Thank you for inviting me to this event, it is a pleasure for me to be a part of this panel with my fellow speakers, discussing an issue that is as delicate as it is crucial.

I would like to start by stressing what a time of great uncertainty we are going through. Europeans are called to face many challenges, and energy has gained an even more central stage in the plans for the future of the Union.

First of all, we are all witnessing that energy has become a precious and expensive good. The energy supply crisis and the high increase in energy prices following the military invasion of Ukraine by the Russian Federation have pressured us into rethinking a number of key issues: the entire EU's energy system; accelerating the energy transition; and how to achieve independence from fossil fuels. This has put European citizens, workers and business in a dire situation.

This perfect storm has aggravated the position of the most vulnerable groups. Energy poverty, a silent phenomenon that has many impacts on European households, has been at the center of our concerns for years. It is now becoming a serious challenge.

Back in 2020, amidst the consequences of the COVID-19 pandemic, over 36 million people claimed to be unable to afford keeping their homes warm. Today, the current crisis is further pushing up the numbers. Thus, we need to make sure that energy supply is available at affordable prices, and to make it a priority in the framework of a fair and just transition.

It is with this in mind, that the EESC, with the support of the French Presidency of the Council, organized a conference on "Tackling energy poverty at the heart of the ecological and energy transition" back this April. The conference put the focus on how to tackle energy poverty in the perspective of a socially fair and just transition towards a climate-neutral Union by 2050. The conference saw the participation of civil society organization and representative of EU decision-makers, allowing for a crucial dialogue between the two levels.

Secondly, we all know that the energy transition indeed is not just a matter of technological innovation, but also calls for deep social and political changes. In order to achieve a fair and inclusive energy transition, EU citizens must be at the heart of this transformation.

I would like to highlight again the fundamental role of civil society in tackling today's challenges. In their role, voicing the perspective of the European organized civil society, the Members of the EESC have been called to consider the new Commission plans in reaction to the multiple crisis we are facing.

On REPowerEU the EESC has expressed its support to the Commission's objective of achieving independence from Russian gas. Nonetheless, it fully recognizes the extreme difficulty that this entails for the European economy and society. Several recommendations have been put forward, including: streamlining and accelerating permit-granting procedures for renewables, subject of the Commission recommendation of the 18th of May; exploring different energy technologies like bio methane and geothermal sources; and supporting the necessary fiscal or regulatory intervention to secure affordable prices. All this, without hampering the functioning of the internal energy market and jeopardising decarbonisation and energy efficiency efforts.

In the context of the new gas storage Regulation, the EESC has urged the Institutions to introduce a short-term investment instrument, which will improve EU’s energy independence, because merely accelerating existing plans is not enough to guarantee Europe’s energy security. Moreover, the EU should consider using gas storage facilities in bordering third countries, which will bring a value-added to providing security of supply, especially in Ukraine.

Finally, the EESC is already engaged in preparing its reaction to the latest REPowerEU package that came out in May.

And now I would like to concentrate on the EESC stand on the future of Nuclear Energy in Europe. Nonetheless, I must stress that our official position has not been adopted yet, therefore our Members are still discussing the different approaches.

First and foremost, I believe that the European Union has the duty to protect and empower the citizens through an effective energy policy, demonstrating that it is possible to achieve the energy transition and reach the climate objectives, while ensuring that no one is left behind.

It is without doubt that the current situation has reopened the debate around the potential of nuclear energy. Can nuclear energy contribute to an independent and resilient energy system, support the transition towards more sustainable sources as a key component of the fight against climate change, and ensure the stability of the energy prices?

At the beginning of the year, the Czech Presidency of the Council asked the EESC to produce an exploratory Opinion on the role of nuclear energy for the stability of the EU energy prices and energy supply. This was even before the war started. At that time, the EESC had already joined other voices in the EU stressing thatthe current energy price crisis would not hit European citizens and companies so hard if Europe was not so highly dependent on imports of fossil fuels. Unfortunately, our energy policy was not reactive enough.

The response of the EESC to this question from the Czech Presidency will not be a simple one, and the role of Russia in the current situation will certainly not make it easier either. Numerous interests and concerns are in place. Several events throughout our history have reinforced the concerns of citizens on the use of nuclear energy. Therefore, this debate needs to be treated with the utmost attention.

While it is for each EU country to choose whether to make use of nuclear power, the role of the Union is to develop strategies to support the independence of our energy system and the best outcomes for the wellbeing of the EU citizens.

What, if any, can be the role of nuclear energy in the transition towards a climate neutral EU by 2050? How does nuclear energy interact with the growing share of renewables in our countries? Can nuclear power substitute natural gas and other fossil fuel in the efforts to achieve Europe strategic autonomy? These are the questions that we are looking to answer.

We already know that, in the short term, nuclear energy will not have a great impact on our energy prices, which are mostly depending on the current gas price. Nonetheless, the presence of nuclear energy in a country's energy mix can be instrumental, at least temporarily, in minimizing the impact of fossil fuels prices on the cost of electricity. In the long term the low operational costs and independence from gas market price, can help reducing the volatility of electricity prices.

Moreover, nuclear power could have a fundamental role in our transition towards a zero emission system. I think we all know that the sustainability goals that the EU has set within the Green Deal First and the Fit for 55 package not even one year ago are quite ambitious. To be able to achieve the climate neutrality we strive for, a concrete plan is needed, and with that, transitional, low carbon, energy sources are necessary.

The current relations with Russia are putting a great part of European energy supply at risk, and the gravest short-term concerns focus on being able to meet the demand for the next winter. Nonetheless, we must remember that natural gas was also given a role in the medium-term transformation of our energy system. The use of natural gas was considered a transitional measure, in order to grant a gradual and smooth transition towards a zero-emission Europe. Now, this path is no longer viable.

Several studies have found that nuclear power can have a fundamental role in our path towards decarbonization. Thanks to its stability, it can complement the supply coming from renewable sources, prone to disruptions. The potential of this technology has also been recognized by the Commission with the latest Complementary Taxonomy Delegated Act, adopted on 9 March 2022, which includes specific nuclear energy undertakings in the list of economic activities covered by the EU sustainable finance taxonomy. But we are well aware of the many voices that oppose very important arguments against this technology, also within our institution.

In this framework of supply uncertainty and strategic restructuring, closing the existing capacity means needing more fossil fuels and therefore an even greater energy dependency for Europe.

After saying all of this, one objective rises above all to contain the negative impacts of the crisis we are living: the necessity to advance on strategic autonomy reducing energy dependence from third countries, including Russia, reducing energy consumption, fighting energy poverty and keeping the pace of the energy transition.

To reach this objective, let me underline that the Economic and Social Committee remains fully committed to support the achievement of the goal of becoming the first climate neutral continent, and to do so through its role as a voice of organized civil society. Because the dialogue between the citizens and the decision-makers is one of the crucial pillars of our Union.

Thank you for your attention.

European Economic and Social Committee

# The importance of Civil Society's involvement to tackle today's Societal Challenges

**Baiba MILTOVIČA**
President of the EESC Section for Transport, Energy, Infrastructure and the Information Society (TEN)

European Economic and Social Committee

- "Tackling **energy poverty** at the heart of the ecological and energy transition", 21st April 2022.
- EESC Opinion on the **REPowerEU Communication** (May 2022):
  - Streamlining and accelerating permit-granting procedures for renewables.
  - Exploring different energy technologies like bio methane and geothermal sources.
  - Supporting the necessary fiscal or regulatory intervention to secure affordable prices.
- EESC Opinion on the new **Gas Storage Policy** (May 2022):
  - Introduce a short-term investment instrument to improve the energy independence.
  - Using gas storage facilities in bordering third countries.
- EESC Opinion on **The role of nuclear energy for the stability of the EU energy prices and energy supply** (July 2022):
  - What can be the role of nuclear energy in the transition towards a climate neutral EU by 2050?
  - How does nuclear energy interact with the growing share of renewables in our countries?
  - Can nuclear energy contribute to the stability of energy prices?
  - Can nuclear power substitute natural gas and other fossil fuel in the efforts to achieve Europe strategic autonomy?

European Economic and Social Committee

# Thank you!

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# KEYNOTE - ENSREG COMMITMENT TO CONTINUOUS IMPROVEMENT OF NUCLEAR SAFETY WHEN NEW KNOWLEDGE AND EXPERIENCE ARE AVAILABLE: PROGRESS, LESSONS LEARNED AND CHALLENGES

**Marta ZIAKOVA** (ENSREG), Chair of the European Nuclear Safety Regulators Group

Dear Ladies and Gentlemen, distinguished guests.

I´m honoured to have this special opportunity to speak at the 10th Euratom Conference on Reactor Safety and Euratom Conference on Radioactive Waste Management.

In my capacity as Chair of the European Nuclear Safety Regulators Group - ENSREG, I would like to use this opportunity to inform you shortly about the Group´s ongoing and future activities.

ENSREG's fundamental key mission is to promote the highest standards and continuous improvement of nuclear safety, radioactive waste and spent fuel management and their regulation, as well as to promote openness and transparency in those areas. The 2021-2023 ENSREG work programme continues to be shaped largely by the Amended Nuclear Safety Directive and the Council Directive 2011/70/EURATOM related to the safe management of spent fuel and radioactive waste. Hence, a major proportion of ENSREG's work within the current time framework focuses on supporting the safety objectives established by these Directives and on assisting the EU Member States with their implementation. During this period ENSREG will also continue to facilitate the follow-up implementation of the National Action Plans following the European Stress Tests. Furthermore, as in its previous work programme, ENSREG will continue to provide advice to the European Commission in matters such as nuclear power plants long-term operation, decommissioning, nuclear safety cooperation and emergency preparedness and response. An emerging, new topic, which could arise within the current period is related to the safety aspects and licencing of Small modular reactors arousing great interest among the international nuclear community. This particular topic requires further ENSREG´s discussions with the Commission with an aim to identify the specific areas where ENSREG could provide its advice. The ongoing work programme also covers certain actions of a longer programme framework that have started during an earlier period. This refers mainly to the follow-up actions stemming from the first EU Topical Peer Review on ageing management of nuclear power plants and research reactors as well as actions related to the arrangement and implementation of the second EU Topical Peer Review on fire protection at nuclear installations.

Allow me now to highlight some of the ENSREG’s main activities focusing on the following topics.Firstly,

- **Supporting the implementation of the Nuclear Safety Directive and the Spent Fuel and Radioactive Waste Directive**: Whilst it is the Member States' responsibility to transpose and implement the European legislation, ENSREG continues to play a role in assisting Member States and the Commission in several areas of work under these Directives. Whereas no further formal reporting is envisaged under Article 9 of the Nuclear Safety Directive, the implementation will focus and continue in particular on Articles 8a-8c (the Nuclear Safety Objective). In addition, ENSREG will also provide support to the Commission and Member States in addressing any issues identified in the Commission´s Report to the Council and Parliament on the implementation of the NSD.

- Another essential task for ENSREG during this period will be the establishment of framework to implement the second EU Topical Peer Review in close cooperation with WENRA as required by the Nuclear Safety Directive and building on the experience of the first such peer review completed in 2018. The second Topical Peer Review, as decided by ENSREG at its plenary session in November 2020, is dedicated to the topic of fire protection at nuclear installations. While the preparations for the second TPR are ongoing, those countries that had participated in the first TPR on ageing management will also need to report on the activities identified in their respective National Action Plans.

- With regards to the implementation of the Spent Fuel and Radioactive Waste Directive, ENSREG will continue supporting Member States, particularly in relation to the specific aspects of interface between National Programmes and National Reports. The three-year reporting cycle under Article 14 of the Spent Fuel and Radioactive Waste Directive proceeds as foreseen.

Among other main activities of ENSREG are the following:

- **Provision of advice to the European Commission as well as coordination of Member States´ Regulatory Authorities**, in particular on matters related to safety of nuclear installations and management of spent fuel and radioactive waste: Under this thematic area the European Commission has requested the advise of ENSREG regarding the revision and implementation of international assistance and technical cooperation programmes, such as those carried out under the European Instrument for International Nuclear Safety Cooperation (EI INSC) formerly known as the Instrument for Nuclear Safety Cooperation (INSC).

- **Facilitating active EU´s participation in the IAEA peer reviews and conducting oversight over the completion of the stress tests´ ‘National Action Plans’**: ENSREG´s continued promotion and facilitation of the EU´s participation in the IAEA´s peer reviews focuses primarily on the IRRS (Integrated Regulatory Reviews Service) and the ARTEMIS (Integrated Review Service for Radioactive Waste and Spent Fuel Management, Decommissioning and Remediation) missions, thereby supporting the continuous improvement of nuclear safety and management of spent fuel and radioactive waste in Europe. The group will also seek opportunities to improve the effectiveness of the missions in cooperation with the IAEA, aimed to identify and exploit synergies, where feasible. The long-term goal of a single peer review mission covering the requirements of both EU Directives will also be explored.

ENSREG played a pivotal role in the 2011 European Stress Tests and has since held two workshops to review progress on the National Action Plans developed by Member States as I´ve already outlined in my earlier remarks. It will continue to provide oversight through its Working Group 1 on Nuclear Safety through the agreed biannual reporting schedule. Further, it will also contribute to the organization of peer reviews in third states (outside of the EU), particularly those located in the EU neighbourhood.

To conclude I would like to emphasise the ENSREG's permanent commitment to transparency **Seeking to further enhance the openness throughout the group's activities**, including by providing a revised set of guidelines to Member States on reporting and transparency as part of the ENSREG wide work on reporting under the respective nuclear safety-related Directives. Another example is the ENSREG´s a communication strategy, implementing a new approach to the ENSREG website. I would be remised not to mention the upcoming sixth European Nuclear Safety Conference in June 2022.

The tasks and expected outcomes stemming from the above topics are expected to be performed by ENSREG following a prioritised approach of a hierarchical nature in the following manner:

- High Priority tasks which must be undertaken by ENSREG in accordance with Commission´s decision no. 2007/530/Euratom; any other legal obligations; or work of major strategic importance to nuclear safety, management of spent fuel of radioactive waste.

- Medium priority tasks which should be undertaken in support of the ENSREG's purpose commonly related to the work of a strategic importance for nuclear safety, management of spent fuel and/or radioactive waste.

- Low priority tasks which could be carried out to support ENSREG's role, but may have a limited contribution to nuclear safety, management of spent fuel and/or radioactive waste. These would for instance comprise of tasks of an administrative nature.

Finally, on behalf of ENSREG, I would like to conclude by using this opportunity to reiterate the group´ s lasting commitment to the continuously enhanced nuclear safety, implementation of new knowledge and experience as well as good practice whenever applicable and available.

I thank you and I wish this conference provides all of us with a valuable format during which we can enrich our knowledge and expand networks with an aim to collectively work together to strive for a continuous enhancement of nuclear safety.

Thank you for your attention.

# KEYNOTE - RESEARCH AND INNOVATION BENEFITS FOR A LOW-CARBON AND CLIMATE NEUTRAL ECONOMY, INDUSTRIAL COMPETITIVENESS AND SUSTAINABLE DEVELOPMENT

**Yves DESBAZEILLE** (FORATOM), Director-General of the European Nuclear Industry Association FORATOM

Nuclear power in Europe today remains a complicated topic. It is true that popularity of this technology is increasing within many Member States, particularly among young citizens. Recent surveys suggest that in Finland and Sweden nuclear technology has reached record levels of support.[19] Even in countries with a strong historical opposition, such as Germany, there is a growing understanding that nuclear should play a complementary role to renewables instead of highly GHG emitting fossil fuels.[20] This change in perception is largely due to external contingencies. Climate change, rising energy prices and the conflict in Ukraine have forced policymakers to critically re-examine the energy transition.

Nevertheless, some political actors have not changed their position on nuclear energy. I firmly believe that no matter how much scientific evidence you present to them, they will remain fundamentally opposed. As an engineer who is also deeply involved in European politics, this is incredibly frustrating. Time after time, with every legislative proposal that is presented, I know that there will be an array of actors who are actively trying to exclude nuclear from benefits that are afforded to other low carbon energy sources.

The most relevant of these legislative proposals for today relate to research and innovation funds, which are key for all sectors. These funds would allow the nuclear industry to develop new technologies, as well as enhance existing ones. It also presents an opportunity to scientifically demonstrate – as has already been done many times – that nuclear is a clean, safe and sustainable energy.

To be clear – without securing sufficient funding for research in the nuclear sector, be it for safety or commercial purposes, the European Union will fall behind its competitors. We only have to look as far as our former fellow Member State, the

[19] https://www.euractiv.com/section/energy-environment/news/record-number-of-finns-now-favour-nuclear-to-go-green/. https://www.nucnet.org/news/support-for-nuclear-power-reaches-record-levels-survey-suggests-4-1-2022

[20] https://www.nucnet.org/news/half-of-germans-see-role-for-nuclear-in-new-europe-wide-survey-12-1-2021

United Kingdom, to see ambitious plans being implemented in support of its nuclear industry.21 This is to say nothing of other countries, such as China, Russia and the United States.

Policymakers must open their eyes and face reality. The European Union is constraining its industries from reaching their full potential. We are running a real risk of losing our position as an industry leader. This will have serious consequences on EU targets related to climate, energy prices, and security of energy supplies.

But we as the industry must also share some responsibility. It is up to us to clearly communicate what these funds would be used for. Logically we should start with what has long been the Achilles heel of our industry, radioactive waste (or rather, the back end of the fuel cycle). Waste has long been a controversial talking point, but the development of both waste treatment and further commercial use also hold enormous potential. Well planned, focused research can present a sustainable solution to European citizens in different ways. From the safe and permanent underground storage of high-level waste, to the development of new reactor technologies that can use the spent fuel produced by current reactors to generate even more power.

Regarding the final repositories, Finland is the first country in the world to start building a Deep Geological Repository. So, once it is completed, I will personally be indebted to the scientists who will finally give me a tangible point to fire back at the predictable "what about the waste" questions from anti-nuclear campaigners. In addition to Finland, Sweden and France are also well advanced in terms of developing their own deep geological repositories. And we expect other Member States to follow suit.

Regarding new reactor technologies, a number of companies around the world, including some start-ups, are developing breeder reactors. These reactors produce more fuel than they consume. Not only is this a fantastic technical feat, but it seems particularly relevant when considering the big talking point of recent times: how can Europe ensure a secure supply of energy. Now imagine what would be possible if the Commission were to properly fund nuclear research and industrial capabilities.

Research on the front end of the fuel cycle also holds a lot of potential. New forms of fuel delivery are taking shape, accompanying new reactor technologies. TRISO fuel for instance will significantly increase resistance to a core meltdown. If you follow the European Taxonomy saga, you may be familiar with Accident Tolerant Fuels. There are already several fuels in use today, which can be considered as "Accident-Tolerant". These are fuels, which have been developed with the primary goal of providing additional protection against accidents. Furthermore, research and testing of 'Enhanced Accident-Tolerant Fuels' is also ongoing in different parts of the world, including in Europe. All of these developments,

[21] https://www.world-nuclear-news.org/Articles/UK-launches-funding-to-encourage-nuclear-new-build

however, require research. And, as the famous saying goes, “research does not grow on trees”. No, research requires funding. In practice this means laboratories need to be set up, testing facilities must be built and researchers and technicians need to be paid.

Regarding the operation of the existing nuclear fleet, average capacity factors are some of the highest we have ever seen (if we don’t account for some recent corrosion problems). The average nuclear capacity factor in Europe is around 82%. This is much higher than any other low-carbon source of energy. Technologies that are currently under development will bring even greater improvements, bringing the capacity factor closer to 100%.

Nevertheless, regardless of this impressive performance, nuclear power is still not properly valued and rewarded by the Commission for its role in climate change mitigation and ensuring security of supply. Euratom research funds have decreased. Of the Euratom 2021-2027 budget for R&D only around 20% goes to fission research, and of this 20% only half is allocated to fission power projects. This results in a meagre 40 million euros per year. By comparison, the US spend more than 1 billion.

Technologies like Small Modular Reactors (also known as SMRs) or Gen IV reactors are triggering an increased interest in new nuclear technologies globally. Our industries should not be prevented from jumping on the enormous potential of these technologies. For SMRs, lower financing costs will allow for more streamlined and phased investments, greatly decreasing risks. Their flexibility and operability can strengthen the national and regional transmission network, balancing the high share of variable renewables. Their small size and autonomy means they can be deployed to answer specific use cases in locations where the nuclear industry could not previously operate.

Moving forward, it is clear that investment in nuclear R&D must increase. To allocate funding, the Commission must abide by the principle of technological neutrality. Decisions for funding must be based on science and not driven by ideology. Ultimately, this means that nuclear energy deserves equal access to the same research, innovation and industrial development funds as all other low carbon technologies such as renewables. The JRC report on taxonomy is clear, nuclear power does not cause more significant harm to populations and the environment than other low carbon technologies.

Let me conclude by saying that yes, it is true that renewables will be crucial to our energy systems going forward. However, flexible technologies require backups. Renewables alone cannot adequately address the following three crises: climate change, rising energy prices and security of energy supplies in Europe. We are currently presented with two options, do we go with dirty fossil fuels such as gas or even coal (which emit large volumes of $CO_2$), or do we choose nuclear? We are fortunate enough to have two case studies in Europe. We can follow the French example, or we can follow the German Energiewende model, based on a nuclear phaseout and partially to blame for Europe’s precarious situation today.

If the Commission is serious about these crises, we will see an abandonment of ideological prejudices towards nuclear. Let’s be clear – Europe is lagging behind much of the rest of the world when it comes the industrial competitiveness of our nuclear sector. China and even the US have recently invested significant resources into various nuclear technologies, both for internal use and export. It's not too late for Europe to do the same. Let me remind you, nuclear is part of our shared European heritage. The Euratom treaty has remained unchanged since its adoption in 1957 and distinctly calls for "promoting research and disseminating technical information."22 It is up to us to live up to the spirit of this treaty, it is time for the Commission to support the only dispatchable, low-carbon and nonweather dependent technology. Only nuclear can support the energy system transition under secure conditions. It is time for Europe to rethink its position as a serious player in the nuclear sector.

[22] https://www.europarl.europa.eu/about-parliament/en/in-the-past/the-parliament-and-the-treaties/euratom-treaty

# KEYNOTE - THE FUTURE OF NUCLEAR: COLLABORATION, VISION AND INNOVATION – PERSPECTIVES FROM YGN

**Jadwiga NAJDER** (ENS YGN), Chair of the Young Nuclear Generation of the European Nuclear Society

Nuclear, as every large domain of activity, constantly faces challenges and needs to reinvent itself adapting to the world and its needs. Like civil, space and aviationindustry, nuclear industry is a huge complex machine that takes time, effort andbudget to progress.

Just to mention a few issues, the nuclear sector is currently dealing with:

- the positioning of nuclear in the climate-aware world, as it is not clear to the public, as well as to the decisionmakers on national and international level,that this source of energy is a safe, essential and powerful long-term component of the environmental mitigation and adaptation.
- the internal challenges of the nuclear industry, among them optimisation and harmonisation of processes, cost reduction, pursuing of development and innovation
- the issue of competitivity - can nuclear be or become a domain attracting,forming, and retaining best talents? Each of those issues is an enormous challenge on its own and it requires holistic and harmonious approach from all the stakeholders looking towards the future.

These stakeholders can be united if they share a common vision, for example, striving to ensure accessible, affordable energy and essential services for the development and well-being of the low-carbon world. Finding the common vision motivates the collaboration between the industry, academia, IGOs, NGOs. Working together creates the ground and stimulation of innovation, research and developmentwhich is essential to address technical and organisational challenges of nuclear.

Innovating enables fulfilling the vision.

The triangle of vision, collaboration and innovation is a set of interdependent factors of transformation in nuclear.

But how does it relate to the communities of young professionals in Europe? The European Nuclear Society Young Generation Network (or ENS-YGn in short) together with national nuclear societies (or YGNs) supports nuclear science and industry in creating the sector of tomorrow. Volunteering our time and effort to lead, sustain, animate the societies, we translate the vision into simple words and actions, as well as share it with our peers and general public, we foster collaboration in a thousand different ways, and we nurture young people towards innovation.

But what is ENS-YGN? It is a Europe-wide community assembling all the young members of nuclear societies. Currently we have 21 member Young Generation Networks. We exist because 1+1>2, together we are stronger. How do we contribute to this triangle enabling the successful future of nuclear?

Firstly, we translate the vision of the nuclear sector to make it understandable and relatable by society, by popularising knowledge among the general public and young people. We go where those people are - to schools, bars, social media, we reach them through approachable TV and streaming emissions. We react to the hot topics and hot trends to smuggle some nuclear knowledge and change the attitudes.

Apart from that, a huge chunk of our activity is to share the vision where it is not well understood and taken into account, for instance in the high level circles of decision making and activism related to climate change fight and environmental protection.

With support of numerous wonderful people, we act on behalf of Nuclear for Climate network, a community of 150 organizations around the world. Since 2015 we mobilize the nuclear world to show their colors at the UN Conference of Parties.

From the position papers, through official and unofficial COP side events and collaboration with country representations, all the way to creative activist actions waking the attention and curiosity, we work to give nuclear its rightful place among all the necessary solutions contributing to fight against climate change. This year's COP will take place in Egypt and together with a team of volunteers from 7 countries, we prepare to once again show that nuclear has to be a part of the climate talks.

Finally, we share the vision with our peers, students, youth to let them see the big picture of their future career, which could be enriched by much more rewarding foundations than money. We encourage them to embark on the journey building the future of nuclear by sharing our stories, experiences, knowledge.

Following, we foster collaboration between people and organisations. Together with YGNs we create and support relations between early career professionals by means of the engaged, passionate communities for more holistic, cross-professional and cross-national development of the future experts. One of the great examples is bi-annual conference European, Nuclear Young Generation Network (ENYGF), the next edition taking place 8-12/05 in Krakow, Poland, featuring scientific sessions, workshops, mentoring program, technical tours. And last but not least, countless occasions for passionate conversations with peers, senior experts and high-level figures of our nuclear world.

But the informal relations and network created during interactions is only the beginning. In scope of formal and informal collaborations, supporting communication of educational and scientific opportunities, recruitments, building an information network facilitating the connection between the employer and the workforce also beyond the national borders is another huge mission of YGNs.

Collaboration between people is supported by collaboration between communities, which is actually a primary objective of the ENS-YGN. 3 times a year, representatives of 21 YGNs as well as observer organisations meet at a Core Committee Meeting for knowledge and experience sharing reunion in one of the member countries. The meeting features discovering local nuclear industry and science during technical tours.

The collaboration does not only focus on young people. ENS-YGN promotes dialogue and cooperation between the generations too. Each year, a senior colleague is elected by the Core Committee and awarded with Jan Runermark prize for his exceptional support to the YGN community and young people in general.

Finally, YGNs nurture youth towards innovative and independent thinking. Themselves using innovative ways to communicate, like TikTok or streaming platforms, the local communities show to young people that nuclear can be cool, waking curiosity and providing a dynamic workplace full of new ideas. From webinars about the latest nuclear startups, to the innovation contests, and scientific contribution prizes, they encourage best talents to join and push nuclear to excellence.

In conclusion, ensuring the successful future of nuclear requires a wide-scale dedication and effort of people of different profiles and levels of experience. ENS-YGN and its hard-working member communities give their share by educating, inspiring, and empowering early career professionals to identify and approach the issues that nuclear power is facing, but most of all to act according to greater vision, collaborate and innovate.


FISA 2022
EURADWASTE'22

# SESSION 1: COLLABORATIVE RESEARCH, DEVELOPMENT AND DEMONSTRATION IN RADIOACTIVE WASTE MANAGEMENT

Co-chair: Daniela DIACONU (RO, RATEN ICN)

Co-chair: Seif BEN HADJ HASSINE (EC, DG RTD)

Rapporteur: Marie-Anne BRUNEAUX (FR, Expert)

EURADWASTE'22

30 May - 3 June 2022
Lyon, France

# IGD-TP - Towards operation and optimization

Tiina Jalonen, IGD-TP Chair



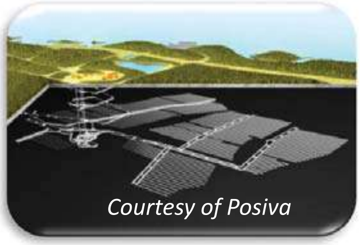
## Implementing Geological Disposal - Technology Platform, IGD-TP

- Steers, initiates and carries out European strategic initiatives to facilitate the stepwise implementation of safe, deep geological disposal of SF, HLW and other long-lived radioactive waste
- Currently 142 member organisations across 29 countries, all interested parties endorsing the IGD-TP Vision and willing to contribute positively and constructively to the group's goals are welcomed
  - The secretariat is solely funded by the 11 WMOs and organisations responsible for implementation-related RD&D who form the Executive Group (EG)

BGE | POSIVA | SÚRAO | Radioactive Waste Management | ANDRA | PURAM | COVRA | nagra | SKB | ONDRAF/NIRAS | enresa

## Moving towards the vision

- Our first vision, Vision 2025
  - 'to have the first geological disposal facilities (GDF) for spent fuel, high-level waste and other long-lived radioactive waste in operation by 2025'
- Major progress has been made towards achieving our vision
  - Posiva has submitted the operating licence application in December 2021 and is planning the start operation in 2025
  - SKB has been granted the construction licence in January 2022
  - ANDRA is planning to enter to the initial construction phase in 2022



*Courtesy of Posiva*

*Courtesy of SKB*

*Courtesy of Andra*



## IGD-TP Vision 2040

**2040 – Towards industrialisation of radioactive waste disposal in Europe**

**Safely operate**
the first geological disposal facilities in Europe

**Optimise & industrialise**
planning, construction and disposal operations

**Tailor solutions**
for disposal of the diverse waste inventories in Europe

- In order to meet the challenges of the next phase the IGD-TP has updated the group's vision
  - Vision covers both small and large disposal programmes in initial or more advanced stage
  - Considers shared repositories and/or mined borehole disposal
  - **Safety is the highest concern,** however, as these are **multi-billion programmes**, optimisation for implementation is very important

10th European Commission Conference on EURATOM Research and Training in Radioactive Waste Management
30 May - 3 June 2022 | Lyon, France

# IGD-TP Strategic Research Agenda

IGD-TP WMOs have agreed a

Strategic Research Agenda (SRA)

to guide the focus of future activities and resource allocation to the challenges common to multiple WMOs

SRA identifies issues that need a coordinated effort for making Vision 2040 a reality

Also provides valuable input to identifying topics for future EURATOM calls



# Some examples of SRA topics

- Post-closure safety
  - Verification and validation of models for the simulation of the transport of radionuclides in the near-field of deep geological repositories
- Waste forms and their behaviour
  - Further development of post-closure criticality safety analysis
- Technical feasibility and long-term performance
  - Industrial-scale operations for buffer and backfill
  - Container materials and their long-term performance
- Implementation and/or optimization
  - Building Information Modelling (BIM) and “digital twinning” of the as-built repository, coupled with numerical simulation of repository behaviour and data chain from monitoring
  - Thermal dimensioning of the repository
- Safety of construction and operation
  - Strategies to evaluate the impacts of construction and operational issues on the disposal system
- Monitoring
  - Data management
- Methodologies for site characterisation
  - Exploration methods for site characterization
  - Confirmation of rock properties
- Strategy for repository project development
  - Transition from surface-based site characterisation to going underground
  - Costing
- Knowledge management
  - Develop a common WMO KM strategy

# Role of international cooperation

Moving from research and development, to construction and, finally, to industrial operation of a final disposal facility, requires a huge amount of work and is very costly

Experience from other programmes might speed up the progress and make savings – this is why international cooperation is of vital importance in the whole European perspective

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REVIEW ARTICLE OPEN ACCESS

# Developments and experiences of the CHANCE, MICADO and PREDIS projects in radioactive waste characterization

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**Abstract.** Characterization is a very important step in dealing with materials and waste streams generated during the operational and decommissioning phases of nuclear installations, including nuclear power plants. Characterization allows differentiation between materials that can be released from regulatory control and those that require further treatment and conditioning to become a stable waste form suitable for future storage and final disposal according to its waste classification. Characterization is also needed in the pre-disposal stages of radioactive waste management to demonstrate compliance with the waste acceptance criteria of the facilities that will accept the different waste forms. This work will present the strategies developed and implemented by the three projects for in-depth and accurate waste characterization and investigation of the different radioactive waste packages considered. CHANCE, MICADO, and PREDIS will present their goals, the methods developed, the technologies used and the (preliminary) results contributing to the improvement of the safety and the data and information quality of the waste packages analyzed at the different stages of the waste management process. Special emphasis will also be given to complementary approaches highlighting the usability of the technologies, the accessibility of the data, and the problem-solving of the three projects within the European panorama.

## 1 Introduction

The characterization of radioactive waste is one of the key aspects of its management. Accurate knowledge of both the volume and the radiological and physicochemical content of nuclear waste generated in each national program will influence the strategies and technologies for its further management. Radioactive waste characterization is considered a key procedure required by national and international legislation, ensuring transparency of information for all stakeholders involved. It is also important with respect to safeguards to prevent nuclear proliferation, to ensure adequate radiation protection for workers in the relevant operation, and for the safety of the entire population and the environment. Detailed knowledge of the radioactive waste package (RWP) contents is also essential to establish the best operational procedures. Radiological and physicochemical assessments are important to determine the type of waste, the safety procedures for its handling, the type of conditioning procedure to be adopted, and the resulting modalities of storage. This assessment in the early stages of waste production is very important to optimize subsequent waste management (treatment, conditioning, disposal conditions, and financial impact). It significantly reduces the risk associated with waste reconditioning.

Precise information on radiation levels is even more important for RWP with content that lies at the border between two categories. Precise information can be critical in determining whether to choose, for example, a surface or geologic repository, which can lead not only to a change in the final location, but also to a change in all activities down to the predisposal phase, and can result in significant costs.

Another important issue to be evaluated during the characterization phase is the identification of the chemical content, which is particularly relevant for contaminated sites and historical waste packages. Waste acceptance criteria at some current or future disposal facilities include chemical parameters that can limit the number of specific species.

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The three projects CHANCE, MICADO, and PREDIS are mainly focused on non-destructive techniques of investigation. This section describes the state of the art of investigation approaches and methods used in Europe, focusing on radiological and physical characterization by using non-destructive methods and on the innovations introduced by the three projects.

## 4 Non-destructive measurement techniques

Non-destructive methods can be divided as follows: radiological methods measure the radiation generated by the content of the package. Non-radiological methods (visual, electromagnetic, acoustic, X-ray, or muon-based) are mainly used to retrieve information about the package's internal geometry, density distribution, or integrity. Active measurements use some kind of source (in X-ray, ultrasonic or electromagnetic methods and in radiological methods based on the emissions due to reactions to neutrons or photons from external sources) and the interaction of the source with the package and its content is recorded by some receivers/sensors. Visual and thermographic methods might also be considered active methods if they use external light or infrared sources, otherwise, they are passive. Passive methods use natural emissions (radiological methods based on spontaneous emissions), events (acoustic emission due to cracking), or particles (e.g., muon tomography) measured or tracked by detectors of various types.

The radiological measurements are used to determine the presence, quantity, and location of radioisotopes or the existence of toxic or reactive materials, neutron absorbers, or moderators in the RWP [9]. The main passive measurement technologies considered so far in waste characterization are:

- **Gamma dose rate measurements** are performed mainly for safety reasons: they are performed at contact and a distance of 1 meter from the RWP surface. They are used for the first radiological assessment and planning of the handling of the RWP by the operators. The dose rate can be converted into activity if the isotopic vector of the radioactive waste is known.
- **Gamma spectroscopy and spectrometry techniques:** mainly tomographic and segmented gamma scanning systems based on HPGe detectors are used to detect, identify, quantify, and localize gamma radioisotopes. They are suitable for scanning open, segmented, and angular geometries. Tomographic systems are also able to reconstruct radiological emissions and hot spots inside the RWP in 3D. They determine the presence of uranium and plutonium as well as the presence of radiotracers. Often, these systems are also equipped with a gamma radiation source to perform transmission measurements to obtain density information on the contents. Gamma results are also used in combination with neutron detection techniques.
- **Passive neutron measurement** is used to quantify actinides, mainly Plutonium. This type of measurement detects neutrons from spontaneous fissions, where several correlated neutrons are emitted per fission, or ($\alpha$,n) reactions with only one emitted neutron per reaction. The measurements foresee both a total neutron count and a time correlation analysis. Looking at event coincidence allows distinguishing the signal due to fission neutrons from the accidental background due to ($\alpha$,n) reactions and hence the type of isotopes in the RWP (e.g., $^{240}$Pu vs. $^{241}$Am). For medium size drums, this technique is less sensitive to high atomic number materials (metals) than to low atomic number materials (especially those containing hydrogen). Another limitation is the presence of curium because it is very high specific activity of spontaneous fission can easily mask the passive neutron coincidence signal of plutonium in the RWP, as in the case of highly active metallic residues from spent fuel reprocessing.
- **Digital autoradiography** is a technique for determining alpha and beta-contaminated waste. It uses photographic-like screens that are applied to the waste. The radiological signature allows to extract graphical information on the presence of low-energy emitters such as $^{3}$H, $^{14}$C, and alpha particles.
- **Gas measurements:** chromatography or scintillation counting can be used to quantify the presence of radioactive or radiolysis gas released when the waste package is placed in a sealed enclosure. The gas can accumulate in this chamber and the quantity of gas emitted by the waste, such as $^{14}$C, $^{36}$Cl, and $^{226}$Rn, can be measured to derive the release rate. In recent years, optical detection of radionuclides has been successfully demonstrated for radiocarbon. Laser spectroscopy can be used to provide selective and sensitive detection of molecules directly in the gas phase. Optical detection offers several advantages over conventional techniques for nuclear applications, such as liquid scintillation counting. One of the most sensitive laser spectroscopy techniques is cavity ring-down spectroscopy (CRDS).
- **Calorimetry** is an experimental technique for measuring the thermal power generated by nuclear decay in the radioactive matter, which is related to the specific power of the isotope to deduce the mass of the tested matter. Several prototypes and commercial instruments are currently in operation at different research centers around the world to determine the quantity of alpha emitters and the presence of tritiated waste.
- **Muon Tomography** is still considered to be in the R&D phase. Muons generated by cosmic rays can penetrate matter and be used to image the internals of structures. Since the early 2000s, several groups have extended the concept of muon radiography to tracking individual muons as they enter and exit a structure. Most current efforts have been aimed at demonstrating the potential of muon tomography for detecting the smuggling of special nuclear materials (SNMs) in cargo, the non-invasive characterization of legacy nuclear waste containers, and for nuclear material accountancy of spent fuel in dry storage containers.
- **Acoustic emission (AE):** this technique records acoustic events caused primarily by cracks in the cement fill of waste packages using receivers placed on the out-

side of the package. Localization and characterization of the events are possible. While AE is used as a standard tool in other applications, its use in waste characterization is so far limited. It can be considered very useful in the development and validation phases of treatment technologies involving cement or geopolymer, as well as in the design and testing of waste containers. This technique is also used to detect and monitor corrosion on the waste container walls.

The active measurement types are:

- **high energy photon** imaging performing radiography and/or tomography of the RWP is one of the initial measurements and provides information about the physical structure of the RWP such as density, cracks, presence of voids, position and shape of elements inside the volume, presence of liquids. This technique is usually used for legacy waste and serves as one of the key elements providing relevant information for further inspections.
- **Dual-energy X-ray imaging:** this technique is still in the R&D stage and is currently under investigation. Using tomographic acquisitions at different energies allows for enhancing the differences in the attenuation coefficients of the elements constituting the imaged materials and provide information about their effective atomic number in each pixel. This information is used in combination with the density already provided by X-ray imaging to improve the identification of materials with similar densities (e.g., aluminium and concrete in radioactive waste).
- **Active neutron interrogation technique** has been used industrially for decades, for instance at the spent fuel reprocessing plant of ORANO La Hague (France), where four measurement stations are currently in operation for the characterization of highly active metallic residues (hulls and end pieces) in the T1, R1 [10], and ACC facilities [11]. The measurement uses the die-away method to quantify the fissile material inside the package when plutonium gamma rays are masked by the intense emission of fission and activation products and when the passive neutron coincidence count signal is dominated by curium spontaneous fission neutrons or when the ($\alpha$,n) accidental background is too intense. It uses the flux of a pulsed neutron generator (DD deuterium-deuterium or DT deuterium-tritium) inducing fissions in the presence of fissile material and counting the emitted prompt and delayed fission neutrons. The prompt neutron signal is detected a few hundred microseconds after the generator neutron pulse and is proportional to the fissile material mass. This is the key advantage of this technique for safety-criticality purposes, although it is more affected than passive neutron counting by the waste package matrix effects. The fission-delayed neutrons are also recorded between pulses from the neutron generator, but after the prompt neutron signal has disappeared. The delayed signal is sensitive to $^{238}$U due to fast fissions, in addition to the fissile isotopes $^{235}$U, $^{239}$U, and $^{241}$Pu (thermal fissions as in the prompt signal). Using both prompt and delayed neutron signals allows discrimination of U and Pu contributions in some instances.
- **Prompt gamma neutron activation analysis** (PGNAA): this technique is still in the R&D stage under study and is not yet widely used in the field. It requires a combination of gamma and neutron measurements to determine the presence of toxic elements (such as B, Hg, Cd, Gd, Cl, As), neutron moderators (such as H or C), or absorbers (such as B, Cl, Fe, Cr, Ni, Cd, Gd). It detects prompt gamma rays from radiative capture or inelastic scattering neutron reactions on the nuclei of interest.
- **Ultrasonic and electromagnetic** (eddy current) **techniques** can be applied to verify the thickness of steel containers. A reduction in thickness in some parts of the container may be caused by internal corrosion.
- **Visual techniques** using special sources (e.g., strip projection) and software, can be used to record and monitor deformations of waste packages caused by either improper handling or internal processes such as the cement-alkali-silica reaction.

## 5 Destructive measurement techniques

When handling samples, non-destructive analysis is preferred and, usually, is the first type of measurement. However, under certain conditions, the second type, characterization of the waste by destructive measurement techniques, becomes mandatory. Legacy or alpha and beta-contaminated waste are examples in which destructive measurements of the content are necessary since the radiological emission from outside the package is not detectable. In these cases, there is a necessity to open the packages and perform precise measurements on-site. The decision on the type of measurement and the number and locations of the samples to be extracted and analyzed is made by the results of the non-destructive techniques and is applicable only to conditioned waste.

The main measurement techniques available are:

- **coring and cutting:** this involves the extraction of a coring element to perform multiple tests and controls, beginning with a visual examination, evaluation of composition components, and ending with the extraction of waste samples for analysis.
- **Chemical, radiochemical, and physical analyses** are performed on the extracted disks coming from the coring. Tests to check containment, detect and measure the presence of toxic materials, identify long-lived radioactive elements, measure pure alpha and beta emitters, and determine isotopic composition will be conducted.

## 6 The three projects and their innovations

The previous sections refer to the main characterization and conditioning technologies used nowadays in the nuclear waste management sector. The list is not exhaustive but gives an overview of the measurement techniques used. The three projects fit into this framework and are focused on these measurement techniques.

This section describes the aims of the projects and the technologies developed, examining the innovations in light

In this context, the CHANCE, MICADO, and PREDIS projects were launched under the Euratom calls. They focus on optimizing the handling, characterization, and monitoring of RWP, optimizing the data flow, and sharing the acquired knowledge within the community.

This paper describes the state of the art in characterization technologies and the innovations introduced by the three projects.

## 2 European nuclear waste and its sources

More than 60 000 tons of spent nuclear fuel are stored throughout Europe (excluding Russia and Slovakia), most of it in France. High-level waste, which also comes from the reprocessing of spent fuel, accounts for the largest share of radioactive waste. In Europe, more than 2.5 million $m^3$ of low and intermediate-level waste has been generated, of which about 20% (0.5 million $m^3$) has been stored and 80% (close to 2 million $m^3$) has been disposed of.

The decommissioning of the European reactors may generate more than 1.5 million $m^3$ of low and intermediate-level waste. During the entire lifetime of European nuclear reactors, about 6.6 million $m^3$ of nuclear waste may be generated. Four countries account for more than 75% of this waste: France (30%), the UK (20%), Ukraine (18%), and Germany (8%) [1,2].

Excluding fuel chain facilities, the European power reactor fleet alone could generate at least another million cubic meters of low- and intermediate-level waste from decommissioning. This is a conservative estimate, as decommissioning experience is still growing.

There are more than 140 operating nuclear power plants in Europe. The ongoing generation of nuclear waste and the imminent decommissioning of nuclear facilities poses an increasing challenge as storage capacity in Europe will soon be exhausted. Moreover, in countries such as the United Kingdom and France, decommissioning waste is also strongly influenced by activities that are independent of the power reactors.

All countries publish information regularly but differ significantly in how they define, categorize nuclear waste, and report quantities of nuclear waste. The different national approaches reflect a lack of common standards and coherency in how countries manage some aspects of nuclear waste. To this end, initiatives have been taken, e.g., within the OECD-NEA, to achieve more consistent and standardized reporting [3,4].

The CHANCE [5], MICADO [6], and PREDIS [7] projects contribute to improving the characterization of radioactive waste at different stages of the waste management process in order to reduce the impact of final disposal. The three projects focus on the largest part of the existing waste volumes, which are mainly composed of low and intermediate-level packages, legacy waste, and waste from European D&D activities. In the various European countries of origin, these are stored for final disposal or in geological repositories.

The future optimization of the waste management process towards the final repository is a combination of multiple activities that form the core of the three EU projects described here: monitoring, handling, conditioning & packaging, and characterization with the digitization of key information.

Characterization aims at providing accurate knowledge of the radiological and physicochemical content of the waste package. To optimize the conditioning process, better manage the radiological inventory, digitally track the information, and support decisions to minimize volume and cost, several techniques are used simultaneously. This article addresses these radiological and physicochemical characterization techniques. Other important techniques, such as long-term waste monitoring assuring real-time knowledge of the nuclear waste status and enhancing global safety, pre-treatment and conditioning techniques, or knowledge transfer of lessons learned to future generations and countries not involved in this D&D phase, are not addressed in this article.

## 3 The importance of nuclear waste characterization

The RWP characterization is a complex analysis that involves not only the qualification and quantification of the radiological content but also the analysis of the physical (density, volume, shape, mechanics, cracking, diffusion, etc.), chemical (element composition, toxicity, presence of reactive substances, gas production, liquid, solid materials, etc.) and radiological (dose rate, spectroscopy, isotopic composition, spectrometry, calorimetry, etc.) parameters required to optimize the waste management. Destructive and non-destructive methods are used to measure and verify these parameters.

Destructive analysis (DA) offers the most accurate and unbiased activity determination, and the sampling provided should represent the whole package. This technique is mandatory since pure alpha and beta-emitting radionuclides or those emitting gamma or X-rays with a too-small intensity or energy are extremely difficult to measure even in already conditioned waste packages. Destructive analysis includes a sampling of the package, sample preparation, and chemical separation methods. Sampling is a critical step in the characterization process. Determination of representative samples and full compliance with sample-drawing procedures ensure the reliability of results. Chemical and radiochemical treatment of the primary waste also enables measurements that assure traceability of the determined activity.

Non-destructive analysis (NDA) and testing methods are used to minimize the radiation dose to personnel, avoid secondary radioactive waste production, minimize costs, and provide a comprehensive characterization of waste packages in reasonable measurement times with respect to sampling. Several non-destructive methods for quality checking of radioactive waste packages have been developed and tested [8].

Despite the methods employed today, there is a need for the development of new non-destructive methods focused on conditioned waste.

of the panorama described earlier. The innovations behind these projects not only refer to the investigation technologies under development. Describing the single technologies falls short, as the waste management procedures can improve the waste package characterization itself and can be considered an element of innovation. These processes under study combine information from the different detection techniques to improve the knowledge of the package contents.

Figure 1 reports all the technologies of the CHANCE, MICADO, and PREDIS projects, as well as the leading institutes or partners of the projects during their lifetime. The timing of the projects varied: CHANCE ended in March 2022, MICADO will end in February 2023, and PREDIS will end in 2024, so it is not possible to report results for all elements in the table.

The three projects are in the field of decommissioning and/or general waste treatment. The CHANCE project (Characterization of conditioned nuclear waste for its safe disposal in Europe) aimed to further develop, test, and validate techniques that will improve the characterization of conditioned radioactive waste, in particular for radiological and physicochemical characterization. Besides the technological developments, another objective of the project was to establish a comprehensive understanding at the European level of the current conditioned radioactive waste characterization and quality control schemes across the different national radioactive waste management programs and the remaining needs in this field. In order to collect information on characterization, particularly on the links and overlaps between these requirements and the waste specifications for the different national disposal facilities, a questionnaire was produced and distributed to the operators of radioactive waste disposal facilities in Europe through the CHANCE project end user group (EUG). A Synthesis of the questionnaire answers is provided in the deliverable [12]. Another report has been prepared to describe the state of the art regarding techniques and methodologies on waste characterization in the R&D stage to meet the needs identified by end users [13]. An important document is the CHANCE report D2.3 [13] enlightens important points on the expected challenging R&D techniques in the field. The most relevant topics are:

- high energy and dual-energy X-ray imaging to characterize the physicochemical content and structure of large and dense waste packages
- photofission: active photon interrogation with high-energy X-rays to measure and identify nuclear materials in large, dense, concrete matrixes or containers
- passive neutron measurements: neutron coincidence counting techniques based on cheaper alternatives to 3He detectors
- active neutron interrogation techniques to measure the fissile mass for high-level radioactive waste
- neutron activation analysis to characterize chemical elements and long-lived isotopes difficult to measure by gamma-ray spectroscopy
- radiation attenuation corrections depending on the waste matrix and the localization of radioactive products in the package based on machine learning techniques trained by intensive calculations (e.g., Monte Carlo simulations of large measurement data sets covering a wide range of waste matrices and activity distributions)
- bayesian approaches interactively adjust the prior distributions of activity, radionuclide location, matrix density, composition, etc. according to all available measured data
- mobile measurement systems are to be reused at different sites and avoid the transport of the radioactive waste packages to the measurement system, which is generally very difficult for legacy waste.

The list does not include technologies already available under the CHANCE project. The remaining 6 of 8 points are already covered by the MICADO and PREDIS projects.

The techniques studied in the CHANCE project have seen major improvements in development, data acquisition, and modeling. However, as future developments remain:

- for muon tomography:
  - development of algorithms for the monitoring of gas bubbles in bituminized waste to study their formation and behavior and assess the associated safety risks
  - improvements in the algorithms for material identification of objects inside the waste drums to limit the data acquisition time and identify smaller objects
  - imaging of the contents of CASTOR drums; not only to verify the presence of fuel assemblies but also their structural integrity and to image the contents of waste silos.
- For calorimetry:
  - developments to improve the insulation of the calorimeter to measure the smaller effect and be able to work in facilities with significant room temperature fluctuations
  - developments to decrease measurement time and increase accuracy in quantifying radioelements emitting high gamma radiation.
- For cavity ring-down spectroscopy:
  - validation of the method under real industrial conditions
  - characterization of the method in different gas matrices to ensure the functionality of the CRDS in all situations
  - implementation of simultaneous detection of different radionuclides of interest (e.g., $^{14}C$, tritium, $^{36}Cl$) to have a single system capable of detecting all relevant radioactive elements present in outgassing.

Most of these topics are covered by the three projects with their different collaborations and backgrounds.

MICADO (Measurement and Instrumentation for Cleaning And Decommissioning Operations) started as the second project in 2019 and will run until the beginning of 2023 [6]. MICADO aims at changing the manual procedures used for the non-destructive assay (NDA) characterization techniques of the waste packages. To better qualify the waste package to be analyzed, a waste type-dependent analysis procedure is applied and information from different relocatable detection stations is combined. The project

| Method/Technology/Sensor | | Lead Institute | Purpose | Project |
|---|---|---|---|---|
| Calorimetry | | KEP | Quantification of the alpha emitters or low energy emissions | CHANCE |
| Cavity ring-down spectroscopy (CRDS) | | VTT | Characterization of radioactive waste outgassing | CHANCE |
| Gamma station | Gamma camera | ORANO ENEA | Hot spot search and identification | MICADO |
| | Gamma dose rate and spectroscopy & RFID | CAEN | Gamma dose at contact and fast open geometry measurement for survey application | MICADO |
| | Gamma spectrometry | ENEA | Quantification of gamma emitters (open geometry, angular scanning, tomography) | MICADO |
| Neutron station | Neutron active measurements | CEA | Quantification of nuclear materials (Pu, U) in not cemented packages | MICADO |
| | Neutron passive measurement | CEA | | MICADO |
| Photofission station | Photofission measurements | CEA | Quantification of fissile materials in cemented packages | MICADO |
| Long term monitoring | SciFi technology | INFN | Gamma dose rate monitoring for storage or repository sites | PREDIS / MICADO |
| | SiLiF technology | INFN | Neutron monitoring for storage or repository sites | PREDIS / MICADO |
| | Timepix network | CTU | Gamma and neutron monitoring system | MICADO |
| Data assessment | Uncertainties analysis | SCK·CEN | Monte Carlo error propagation, including pre- and post-processing of measurement data and results, tailored to radiological characterization | MICADO |
| Muon tomography | | UNIBRIS / INFN | Internal structure of drum | CHANCE / PREDIS |
| Ultrasonic echo (high frequency, metal) | | BAM, NNL | Container Wall: thickness, internal, corrosion, cracks | PREDIS |
| Ultrasonic echo (low frequency, concrete) | | BAM | Container fill: structure, objects, cracks | PREDIS |
| RFID Monitoring inside of the package, p , T, H | | BAM | Tracking cement hardening, monitoring fill evolution | PREDIS |
| Acoustic emission analysis (AE) | | MAGICS | Changes in concrete fill, crack development, stiffness | PREDIS |
| RFID solid state gamma and neutron sensors for long term monitoring | | UNIPISA | Gamma and neutron monitoring for waste packages | PREDIS |

**Fig. 1.** Technologies investigated in the CHANCE, MICADO, and PREDIS projects.

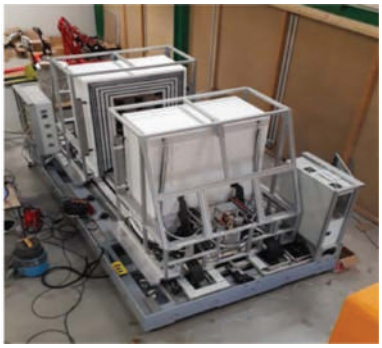

**Fig. 2.** The CHANCE calorimeter at the SCK−CEN being tested with real waste packages.

established a characterization procedure, data analysis, and information storage suitable for different types of waste activities (VLLW, LLW, ILW, legacy waste), matrix types (metallic, organic, and concrete fillings), and drum dimensions, including unconditioned waste but excluding high activity level waste (HLW) packages.

The infrastructure for data collection and visualization of the data provided by each technology represents another innovative approach in addition to the newly developed technologies. The RCMS software infrastructure can collect, store, display all data and implement advanced algorithms (such as Monte Carlo calculations, machine learning, or Bayesian inference) for error propagation analysis. This software allows a new approach to data management and more secure data processing. These aspects and the mobility of the detection devices are included in the list of topics prepared by CHANCE in Deliverable D2.3. These topics demonstrate the importance and complementarity of the projects, which provide continuity in the nuclear waste characterization field.

The third project PREDIS (Pre-disposal management of radioactive waste) started in 2020 and will run for 4 years. The PREDIS project aims to develop and increase the technological readiness level (TRL) of treatment and conditioning methodologies for wastes for which no adequate or industrially mature solutions are currently available. PREDIS project is also developing innovations in cemented waste handling and pre-disposal storage by testing and evaluating them. PREDIS will develop decision-making tools regarding the added value of the developed technologies and their impact on the design, safety, and economics of waste management and disposal. PREDIS encompasses the wider European Community allowing cross-fertilization and interaction between different national programs. The main objectives of the project are to develop solutions (methods, processes, technologies, and demonstrators) for future treatment and conditioning of waste, to improve existing solutions with safer, cheaper, or more effective alternative processes where they bring measurable benefits, and to analyze criteria, parameters, and specifications for materials and packages with associated waste acceptance criteria (WAC) for pre-disposal and disposal activities to support homogenization of waste management processes.

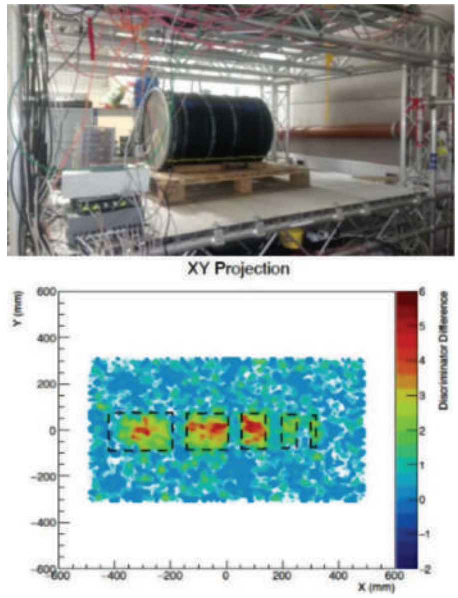


**Fig. 3.** Mock-up drum charcterization for the CHANCE project and reconstructed data.

## 7 The investigated technologies

**Calorimetry** [14] technique is used as a comprising non-destructive technique to reduce uncertainties in the inventory of radioactive waste containing shielded and hidden material difficult to measure by other means. Calorimetry is a method for the determination of nuclear material masses (or activities) by the quantitative measurement of the heat flux emerging from a sample. Calorimetry is used for NDA, which means that no sample needs to be tempered or destroyed by the analysis. In combination with gamma spectroscopy and neutron measurements, calorimetry is well suited for multi-nuclide assay of conditioned waste drums with large volumes and possibly heterogeneous contents and for reducing uncertainty assessment. Figure 2 shows the CHANCE calorimeter prototype being tested with real waste packages. It is designed to measure 200-l drums emitting heat in the range of 10−3000 mW and has already been tested with mockup drums containing Pu pellets in the center of a concrete matrix. A value of $99.7 \pm 16.4$ mW was measured and compared to the expected value of $110 \pm 6$ mW from simulations. Increasing the power emission showed better accuracy than expected.

**Muon tomography** is an NDA technique with a long exposure time (days/weeks) that can produce a full 3D image of a volume of interest. It allows viewing individual objects inside the drum and obtaining information on their atomic number $Z$ and density. The CHANCE system (Fig. 3) is a device tested in a real environment that consists of two detection technologies: drift chambers and resistive plate chambers (RPCs). Data in combination with multivariate analysis (MVA) classifiers and clustering algorithms allow us to approximately identify the locations and shapes of objects stored in a concrete-filled waste drum. Once the categorized data is trained in terms of different materials (lead, iron, etc.), machine learning techniques are applied to the reconstructed data to identify the unknown material inside the package [13]. The possibility of identifying bubbles of 5 cm in 4 weeks of measurement time was also tested. Finally, Monte Carlo simulations were used to evaluate the possibility of using this technique for large CASTOR drums with weeks-long measurements to determine the presence of materials or the absence of materials due to unauthorized material removal. The same type of measurement is performed with the prototype developed by INFN for the PREDIS collaboration. Within this project, the prototype is made of 2 layers of drift chambers (Fig. 4). The main aim is to validate the properties of concrete waste packaging including density analysis. At this stage of the project, an initial test was conducted to detect iron and other objects inside a concrete block.

**Cavity ring-down spectroscopy (CRDS)** is a transportable instrument for in situ airborne radiocarbon detection. It operates in the mid-infrared range. Within the CHANCE project, the system demonstrated the feasibility of the method to measure the $H^{36}Cl$ and the application of the technique to monitor the outgassing of $^{14}C$ waste, showing good repeatability and accuracy. Figure 5 shows a sample line developed to be connected to the CRDS prototype for the measurement of $^{14}C$ outgassing.

**The waste management procedure** was devised to characterize the different waste packages in order to minimize the measurement time of each step and be able to select the required detection technology based on previous measurement results. This procedure avoids multiple identical measurements and optimizes the process. An example of a predefined procedure is represented by the block scheme in Figure 6. This is the decision-making process developed for the MICADO gamma station, in which the data provided by two detection systems drives the choice of the spectrometric system.

**The gamma station** procedure is used for gamma characterization as one of the first and mandatory analyses for all waste packages. The MICADO station is not a single detection technology, but a procedural integration of three technologies. It is the first measurement station to pass through the waste package. The RadhHAND system [15] is used for contact, dosimetry, and spectroscopic measurements in open geometry. The Nanopix [16] is a gamma imaging system for the localization and identification of hot spots in open geometry. The SEA radioactive waste gamma analyzer (SRWGA) [17] is a tomographic segmented gamma scanner performing spectrometry and tomographic measurements of the package.

Although gamma spectrometry and tomography are considered traditional techniques, the main innovation is the procedural integration of the three techniques. The procedure consists of four steps (see Fig. 6): identification, screening, preliminary, and characterization phases. The identification phase starts with a UHF-RFID tag used to tag the waste package, providing a unique identifier, and associating its EPC number to the entry in the database identifying the package and its characteristics. During the inspection phase, an initial dose rate at contact is taken for safety reasons and radiation protection activities. The preliminary characterization phase consists of measurements of radiological homogeneity/inhomogeneity of the contents, identification of higher intensity radionuclides, acquisition of package picture recordings using the Nanopix and RadHAND systems, and identification of the tag on the package. During characterization, SRWGA will complete the gamma characterization phase. The SRWGA measurement type will be decided based on the results of the preliminary phase helping to select the best measurement technique for a complete package characterization. The result provided by the gamma station is used to determine the second step of the characterization process and select the measurement to be performed (neutron or photofission measurements).

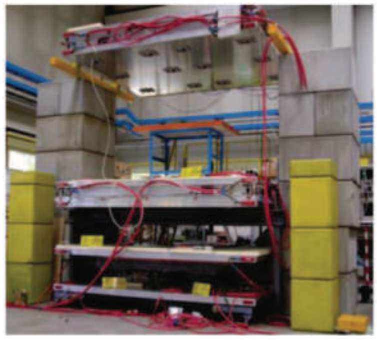

**Fig. 4.** Muon tomography system of the PREDIS project.


**Fig. 5.** New sampling line for use with $^{14}C$ CRDS prototype.

**The neutron station** presented in Figure 7 combines passive neutron coincidence counting and active neutron interrogation techniques for waste packages containing nuclear material. Packages with fissile or fertile material, but also large metallic waste packages, which are difficult to characterize by gamma spectroscopy, come to this station. The structure is mobile and can process packages of different sizes up to 220 l. Moreover, this technique is combined with data analysis based on matrix characteristics (material, density, filling) using artificial intelligence with trained data (based on many MCNP simulations) to apply signal attenuation corrections (also called "matrix effect" corrections) based on internal monitors and neutron transmission measurements to characterize the matrix. Monte Carlo simulations [18] were performed to optimize the design. In order to achieve a good compromise between the performances in passive mode and active

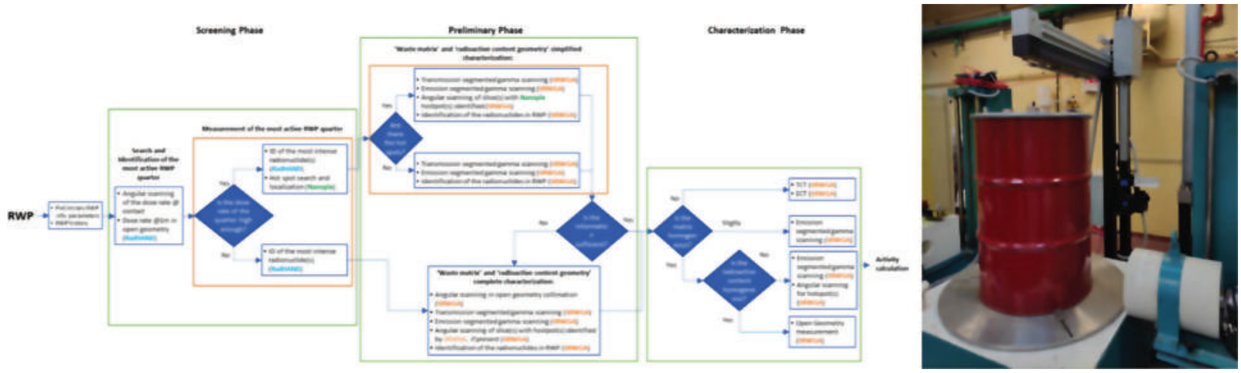


**Fig. 6.** Gamma station procedure on the left and the integration of the RadHAND sensor with the SRWGA on the right.

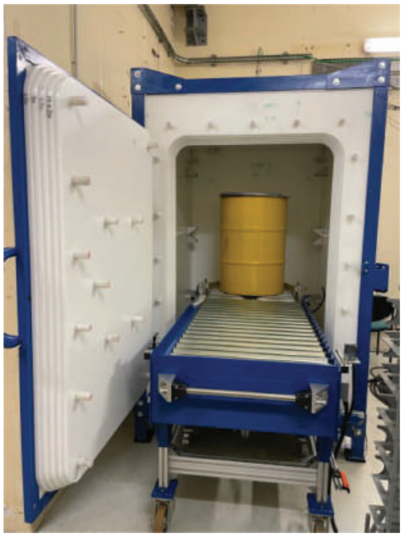

**Fig. 7.** Neutron detection system installed at CEA Cadarache.

interrogation mode, the differential die-away technique was used. Since the latter strongly depends on the characteristics of the nuclear waste drums to be measured, the matrix effect correction is mandatory to limit the measurement uncertainty.

**The photofission station** is used to characterize large volumes of packages with concrete or polyethylene matrices, which are considered difficult to characterize with both passive and active neutron measurements. Within MICADO, the possibility of using a mobile photofission system based on “low energy” X-rays (6 MeV) has been studied to minimize the hazard and safety shielding usually required for this technique. To provide this information, simulations and laboratory tests are performed to test two-photon beam energies, 7 MeV and 9 MeV. It is common practice to use 9 MeV. However, the ability to perform a package characterization using a 7 MeV beam as well will facilitate the use of a mobile system. This will require a more flexible shielding structure that is transportable or can be easily prepared on-site to ensure safety procedures.

**Pipeline data assessment**: the data analysis pipeline (DAP) is not a detection technology for characterizing a waste package, but rather a software infrastructure capable of propagating the uncertainties related to the individual techniques and combining the results of the individual techniques to reduce the global uncertainty of the final inventory. One of the main goals is to better determine the levels of radioactivity to optimize the waste package classification. This concerns in particular radioactive waste packages whose values approach the limits for surface storage or storage in a geological repository. This software infrastructure uses Monte Carlo particle transport (MCPT) simulations [19] to evaluate the sources of uncertainty in all detection technologies involved in the MICADO project. An analysis of the feedback mechanisms between different measurements enables the results integration and provides the overall uncertainty based on a full Bayesian uncertainty quantification using a probabilistic programming language (PPL) for Markov chain Monte Carlo (MCMC) sampling. The combined data analysis fuses different measurement results to extract information that is not available in the individual systems and to reduce individual uncertainties. This reduction is a solution to the problem of properly categorizing complex waste packages, for release or more accurate disposal.

**Data digitalization**: all MICADO technologies, software, and hardware provide data that is saved in a common software framework. This framework stores, processes, and displays the information required during and after the characterization of an RWP. A key element is the RCMS database, from which the organized collection of stored data can be accessed by multiple computers and operators. Using blockchain technology this data is securely stored to ensure the reliability of the data content.

**Small and affordable gamma and neutron sensors** are developed under MICADO and upgraded under PREDIS with a focus on electronics. Unlike the other projects, the main aim is long-term monitoring of waste packages (e.g., in intermediate storage facilities). There are two types of sensors, scintillating fibers for gamma detection (SciFi) [20] and a solid-state detector with lithium (SiLiF) for the detection of neutrons [21]. The sensors are coupled either directly to the package or the surrounding framework and provide continuous trends of neutron and gamma count rates to monitor the status of the stored package in real-time. Wireless communication with a prototype data collection platform is studied in PREDIS.

**Internal monitoring RFID devices** to be integrated into new waste packages are developed in PREDIS to wirelessly deliver data on temperature, humidity, pressure, and other parameters.

**Ultrasonic techniques** [22,23] are used and developed in several variants in PREDIS to verify the physical state of the packages. The high-frequency ultrasonic echo technique is used to measure the thickness of the outer metallic container wall and to detect and monitor corrosion and cracks on the metallic container wall. A low-frequency variant can be used to inspect and monitor the concrete fill and to detect voids, objects, and cracks in the cemented matrix and potentially in the wall of concrete containers.

**Acoustic emission**: in this technique, sensors are placed on the container wall to detect events that generate elastic waves (“sounds”), e.g., cracking, crack extension, or internal friction. TAE can be used to monitor concrete hardening or any change in the cemented matrix of RWP due to degradation processes.

**Machine learning algorithms** are used in PREDIS to provide a fast and accurate prediction of RWP geochemical evolution and integrity, continuously updated by monitoring data (digital twins).

## 8 Treatment and conditioning of the waste

The only project that focuses on technologies for the physical treatment and conditioning of waste is PREDIS. The project investigates technologies for the treatment and conditioning of radioactive wastes, such as metallic and radioactive organic wastes, whether liquid (RLOW) or solid (RSOW). The focus is on steel and Ni-alloys radioactive metallic wastes, which are major components in nuclear installations. These metallic wastes are often surface contaminated, in the form of corrosion layers of a few tens of micrometers retaining radionuclides, including but not limited to activation corrosion products ($^{60}$Co, $^{63}$Ni, $^{55}$Fe) and fission products such as $^{137}$Cs. Treatment of surface-contaminated metallic wastes includes chemical decontamination using chemical solutions for complex geometries (pipes) and gels for simple geometries such as flat surfaces and walls. Optimization of chemical formulations is being conducted and includes several parameters such as the reactants concentrations, treatment cycles, and temperature. Optimization of the gel-based treatment process will investigate the adherence capacity and the dissolution of the contaminated metal surface.

The PREDIS project also develops innovative solutions for the direct conditioning of RLOW as well as reactive metallic waste such as Al and Be. Hence, three geopolymers (based on blast furnace flags, metakaolin, and mixtures) have been selected to study the encapsulation of different types of RLOW, such as oils, organic solvents, scintillation cocktails, and decontamination liquids. Due to the nature of the RSOW (e.g., ion exchange resins, cemented and polymerized/bituminized wastes) and their current incompatibility with long-term waste management solutions, the physicochemical characteristics need to be modified. Within PREDIS, several treatments are investigated, promoting thermal processes. Subsequently, the treated wastes are embedded using similar types of geopolymers, as well as cementitious materials or glass coatings, but also densification processes (pelletization or hot isostatic press). Regardless of the type of waste studied, synthesis procedures are currently being finalized. Testing of these materials will be conducted by studying the matrix’s mechanical performance, durability under various conditions (acid and alkaline waters, endogenous conditions, and air), chemical durability, and resistance to radiation. Magnesium phosphate cements (MPC) are studied as the best conditioning solution for the encapsulation of reactive metallic wastes. They allow high protection of metallic waste from oxidation leading to hydrogen production. MPC optimization mainly includes raw material selection and cost reduction. The tested parameters include mechanical and chemical durability as well as resistance to ionizing radiation.

## 9 Conclusions

This paper describes the innovations coming from the three Euratom projects CHANCE, MICADO, and PREDIS for the characterization of RWP. The technologies developed or under development are described, but also the procedures and statistical approaches used to improve RWP qualification and its content. Better determination of the radiological content and physicochemical status of RWP are the key points for better handling and storage of the packages. Improving the current characterization results will not only help stakeholders and end users to reduce costs and operational work but will also help future generations and countries that will approach the process in the near future with more confident and reliable procedures.

## Conflict of interests

The authors declare that they have no competing interests to report.

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## Data availability statement

No data were generated and/or analyzed for this article that cannot be disclosed for legal, ethical, or other reasons.

## Author contribution statement

All the authors of this text are partners in, at least, one of the three projects described. Morichi, Fanchini, Breuil, Perot, and Bruggeman are the main contributors to the MICADO project description, for CHANCE we have Ricard and Perot and finally Niederleithinger, Bruggeman and Breuil have written the PREDIS part.

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# Development of guidance documents in the EURAD and PREDIS projects

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**Abstract.** Particular emphasis is dedicated to Knowledge Management activities within the EURAD (European Joint Programme on Radioactive Waste Management) and PREDIS (Pre-disposal management of radioactive waste) projects to ensure the capture of existing knowledge, transfer of knowledge between Members States and management of the knowledge for future generations. The EURAD project has three work packages dedicated to knowledge management. One of them, the EURAD Guidance work package (WP12) is developing a comprehensive suite of specific guidance documents that can be used by Members States with radioactive waste management (RWM) programmes that are at an early stage of development but can be beneficial also to more advanced programmes. The PREDIS project does not have a specifically allocated work package for guidance development. Rather, such activities are integrated within deliverables produced as part of the Strategic Implementation and State of Knowledge actions of the Roadmap contributions on predisposal waste management. The EURAD guidance work is based on the existing PLANDIS guide on RD&D planning, developed by the Implementing Geological Disposal of Radioactive Waste Technology Platform (IGD-TP). The guidance documents complement other documents prepared in parallel knowledge management activities inside EURAD project: the State of Knowledge documents. The differentiation is that guidance documents explain in more detail how the process can be established and performed, including illustrative examples. The guides are self-standing documents and integrated with the EURAD Roadmap. The target end users of the guidance are primarily programme owners and managers (i.e., governments/administrations, Waste Management Organisations, Research Entities and Technical Support Organisations) responsible for planning and implementing the RWM programme and the supporting RD&D activities at a national level, even though they might also be of use and interest to other interested stakeholders, such as representatives of civil society. To produce a first list of prioritised topics for guidance documents with the aim to select a topic for a pilot guide, the Guidance WP has developed a screening process that includes review by experts and end users. Based on the priority list, the first pilot guide was developed with the title "Cost Assessment and Financing Schemes of Radioactive Waste Management Programmes". Experience gained during the selection of topics for the pilot guide and during its production are being incorporated into the procedure for identification of new topics for which guides will be developed. First, the degree of coverage of the EURAD Roadmap themes by suitable guide documents will be analysed by the WP 12 team. The analysis will be combined with feedback from experts verifying the needs for missing guides. Finally, the potential end user community representatives will be given the opportunity to comment on the prioritisation of selected guidance documents and make additional suggestions. The potential end users stay involved also during the production of the guides. This procedure aims to optimise the scarce expert resources in relation to the identified needs of guidance documents. This article explains the approach for selecting topics for guidance documents and the results obtained both in EURAD and PREDIS.

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## 1 Introduction

Radioactive waste management (RWM) consists of a large multidisciplinary set of different tasks covering all administrative and operational activities involved in the handling, pre-treatment, treatment, conditioning, transport, storage and disposal of radioactive waste. Typically, RWM has a large time span overarching many decades. These characteristics of the RWM promote the importance of a systematic approach to identify, manage, share knowledge, and enable groups of people to create new knowledge collectively to help achieve safe management of radioactive waste. Activities ensuring this systematic approach are known as knowledge management.

Knowledge management (KM) – including knowledge consolidation – is recognized as a key part of the RWM implementation process and has gained increasing interest in the past 10 years.

The main reasons for the importance of KM are the RW disposal implementation time, spanning several decades, and the complexity and variety of disciplines involved. Each individual phase of a RWM programme from waste generation through processing, disposal, and repository closure, requires continuous RD&D development with improved process understanding.

EURAD supports the implementation of the Waste Directive in EU Member-States, considering the various stages of advancement of national programmes. National RWM programmes across Europe cover a broad spectrum of stages of development, inventories, and level of advancement, particularly with respect to their plans and national policy towards implementing geological disposal.

The PREDIS project targets the development and implementation of activities for pre-disposal treatment of radioactive waste streams other than nuclear fuel and high-level radioactive waste. It is possible to identify several roles which the KM could cover, but within the scope of the project they are closest linked to the technical work package development for characterisation and processing waste streams, as well as waste acceptance criteria (WAC) issues. The long-time span addressed by WM programmes is bringing the need for trans-generation knowledge transfer in all phases of implementation, from pre-disposal through disposal. Another role is to manage effective knowledge transfer inside the multi-disciplinary programmes. The KM is applied to knowledge transfer between different actors within a program or transfer between national RWM programmes themselves. Both EURAD and PREDIS are reactive and responsive while developing ideas for the KM and networking needs of their partner and stakeholder communities.

The KM activities are integrated with technical and strategic activities. This allows KM to benefit from the huge pool of expertise existing within the EURAD programme.

An example of an important programme output which is used not only inside the EURAD project is the EURAD Roadmap [1]. The EURAD Roadmap was prepared as a representation of a generic RWM programme that shall enable users and programmes to orient themselves in the whole area of RWM. The content is focused on what knowledge, and competencies (including infrastructure) is considered most critical for implementation of RWM, aligned to the EURAD Vision and to the EURAD Strategic Research Agenda. The EURAD Roadmap provides detailed information about themes, subthemes and domains and is an efficient tool to map different activities inside a RWM programme.

The Roadmap enables different activities to be linked to the overall RWM process. This addressing provides easier orientation for potential users when they are searching for information on how to start or manage particular activities, taking into account the current best practices.

In the PREDIS project all these items are covered by one work package (WP3), whilst inside the EURAD project there are three different work packages. In EURAD, one team collects existing information (WP11), the second one (WP12) prepares information on how to carry out RWM activities and the third one (WP13) deals with training and networking. The detailed description of the organizational arrangement of knowledge management inside EURAD is given in parallel articles [2–4].

The subject of this article is experience of preparation of guidance documents that are useful for national RWM programs.

In that sense, it is important to identify potential end-users' groups:

- the first group consist of end-users who need to start (or substantially change) a disposal programme implementation. This end-user group is characterized by low experience in a particular area. For this group it is important to get basic orientation. The exchange and sharing of knowledge between advanced programmes and newcomers to the topics is typical. Positive and even negative (if available) examples may be effective but should not be used without taking into account national circumstances. Guides targeted to this end-user are more general, usually covering broad subjects.
- End-users who need to manage knowledge in a relatively narrow area, usually within an established framework, are typical for the second group. Guides for this group are more detailed in a narrow topic. The level of detail and variance in national circumstances often make it difficult to provide guidance that is valid for multiple programmes.

With respect to the nature of the Joint European Programme end-users in organizations at an early stage of the RWM programme were approached to facilitate sharing and transfer of knowledge on "how-to do" different activities in RWM.

Needs are identified from a combination of identification of gaps using the Roadmap and Experts (top-down), and specific needs raised directly by the wider community of stakeholders (bottom-up). This has been done either via surveying the KM needs and gaps among organisations or by listing prioritised topics where gaps exist, or information is not sufficient.

## 2 Method

### 2.1 Selection of pilot guide

Within the EURAD Guidance Work Package (WP12), activities aim to develop a comprehensive suite of instructional guidance documents that can be used by various stakeholders in any country with RWM programmes, regardless of their status in geological disposal implementation.

The goals of the guidance documents are (a) to share existing experience and lessons learned and to assist transfer of knowledge towards Member States with early-stage RWM programmes, as well as (b) transfer of knowledge between generations. Both goals are objectives of EURAD's Vision [5].

Guidance documents can facilitate orientation in the field itself (existing knowledge resources and existing international cooperation and networking) as well as to foster understanding different solutions in different cases and countries.

The main priority of the Guidance WP has been to identify a list of the most needed and prioritised topics of guidance documents from which a topic for a pilot guide could be selected. This included considering topics where there is access (within EURAD) to suitable experts from Member States with an Advanced Programme (AP) who could contribute to the Guidance development.

A pilot guide was compiled to test the guidance development process (and the quality management procedure). The EURAD Roadmap Advisory Committee consisting of experts from AP, proposed areas where expert knowledge of programme history would provide useful strategic guidance to new or early stages programmes. The short list consisted of the following topics:

- funding and financing aspects of radioactive waste disposal.
- Optimization of disposal of radioactive waste.
- Derivation of requirements for the disposal system.
- Waste Acceptance Criteria (reserve).

The Guidance WP team finally proposed the topic of 'Funding and Financing Aspects of Radioactive Waste Disposal' (Domain 1.3.1 [1]) to be developed as a pilot guide as the time and the readiness of resources for its timely development was assessed as reasonable.

### 2.2 Developing further guidance

For future guides to be developed in EURAD the simplified approach – implemented for selecting the topic of the pilot guide – will be complemented by following two strategies, the top-down and bottom-up approach. The bottom-up approach at EURAD level means that the selection process is carried out based on the EURAD Roadmap and the needs for further guidance are identified by the systematic evaluation of the themes, sub-themes and domains. This is implemented using input from the available literature, from experts who have experience from the implementation process and feedback from the potential end-users.

The top-down approach means that experts (selected based on their experience and knowledge accumulated in their respective fields of activities) identify where guidance is needed but not available.

Based on the result of this activity and the ongoing evaluation of end user needs and feedback, the approved list of prioritised topics will be regularly updated as a 'living document'.

#### Analysis of existing guidance literature

The mapping started by establishing a starting reference point related to the mapping of the available guidance and guide-like technical documents, through a detailed literature search of:

- international regulation documents (ICRP and WENRA);
- international guides (IAEA);
- international guide-like technical documents (IAEA, OECD NEA, EC Projects);
- national guides;
- national guide-like technical documents.

Other main sources for the mapping have been EURAD partners' courses and international nuclear entities.

Open web was searched to complete the "big picture" of geological disposal materials.

Based on the survey it was concluded that although the available technical documents and guidance are numerous, early-stage programmes or small inventory programmes often face a challenge of information overload and deciphering which sources of information are most accurate and most recent, thus the guidelines aim at providing concise references to orient the reader.

#### Selection criteria

For selecting guidance topics some basic criteria were defined, clearly linked to and coherent with the EURAD founding documents (Vision document [5], EURAD Roadmap [1] and Strategic Research Agenda [6]):

- interaction with EURAD WPs: are there any outputs from EURAD already available to be used for guidance development? How and to what extent are they used?
- clearly demonstrate European-added value (improved information and knowledge transfer between national programmes and across generations);
- be meaningful, focused and manageable;
- is that any identified guidance gap;
- each contribution should bring complementarity (avoid duplication, keep clear of disconnected, spread or repeated contributions);
- responsive to the end-users needs and expectations (effectively assists the targeted end-users in their programme implementation, i.e. be need-driven);
- importance (it should be evaluated how big an area of the Roadmap is covered by the topic, which more or less correlates with the aspect of how significant a role the given topic has in RWM programme implementation);

- urgency in terms of programme implementation stage (in what stage of RWM programme development should the guidance be implemented, when should the guidance on the given topic be ready for the target end-users);
- expertise (how much expertise is necessary for the development of the given topic outside from Guidance WP, or outside from EURAD);
- length of development (based on the preliminary assumptions how lengthy could the process of development of the guide be).

There are multiple options of materials available for selection that potentially meet the selection criteria and the guidance will be used to identify the strengths and weaknesses of the options. One may want to create early buy-in amongst a wider range of end-users by engaging them in the selection and development process. There is a longer time frame for the decision-making process that allows for a more thorough selection process.

### Topic selection

On the basis of this long list the Guidance WP team members prepared some topic proposals. The short list consists of the following topics:

1. using the safety assessment as a tool to derive requirements for the disposal system elements;
2. role of implementer in planning and managing repository development programme;
3. developing strategy for data management and preservation of records and knowledge in the context of radioactive disposal programme;
4. using the safety case (and safety functions) to prioritize geological disposal RD&D plans;
5. developer/implementer and regulator interactions during the planning, siting, engineering design, RD&D and construction of disposal facilities;
6. managing interactions in multidisciplinary teams (engineers, geoscientists, sociologists; physicists; modellers, lawyers etc.);
7. establishing and managing programme requirements and how these need to be is linked to the findings of the RD&D programme;
8. developing the design basis for a geological repository;
9. assessing the acceptability of site conditions for the location of a geological repository;
10. characterization of high-level waste at different management stages.

The list was evaluated against predefined selection criteria based on the expert judgement of the Guidance team members in a qualitative and semi-quantitative way.

Each team member could score the topic proposals and the results were discussed at the WP web-meeting. It was emphasised that for any guidance document it shall be ensured that it provides an added value to the target end-users (needs driven) in an area, which is not covered by existing guidance (avoid duplication). Feedback from the potential end-users will also be sought for prioritization suggested topics. Final list of selected topics will be approved by EURAD General Assembly.

After having the topic for the guides approved, experts with relevant experience in the given area will be selected to assist the Guidance WP team in the elaboration of the guidance.

Further guides will be elaborated in current EURAD project in collaboration with experts with experience on the given topic (who 'have done it before'). Experts from countries with different status of geological disposal implementation are going to work together, which will create a network of experts (effectively contributing to knowledge transfer at EURAD level).

In the case of the PREDIS project, guidance development so far has been especially focussed in one specific topical area for Waste Acceptance Criteria (WAC). This has been dealt with using the goal of developing a suite of guidance documents for (i) the selection of optimal methods for the determination of WAC parameters, (ii) principles and procedures regarding the qualification of waste forms for storage/disposal, and (iii) formulation of generic WAC whenever a disposal system has been missing. Information about national experience collected from a number of countries worldwide [7] is being converted into a set of practical advice on establishing the mentioned aspects of a national waste acceptance system. There are also additional guidance documentations that will be part of other technical deliverables within the work packages addressing treatment and processing of waste. However, these are not stand-alone documents within the Knowledge Management part of the PREDIS structure. The format of guidance for PREDIS is more incorporated into the overall knowledge management that is provided through training tools, such as Domain Insights, case studies of best practices and lecture materials that target specific issues in predisposal waste management that are not already covered by other sources, such as the IAEA e-learning modules and Wiki.

## 3 EURAD guideline production

The EURAD Guidance team adopted the Quality Management Procedure for Guidance Development [8] where the quality principles and procedures to be taken into consideration while producing and updating guidance documents for RD&D activities in RWM are outlined. The aim of such a procedure is to set the requirements for a quality management system targeted at production of any guide document to ensure quality, inclusiveness and transparency during its elaboration, further improvement, and implementation. Among others this includes:

- quality assurance (QA) criteria for elaboration of RD&D Guides to be developed in the framework of WP 12,
- quality requirements how RD&D Guides should be developed, maintained and used according to the QA criteria,
- consultation and review process during the development of the RD&D Guides.

## 3.1 QA criteria for production/update of guidance documents

Few norms specify how quality, inclusiveness and transparency is assured in a guidance document. Especially, the criteria for selection of authors and guidance production are considered to be relevant for the development of any RD&D guide within EURAD.

### 3.1.1 The competencies of authors

The authors should have experience and competence for the development of particular guidance document, in line with the scientific area the given guide covers. It is an important quality criterion that the authors of any RD&D guides should have wide experiences and highly qualified competencies to the covered topic.

The authors can be experts having wide experience in RD&D planning, individuals, representing WMO responsible for the development of RD&D plans and Technical Support Organisations (TSO), involved in the reviewing process of these plans and Research Entities (RE), involved in the execution of RD&D activities. End-users of RD&D Guides from early-stage programmes and small inventory programmes participating in disposal should be involved in the drafting process of the RD&D Guides as well.

### 3.1.2 Procedure for selection of authors

The procedure of selection of authors for a given RD&D guide should be compatible with the general EURAD rules and it would apply within the Guidance work package.

### 3.1.3 Guidance production criteria

The guidance production criteria have been developed from a list of the scope of criteria for evaluating the overall EURAD Programme and are given in EURAD Quality Management Plan (QMP) [8]. Most important are:

- to support the overall EURAD Roadmap [1], EURAD Vision document [5] (and also Strategic Research Agenda [6]),
- to be ambitious, creative, innovative, and address key needs of End Users with Programmes in Early Stage and with Small Inventories,
- to reach a major impact of the RD&D area of the procedures at relevant phases,
- to systematically outline the set of activities to be implemented,
- to demonstrate procedures intended to be used to attain the stated objectives,
- to describe clearly how appropriate they are for the planned activity and their feasibility,
- to identify the most significant steps to achieving the stated objectives and explain how these will be addressed,
- to show clearly how meaningful and independent peer review can be integrated within the overall implementation plan on a timely basis.

### 3.1.4 Lessons learned on QA from pilot guide development

As there is an expectation of the highest quality of guidance, the process of its development shall comply with all quality assurance requested in the “EURAD Quality Management Plan” [8] and the “Quality Management Procedure for Guidance Development” [4]. The guidance selection process also must comply with the “Approved list of prioritized topics for further guidance documents and selection process of one topic for the development of a pilot guide” [9].

The quality management procedure consists of the requirements for a quality management system on guides production with special emphasis on the quality assurance criteria, quality requirements on guides development and utilisation. The high importance is given to the reviewing process during the guide production.

The whole process must be performed in a close cooperation with the EURAD Chief Scientific Officer, Bureau/PMO and the Editorial Board, ensuring a thorough review process, transparency in guides topics selection and a requested quality of guidance content. All selected topics must be approved by these EURAD governance bodies and EURAD General Assembly members.

## 3.2 Guidance production procedure

Development and approval of a guide is performed in several steps. These steps include initiation, drafting, peer review, finalization, approval and “socialization”.

At the “Initiation” step the Terms of Reference (ToR) is developed by WP12 team and approved by Bureau/PMO. The ToR defines the whole process of development of the guide, including topic justification and selection based on the performed gap analyses and the interest from the target end users. In the ToR there is clear definition of the scope of the guide, the timeline, responsibilities (and their distribution between authors, reviewers, other experts and end-users), requirements in volume and contents, etc. In this step special attention is devoted to the clarification of tasks for the individual authors, confirmation of the guide development schedule and organization of a kick-off meeting(s) between the authors.

At the “Drafting” step, detailed development of structure and contents of the guide is completed with identification of reliable and trusted sources of information (e.g. IAEA, EC and international projects, IGD-TP, SITEX Network, EURADSCIENCE). The writing of the guide is performed based on the collection of information from the identified sources according to the established structure and contents of the guide. In the ToR the supporting experts' team and end-users are identified and consulted to incorporate their feedback. Finally, draft guide is submitted to Bureau/PMO for peer review.

The “Peer review” step includes independent review of the draft guide organized by Bureau/PMO (including selection of reviewers) and submission of Bureau/PMO feedback to the development team.

The “Finalization” step comprises of revision of the guide according to comments and recommendations received from the peer review, agreement of finalized guide by Guidance WP and submission of finalized guide to Bureau/PMO for approval. At the "Approval" step the final checking the management of reviewer comments or statements by Bureau/PMO and approval of the guide by Bureau/PMO is done. During the "Socialization" step distribution of the guide among Communities of Practice (CoP) is performed including the collection of feedback to be used for future revision.

### 3.3 Consultation, incorporation of feedbacks and final reviews

Consultation with experts and target end-users during the development of a guidance document can bring significant inputs to the deliverable and as a result, can increase its quality. Consultations with PMO representa- 121
tives/coordinators on the objectives and scope of the given Guide is important to be in line with the general expectations of EURAD. Consultation can be organized especially with Bureau (College representatives), end-users representatives or other EURAD WPs including KM WPs.

When a guidance document is developed in such details that the usability and applicability (whether the document meets the pre-defined goals) can be tested, the feedback from some potential end-users can be asked. Potential end-users of guidance documents can be representative of mandated actors (WMO, TSO, RE) from Advanced Stage Programme (AP), from Early-stage Programme (ESP), from Small Inventory Programme (SIMP) Member States in line with the scope and topic of the given guide. The potential ways of obtaining feedback concerning a draft guide could include asking independent views about the applicability of the given guide, organizing events for the end-users to identify collective viewpoints, compiling questionnaires for dedicated topics.

## 4 Pilot guide and lessons learned

### 4.1 Objectives of the pilot guide

The first guide produced (pilot guide) was on "Costing and Funding" for implementation of a radioactive waste disposal [10].

Cost estimations are needed for all projects, programmes and operations. Information on this topic is abundant, and guidance on various approaches and methods is widely available. However, the estimation of the costs of disposal programmes remains challenging due to their complex and societally sensitive nature and long implementation periods, and practical guidance on this issue remains insufficient.

Countries that are just starting to develop their disposal programmes and which have little or no experience in this area may have difficulties in finding the relevant advice on how to perform cost estimations. This guide aims to describe the cost estimation process specifically focusing on radioactive waste disposal programmes, and to provide practical advice on how to conduct this process to result in a consistent, reliable and well-documented cost estimation.

The guide suggests a stepwise approach to costing to make the whole process more transparent and easier to manage. The steps are interdependent and logically cover all the important phases in the cost estimation from defining the purpose and scope of the estimate, selecting the method and obtaining the input data, to performing the cost estimation and the consideration of, including suitable approach to, addressing cost uncertainties and risks management.

The guide also addresses possible mechanisms for financing disposal of radioactive waste. Since details on various financial mechanisms can be found in a number of documents this guide describes only the financing of RWM activities from a pre-collected fund, which is the most commonly applied method.

The intended end-users of this guide include primarily waste management organisations (WMO) or designated organisations if no WMO has yet been established in small inventory programme and early-stage programme countries (including countries that are initiating a new-build nuclear programme), which are, in most cases, responsible for conducting the cost calculations for their respective national programmes. The guide may also be beneficial for those entities (ministries, regulatory bodies and/or their technical support organisations) responsible for reviewing the cost calculations or those obliged to implement the "polluter pays" principle (e.g., waste generators).

The target audience may also include project managers and costing experts (who establish, revise and justify estimations) and those entities which are responsible for financing the national RWM programme.

### 4.2 Scope of the pilot guide

The guide focuses primarily on the cost assessment methodology for geological disposal, but with certain adaptations it can also be applied to near-surface or borehole disposal programmes since the principles are the same and, from this perspective, the guide may also be beneficial for small inventory disposal programmes.

The report provides general guidance on developing a cost estimation for radioactive waste disposal programmes, including more detailed advice on using a structured approach.

Initially, the guide explains the necessary prerequisites and boundary conditions for the disposal programme and its cost estimation, and emphasises the importance of a national RWM policy and national RWM programme, the existence of a national legislative framework and waste inventory, stakeholder engagement, etc.

The guide provides a brief description of each of these steps including information on additional literature that contains more detailed information.

In the guide the cost assessment of the disposal programme is described as a process consisting of several steps, starting with defining the purpose of the cost estimation, the scope of the work and the timing of activities included in the estimation, selecting the appropriate method for cost estimation, and preparing the Work Breakdown Structure (WBS) as a framework for a detailed cost estimation. After performing the cost estimation, the process also includes the analysis of uncertainties and risks in cost assessment and provisions for addressing them as well as thorough documenting of the whole process to provide traceability and performing an independent review of cost estimate to establish confidence in the estimate.

In the guide each of these steps is briefly described and wherever possible additional guidance referring to geological disposal provided. Specific attention is given to the development of the WBS as an essential and practical tool for performing the detailed cost assessment. Based on several disposal programmes and their respective WBSs an attempt was made to summarize the approaches and develop a more generic WBS for geological disposal that would be useful for countries and organisations that have just embarked upon or plan to launch the cost estimation process in the near future.

Similarly, when considering the uncertainties and risks in cost estimation of the disposal programme, the guide provides information on the most common uncertainties and risks in geological disposal (GD) programmes and suggests how they might be addressed.

The guide emphasises that the cost estimation is an iterative process that requires regular updates and improvements in the input data, as well as transparency and quality assurance in the cost assessment process and the data and information management systems.

### 4.3 Benefits for users of the pilot guide

Potential users of the guide may find beneficial the presentation of a practical example of how the work scope of the geological disposal programme could be broken down into smaller, meaningful elements and hierarchically organised in the form of a WBS, and a discussion on the possible cost uncertainties and risks related to the various WBS elements of geological disposal programmes.

The presentation of selected lessons learnt and experience obtained from the cost estimation processes in a number of national programmes may also be helpful for gaining a better understanding of the process.

The potential users may also find very useful several examples of cost estimations for various aspects of the disposal programme from different countries (e.g., Hungary, Slovenia, Czech Republic) that are included in Appendices as illustrations of how cost estimations are performed in practice.

### 4.4 Lessons learned

The crucial aspect of the guide production process is a mutual interaction with potential end users which can ensure a complementarity of selected topics and end users needs on guides development. With respect to this, the first short priority list of selected topics developed by WP12 has been communicated with a group of potential end users what provided a valuable contribution to the WP12 team when selecting topic for pilot guide.

Within the process of guidance development, an interaction with international entities is recommended (e.g., the IAEA and NEA) with special emphasis on already published or planned guides. Also, other relevant documents (technical, strategical, methodological, etc.) from publicly accessible sources has been considered and evaluated during a gap analysis leading to the topics selection.

This approach has been consistently applied within pilot guide topics selection and its subsequent development. The feasibility of the guide production process from a technical point of view and the expected timescale has been demonstrated, thus the process can be applied for the next guide production. In addition to the urgency criterion, the accessibility of the experts contributing to the guides must be seriously taken into account when selecting the next topics for guide production. With respect to the demanded experts limited availability, the EURAD cooperation with PREDIS can be highly recommended for planning further RD&D programmes as both projects have available large spectrum of experts.

## 5 Conclusions

EURAD as a European Joint Programme in the field of RWM research is managing three Knowledge Management WPs (WP11, WP12 and WP13) contributing to the expected KM goals. Within PREDIS, there is one KM WP (WP3) for all KM, closely working with other PREDIS WPs. During implementation of both projects, we begin to coordinate our activities to avoid potential duplication (e.g. EURAD WP12 excluded guide on waste acceptance criteria from its list as it is foreseen in PREDIS activities). The initial informal coordination was developed to more formalized form as EURAD and PREDIS representatives signed Joint Statement on knowledge management in 2021 [11].

EURAD WP12 is contributing to the KM through developing a comprehensive suite of instructional guidance documents that can be used by every interested end user involved in the RWM programmes, preferably those in early stage of its implementation and/or dealing with small inventory, but guidance documents developed within WP12 could be beneficial for advanced programmes as well.

KM should represent an integral part of all RWM programmes in order to support their efficient establishment and successful implementation during all programme phases. The main goal is dedicated to the knowledge enhancement and transfer between involved stakeholders/institutions, possibly between national RWM programmes and, in particular over generation to contribute to the RWM programme sustainability. KM should be considered already from the phase of conceptual planning of the programme. It needs to be implemented as soon as feasible to be an integral part of radioactive waste disposal implementation process.

The necessity of KM integration into RMW programmes, including RD&D, is also identified through the EURAD Founding documents (EURAD Roadmap [1], Vision Document [5], Strategic Research Agenda [6], Deployment Plan [12]), in the field of radioactive waste disposal and complemented with PREDIS KM strategy dedicated to the pre-disposal activities.

The produced pilot Guide on Cost Assessment and Financing Schemes of Radioactive Waste Management aims to fill identified gap and orient the early stages RWM programmes including those programmes dealing with small inventories on how to plan budget activities with special impact on radioactive waste disposal. This pilot guide may contribute to the learning process on costing strategy and methodology as well as on establishing and operating a funding scheme. The experience gained during the drafting of the pilot guide can serve as a sound basis for the development of further guides the topics of which will be defined based on a systematic and transparent selection process.

## Conflict of interests

The authors declare that they have no competing interests to report.

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## Author contribution statement

Mr. Peter Ormai prepared the basic version based on the initial discussion. The PREDIS detail were provided by Anthony Banford and Erika Holt. The EURAD details were provided by Bálint Nös, Peter Ormai, Nadja Železnik, Irena Mele, Paul Carbol, Jitka Mikšová and Jiří Faltejsek. The article was produced as teamwork with participations of all co-authors.

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REVIEW ARTICLE OPEN ACCESS

# Long-term radionuclide retention in the near field: collaborative R&D studies within EURAD focusing on container optimisation, mobility, mechanisms and monitoring

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**Abstract.** Within EURAD, targeted collaborative research activities are performed to further deepen understanding regarding the long-term behaviour of key components in the repository near-field, assess specific radionuclide retention processes as well as developing methods for monitoring safety relevant parameters of repository systems. The ambition of the four EURAD Workpackages (WPs) – CONCORD, FUTURE, CORI, MODATS – presented here, is to investigate topics to meet implementation needs and contribute to Safety Cases in Europe at the highest level of scientific excellence. Work is fully integrated into the EURAD concept, emphasizing interactions between different WPs, involvement of End Users, assuring the link to national programmes and contributing to overarching features like Knowledge Management, Training and Education, or European Integration. Comprehensive initial State-of-the-Art reports were prepared by the WPs or currently under development and are available at the EURAD website. The technical/scientific work performed in the four WPs - CONCORD, FUTURE, CORI, MODATS – is discussed in this contribution.

## 1 Introduction

In the development phase of each of the four EURAD Workpackages (WPs) CONCORD, FUTURE, CORI and MODATS, presented here, topics were jointly identified by Waste Management Organisations (WMOs), Research Entities (REs) and Technical Support Organisations (TSOs) which could be significantly advanced by a joint research effort performed at the European level. Within the integrated research concept in EURAD, each WP focusses on specific important sub-topics. CONCORD contributes to the optimization of container performance and of its assessment and evaluates novel container materials. FUTURE investigates the transport and retention mechanisms of radionuclides and provides mechanistic models for reactive transport simulations in real clays and crystalline rocks necessary for performance assessment studies. CORI research improves understanding of the role of organics and their influence on radionuclide migration in cement-based systems with high organics inventories, being mainly relevant to L/ILW waste disposal. MODATS works to consolidate the implementation strategy for monitoring systems by developing methods through which confidence can be demonstrated in the data acquired and benefits derived for repository implementation.

In this overview paper, examples from the ongoing research programs in CONCORD, FUTURE, CORI and MODATS are used to highlight research tools, strategy and results in each work package. The research is put into context by stating the motivation and fundamental technical/scientific challenges driving the WPs, as well as indicating potential relevance of the studies in view of potential applications in repository programs and the Nuclear Waste Disposal Safety Case.

## 2 CONCORD – Optimisation of SF/HLW container performance and the tools available for its assessment

The containers (or canisters) for the disposal of spent fuel and high-level waste are the only barrier providing absolute containment of radionuclides for a certain period of time in the overall multi-barrier disposal system of a deep geological repository. As such, the duration of

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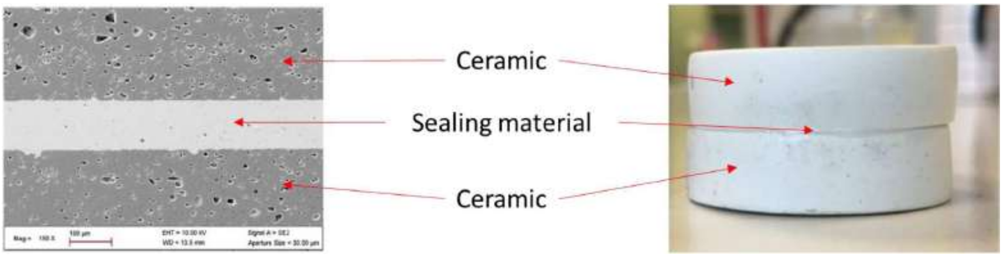


**Fig. 1.** SEM micrograph of the interfaces between the seal and the ceramic parts (left) and photo of a sealing test (right). (Courtesy of I. Cornu and F. Rossignol, IRCER, Université de Limoges).

their primary barrier function depends on the time until they breach or their lifetime. SF/HLW disposal containers have been developed to varying degrees of maturity in many national programmes. Primarily, existing canister concepts have been either steel-based or dual material concepts based on an outer copper shell or coating and inner cast iron or steel structure. In several instances, detailed performance assessments supporting Safety Cases have been done, demonstrating that manufacturing long-lived SF/HLW disposal containers is feasible and can satisfy the safety-related requirements. In parallel, there is widespread interest in repository component optimisation. The systematic exploration of novel materials, while placing existing solutions in a broader context, can provide a solid state-of-the-art for the pursuit of container optimisation according to geologic, inventory and regulatory environments of each national programme. Furthermore, an improved ability to predict container lifetimes can reduce conservatisms and support future Safety Cases.

The goal of WP ConCorD (Container Corrosion under Disposal conditions) is to explore the potential of container optimisation, focusing on long-term performance. Another goal is to improve available performance assessment tools, thus making canister lifetime prediction more accurate and robust. More specifically, ConCorD aims to:

- explore the performance optimisation potential of novel container materials and design within the engineered barrier system.
- Deepen the understanding of coupled interfacial processes influencing container performance under repository-relevant conditions, with a focus on:
  - irradiation-accelerated corrosion,
  - microbially-influenced corrosion,
  - corrosion during nearfield transients.
- Improve performance assessment by demonstrating a mechanistic understanding of relevant processes and developing accurate and robust predictive models.

### 2.1 Novel materials

The main goal is to explore the potential of novel materials and processes for optimising long-term container performance. After the first selection of the most promising materials, experimental studies contribute to understanding corrosion/degradation processes. The ongoing work is organised according to two main types of materials: ceramic and metallic materials.

For containers made of bulk ceramics, silica-alumina and silicon carbide are the most promising material options. The key properties for long-term performance are fracture toughness and leaching/alteration, while the key step in manufacturing is the final seal. Within ConCorD, the materials (core-shell ceramic glasses) and processes (microwave heating) for sealing silica-alumina containers are studied (see Fig. 1). The leaching properties of the seals are determined as well as the evolution of the mechanical properties of the assemblies before and after leaching in porewater. SiC doped with Cr is assessed as a bulk canister material, with a primary focus on determining the microstructure and physico-chemical properties of these new ceramic composites. Ceramics can also be employed as thin films acting as corrosion barriers to protect an underlying metallic substrate. In this application, a critical parameter for long-term performance would be the absence of porosity and defects. Research is focused on developing $TiO_2$ and CrN coatings deposited by physical vapour deposition (PVD). Corrosion tests can support material selection and validation of the application of ceramic coatings for SF/HLW containers.

In the field of metals, the focus is on implementing innovative solutions for metallic anti-corrosion coatings and optimised bulk metallic options. For metallic coatings, Ti, Cr and Cu obtained by PVD and novel copper/alumina composite coatings deposited by cold spray are developed and studied. The novelty of metallic/ceramic composite is the ability to use nitrogen as carrier gas and the expectation of decreased porosity and improved adhesion. For all coatings, deposition parameters optimisation is followed by corrosion studies performed in repository-relevant conditions. For bulk metals, the focus is on optimising bulk copper alloys for the KBS-3 concept and, more specifically, on the effect of impurities on corrosion properties. The uptake and diffusion of hydrogen and its interactions with the matrix and the possibility of micro-galvanic corrosion due to impurities are studied. The relationship between hydrogen diffusion into the matrix, creep rate, and SCC crack growth is assessed by complementary experimental testing and molecular dynamics (MD) simulations.

### 2.2 Corrosion under irradiation

The research done within ConCorD assess whether irradiation influences the corrosion of canister materials under disposal conditions. To reach this goal, it is necessary to identify the critical parameter that determines the irradiation-induced material degradation. Once this is identified, appropriately designed irradiation-corrosion experiments under representative disposal conditions mimicking different periods of the typical repository evolution are performed.

For the identification of the critical irradiation parameter, experiments in simplified model systems that cover 4 orders of magnitude in dose rate leading to total doses spanning 2 orders of magnitude are ongoing. The experiments include unirradiated controls and explore carbon steel, copper and, to a limited extent, novel container materials. To complement the simple bulk solution environments, experiments are conducted in the presence of compacted bentonite, with different degrees of saturation, and over a range of temperatures. The expected outcome will be a definitive statement regarding the relative importance of dose rate and total dose on the corrosion behaviour of canister materials over various environmental conditions.

As a second step, conditions representative of the repository will be explored. More specifically, the potential influence of (i) the type of bentonite used, (ii) the nature of the irradiation source, (iii) the effect of saturation, and (iv) the dose rate at which there is no significant effect of irradiation.

## 2.3 Microbial effects on corrosion

The main goal is to elucidate the role of microbes in corrosion in the context of nuclear waste disposal. Sulfate-reducing bacteria have long been the focus of this type of investigation as their activity is expected to release sulfide. But a more comprehensive approach that includes molecular tools to probe the microbial community and targeted cultivation is needed, along with carefully designed experiments to isolate specific factors and document their impact on microbial activity and the resulting corrosion.

In particular, the topics addressed are: (i) how irradiation controls microbial survival in bentonite, (ii) the fundamental mechanisms underlying the dry threshold density that inhibits microbial activity, and (iii) the role of $O_2$ persistence in the inhibition of the growth of sulfate-reducing bacteria in bentonite.

Previous work on irradiation and microorganisms (for instance, in MIND) has focused on the role of irradiation in changing the bioavailability of organic carbon in refractory compounds. In ConCorD, the goal is to evaluate the role of multiple stressors (including irradiation) on the activity and viability of microorganisms in bentonite. The aim is not necessarily to identify a survivability threshold but rather to decipher how repository conditions will impact the potential microbial generation of sulfide in bentonite. Of particular interest is the impact of dose rate vs. total dose on microbial activity and survival. The experimental system consists of compacted bentonites in which metal coupons are embedded and subjected to long-term low-dose or short-term high-dose irradiation. This work will allow the integration of the impact of irradiation on bentonite and on the corrosion of that microbial community. These experiments integrate microbial community characterisation with the characterisation of the bentonite pre- and post-irradiation.

Furthermore, bentonite characteristics and their impact on microbial activity are tackled. It is well established that dry density correlates with microbial survival in bentonite, but the underlying mechanism constraining microbial activity is not well understood. Thus, several systematic experiments are carried out with varying dry densities. A cell containing compacted bentonite is exposed to $H_2$, and the bentonite microbial biomass is measured through a DNA concentration proxy to establish the dry density threshold at which no growth occurs. In addition, the particle size distribution will be varied for the same dry density to test the hypothesis that pore size distribution is a determinant of microbial growth. Characterisation of the rate of metal corrosion and the change in the microbial community will provide an understanding of the role of dry density in corrosion.

Previous work has shown that compacted bentonite exposed to an anoxic environment for several years still harbours a majority of viable aerobes while no sulfate-reducing bacteria are detected by molecular tools. Thus, the hypothesis is that oxygen persists in the pore space and/or on the surface of bentonite, allowing for the persistence of aerobes and inhibiting the growth of anaerobes such as sulfate-reducing bacteria. The goal is to evaluate the role of $O_2$ in shaping microbial activity in bentonite. Bentonite that has undergone various treatments and in which metallic coupons are embedded can be deployed in situ. The bentonite pre-treatments will result in varying amounts of residual $O_2$, thus presumably impacting the growth of anaerobic microorganisms.

## 2.4 Corrosion under transients

As the durability of waste containers is strongly related to the evolution of the environmental conditions during the repository lifecycle, work is dedicated to corrosion during redox, hydraulic, and thermal nearfield transients. Those transients lead to chemo-mechanical interactions between the container material or coating (if present), corrosion products and buffer. The effect of evolving redox potential, chemical conditions, temperature, bentonite saturation and gas evolution, both in laboratory and in-situ, are the main key processes studied to address existing uncertainties and provide relevant experimental data to adequately account for these processes in performance assessment. The experiments are focused on the effect of representative processes, where at least one parameter can change with time. A systematically coordinated approach by the various partners allows the exploration of a wide range of conditions and container materials.

## 2.5 Integration

The main goal of this activity is the synthesis of the newly acquired knowledge into a form applicable for container performance assessment considering the specific needs of the Safety Cases developed by implementors. This will be based on the experimental evidence acquired in the research activities described above and the modelling of the experimental observations of processes occurring at the container-oxide-buffer interface. This will demonstrate a mechanistic understanding of ongoing processes and support container lifetime predictions for traditional and novel materials. Integrating the experimental outputs leads to developing coupled models considering transient thermo-hydro-mechanical-chemical-biological phenomena at a relevant scale. This will be a supporting tool when integrating the container as a barrier in performance assessments, especially when addressing the relevant timescales and the probabilistic nature of the involved phenomena.

Further development of existing modelling frameworks will enable coupling geochemical models, solute transport, water radiolysis, heat transfer, variable saturation, microbial activity, and electrochemistry. They can be used to rationalise the data generated within the project with the intent to increase the system understanding of the interface between bentonite barriers and metals in a geological disposal framework.

Finally, to ensure that ConCorD outputs are useful for performance assessment performed by implementors, research output will be integrated with the broader scientific basis and the ongoing treatment of container degradation in performance assessment. The focus is on providing the technical steer and evaluating the implications highlighted by the coupled modelling activities described above using technical literature and considering how the relevant processes are treated in Safety Cases.

## 3 FUTURE – research towards fundamental understanding of radionuclide transport in crystalline and argillaceous rocks

The radiological impact of a repository is one of the central criteria for the safety assessment of repository systems. Reduced mobility of the radionuclides in porous media due to the tortuosity of the transport path and the strong interaction of radionuclides with mineral surfaces are the main pillars contributing to repository safety [1]. Low permeability argillaceous and crystalline rocks are considered appropriate geological formations for the deep underground disposal of spent fuel and high-level radioactive waste in several European countries. The work package FUTURE deals with radionuclide retention and transport in repository systems, with particular emphasis on processes and in situ conditions relevant for the near and far-field repository for high-level waste. Many disposal concepts foresee the disposal of high-level waste and spent fuel in thick-wall cast-iron casks surrounded by clay-rich buffer material. It is anticipated that corrosion processes in the repository nearfield will make an important contribution to the evolution of the in situ conditions in the repository nearfield at the time scale relevant for the corrosion-induced breaching of disposal casks followed, eventually, by the release of the radionuclides due to interaction with pore water. The scope of the work package FUTURE is specifically tuned to address these aspects from different research perspectives.

To address the safety relevant aspects of radionuclide retention, work-package FUTURE is thus organised into two main tasks: (1) MOBILITY, comprising work on diffusion-dominated mobility of radionuclides in compacted clay and the transport mechanism of radionuclides in crystalline rock, including reversible and irreversible sorption phenomena (2) REDOX, comprising work on redox reactivity of radionuclides on mineral surfaces. In particular, the surface-mediated redox reactions on iron oxides and Fe-rich minerals formed during corrosion processes are investigated.

Based on already available knowledge obtained in the past for the simplified "model" systems, the FUTURE project seeks fundamental insights into the impact of chemical boundary conditions and the role of microstructures on radionuclide speciation and mobility in "real" clay rocks as well as crystalline rocks. FUTURE aims at the quantitative and mechanistic understanding of the impact of (i) specific surface properties of materials (diffusive double layer, surface potential), (ii) the role of grain boundaries, (iii) the effect of water saturation, content and chemistry (pH, ionic strength) as well as (iv) the impact of pore size variability and heterogeneity on the mobility of chemical species. Our study delivers a refined understanding of the relation between fracture/pore structures and transport as well as the feedback of mineral reactions (dissolution/precipitation, clogging) on pore structure and connectivity. Eventually, the project closes knowledge gaps regarding sorption reversibility, uptake mechanisms (adsorption vs. incorporation, precipitation), sorption competition and surface diffusion. Particular focus is aimed at fundamental understanding and thus reducing uncertainties of surface-induced (heterogeneous) redox processes with regard to coupled sorption and electron transfer interface reactions governing the retention of redox-sensitive radionuclides at Fe(II)/Fe(III) bearing minerals surfaces.

### 3.1 Chemical analogy and transferability of data from compacted to dispersed systems

Safety assessment scenarios considering pore water interaction with spent nuclear fuel indicate that $^{226}$Ra can become a main contributor to the total dose after $10^4$–$10^5$ years of waste disposal. Retention of $^{226}$Ra is often considered by co-precipitation or recrystallisation of Ba-sulfate minerals. It can be expected, however, that $^{226}$Ra is also absorbed by smectite minerals. Due to a limited number of experimental data, Ba is often used as a chemical analogue for $^{226}$Ra. To test the chemical analogy of Ba with respect to sorption behaviours of $^{226}$Ra on montmorillonite, a parallel set of experiments were carried out for Ba and $^{226}$Ra systems [2]. The experimental sorption isotherms obtained at fixed pH and ionic strength, as well as the pH edges at varying ionic strength, indicate that the assumption of the chemical analogy of $^{226}$Ra and Ba does not always hold for sorption on montmorillonite. Available experimental data could be modelled by a combination of cation exchange reactions which dominate the uptake in a broad range of chemical conditions, and a surface complexation reaction

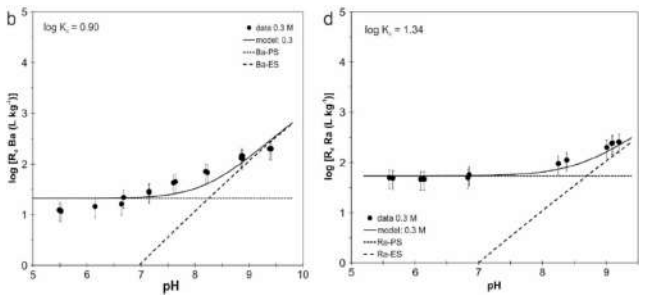


**Fig. 2.** Experimental and modelling results for pH-dependent sorption edges of Ba (left, b) and $^{226}$Ra (right, d) on *Na-SWy-2* in 0.3 M NaCl background electrolyte. Ra/Ba-PS = planar sites; Ra/Ba-ES = edge sites (modified after Klinkenberg et al. [2]).

on the amphoteric edge sites, which need to be considered to obtain the best-fit surface complexation constant at high ionic strength and high pH (Fig. 2).

Further ongoing research is focused on evaluating the interplay between the sorption and co-precipitation in reactive transport diffusion experiments conducted in compacted pure minerals and clay rocks (Opalinus and Callovo-Oxfordian Clays).

### 3.2 Role of particle orientation, porosity and mobility

Connectivity and geometry of pore space are critical factors controlling the diffusive mobility of radionuclides in clay samples. In the recent study [3], the role of the inter-particle and interlayer porosities, as well as the effect of the preferred particle orientation on water diffusion, was investigated by the combination of X-ray scattering and numerical pore-scale transport simulations using synthetic porous media representative for dual-porosity clayey rocks. Vermiculite was selected as an experimental proxy as it allows clear discrimination between the antiparticle and interlayer porosities thanks to the absence of osmotic swelling. Through diffusion and pulsed gradient spin, echo attenuation measurements by the nuclear magnetic resonance of protons were used to probe water mobility. At the same time, the orientation of the particles was quantified by X-ray scattering analysis. Experimental diffusion measurements were conducted for Na-vermiculite samples (swelling clay) and Na-kaolinite particles (non-swelling clay mineral) having only inter-particle porosities. The experimental measurements were used to test a model for Brownian dynamics with virtual porous media representative for the real clay samples. For the range of porosities investigated, a good agreement was observed between measured and simulated water mobility. The obtained results confirmed the pivotal role of the preferential particle orientation on the water dynamics in clayey media through an important reduction of overall water mobility between the isotropic and anisotropic samples. The obtained data also showed that for the same total porosity, the presence of interlayer porosity and associated nano-confinement led to a logical reduction in the pore diffusion coefficient of water. Moreover, the com-

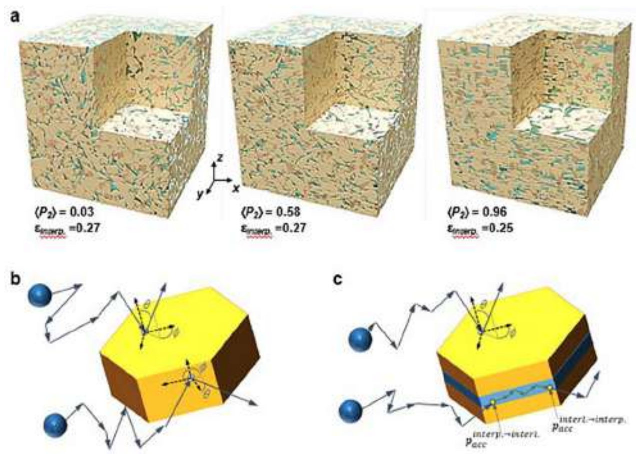


**Fig. 3.** (a) Development of synthetic porous media with similar interparticle porosity but different degree of anisotropy for particle orientation described by order parameter (i.e., $\langle P_2 \rangle$ order parameter). Illustration of Brownian dynamics characteristic to water in a Na-kaolinite (b) and Na-vermiculite (c). In contrast to interlayer, free kaolinite transport in vermiculite takes place in the intra-particle space and the interlayer (modified after Asaad et al. [3]).

puted results revealed that the anisotropy in water diffusion could be directly predicted based on the degree of particles' preferred orientation, irrespective of the total or the distribution of the different porosity types (Fig. 3).

### 3.3 Methodological development in high-resolution spectroscopy

X-ray absorption near edge structure (XANES) spectroscopy is a valuable tool for characterisation of chemical speciation of radionuclides. The spectroscopic technique allows for the identification of oxidation states and provides insight into the electronic structure, and coordination of ions in solution, in crystal structure or at the mineral-fluid interface. High metal loadings are often necessary to obtain EXAFS spectra with a sufficiently high signal-to-noise ratio (S/N). Poor data quality at low loading is often challenging for studies on actinides due to low solubility limits. A significant effort has been made to push the detection limits of the synchrotron-based measurements. Recently, it became possible to measure Np M5-edge HR-XANES spectra of a sample with ~1 mg Np/g illite (1 ppm) [4]. These concentrations are up to several thousand times lower than typical Np loadings on mineral surfaces investigated by X-ray absorption spectroscopy. A newly designed cryogenic configuration enables sampling temperatures as low as $141.2 \pm 1.5$ K and is shown to be successful at preventing beam-induced changes in the Np oxidation state (Fig. 4).

### 3.4 Retention by solid solutions

Dissolution-precipitation reactions in porous media change the availability of pore space for the transport

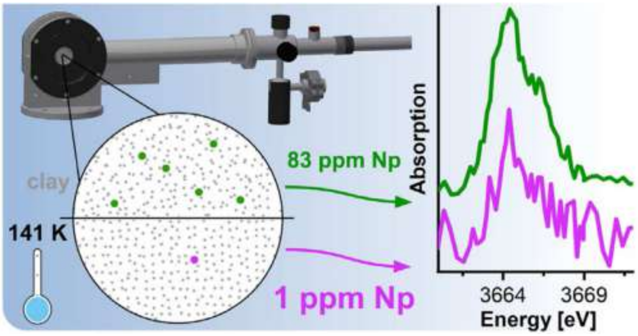


**Fig. 4.** M5-edge HR-XANES spectra of Np absorbed on illite at ($83 \pm 2$ ppm) and ($1.24 \pm 0.04$ ppm) loading recorded at $141.2 \pm 1.5$ K at newly developed setup at ACT station of the CAT-ACT beamline at the KIT Light Source (adapted after Schacherl et al. [4]).

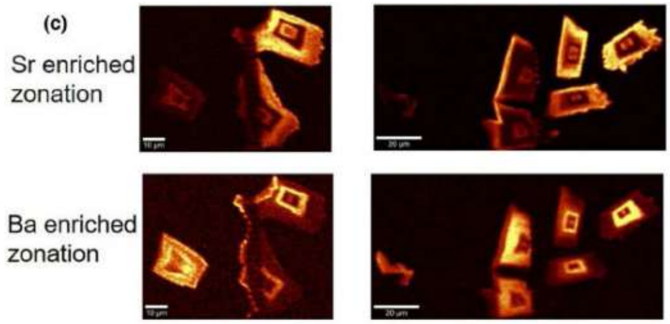


**Fig. 5.** Chemical zoning in Barite-Celestite solid solution crystallised diffusion controlled microfluidic experiment (modified after Poonoosamy et al. [5]).

of solutes as well as contribute to the retention and release of radionuclides. Recent studies indicate that crystallisation pathway and its mechanism in porous media may substantially deviate from the behaviour observed in bulk macroscopic solutions with a high liquid to solid ratio. In particular, the nucleation rate and saturation depend strongly on the pore dimensions, surface energy of mineral-fluid interface and transport regime of solute. With the recent development of in-operando microfluidic experiments and reactive transport modelling, it has become feasible to gauge the driving forces of transport-coupled geochemical processes. With the help of a “lab-on-a-chip” experiment, nucleation and growth of oscillatory-zoned $(Ba,Sr)SO_4$ crystals in a microfluidic reactor (Fig. 5) were investigated by combining laboratory experiment and numerical reactive transport simulations [5]. Analysis of the obtained results suggests that the composition of the nucleating phases can be well described by classical nucleation theory, whereas the oscillatory zoning is controlled by the interplay of diffusion-limited transport of solutes and the nucleation kinetics.

## 4 CORI – research to improve understanding of cement-organic-radionuclide interactions

The work package CORI in EURAD improves the knowledge of the organic release issues, which can accelerate the radionuclide migration in the context of the post-closure phase of geological repositories for ILW and LLW/VLLW, including surface/shallow disposal. CORI addresses topics in the context of cement-organic-radionuclide interactions. Organic materials are present in some nuclear waste and as admixtures in cement-based materials and can potentially influence the performance of a geological disposal system, especially in the context of L/ILW disposal. This potential effect of organic molecules is caused by the formation of complexes in solution with radionuclides of interest (actinides and lanthanides, but also other metal cations like Ni) which can potentially increase the radionuclide solubility and/or decrease radionuclide sorption. Organic substances require increased attention since a significant quantity exists in the waste and the cementitious materials, with a large degree of chemical diversity. Cement-based materials will be degraded with time in the context of waste disposal, inducing a large range of alkaline pH conditions according to their degradation stage. Alkaline pH provides specific conditions under which the organics can degrade, which contributes to increasing their potential impact on repository performance. CORI does not study related topics like microbial degradation of organics, bituminised waste, iron corrosion in cementitious environments, the conditioning of waste in cement materials or studies on natural organics present in certain host rocks. Studies primarily targeting deriving new thermodynamic data for databases are not included, although it is acknowledged that complete and reliable thermodynamic data and databases are essential. These topics may provide input to define future joint research projects.

CORI research builds up systematically on three main topics (tasks) increasing in the number of components and hence complexity, (i) organics degradation, (ii) organics-cement interactions, and (iii) radionuclides-organics-cement interactions. The research progress in these areas, together with selected highlights to exemplify scientific and technical methodology, is discussed in the following. The initial State-of-the-Art document prepared by CORI is available [6].

### 4.1 Organics degradation

Focus is put on the characterisation of soluble organic species generated by radiolytic and hydrolytic degradation of selected organics (PVC, cellulose, resins, superplasticisers). Studies also include the analysis of the degradation/stability of small organic molecules such as carboxylic acids. Determination of degradation rates of polymeric materials and small molecular weight molecules are also performed.

Currently, work in CORI is mainly focused on the characterisation of materials as well as the hydrolytic/radiolytic degradation experimental program. Several partners have finished irradiation experiments, and the

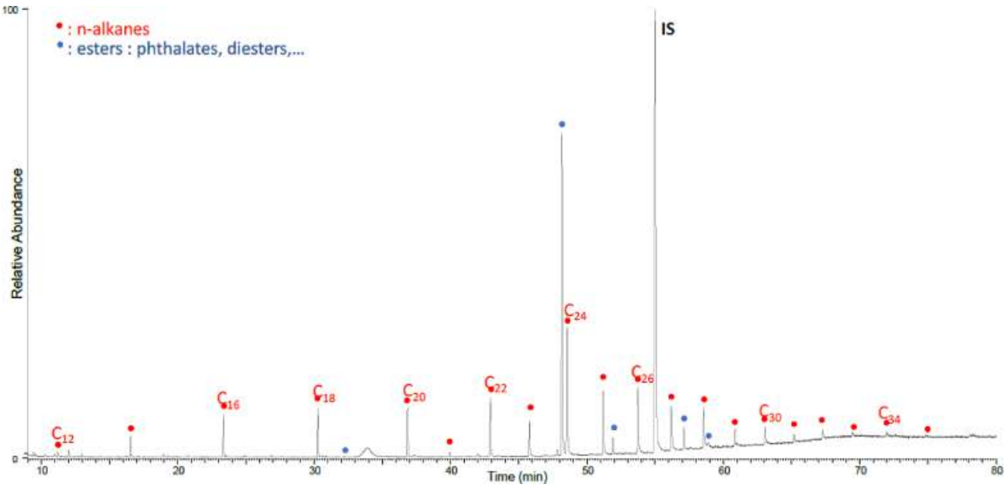


**Fig. 6.** GC-MS spectra of a PVC industrial sample (PVC 1), indicating the presence of alkanes among the additives (courtesy of Le Milbeau et al. [ISTO/BRGM]).

first results of the radiolytic degradation of cellulose and PCE on the related gas production are available. The characterisation of organic species released in solution has been started for cellulose and PAN resins. For PAN, rather slow hydrolytic degradation kinetics were observed.

An example is shown from the studies performed on PVC materials by ISTO/BRGM. The analysis of the initial products was conducted by ISTO/BRGM by combining chemical analyses, XRD, GC-MS and $^1$H NMR. For the pure phases, the results are consistent with the theoretical properties and compositions. For the industrial PVC products, the analyses reveal the presence of several additives; in the case of PVC1, the presence of both n-alkanes (average C number: 22), phthalates (DEHP, DINP) and adipates (2-ethylhexyl adipate) was detected (see Fig. 6) and calcite identified by XRD.

The main results from organics degradation studies are expected for the last two years of CORI and will be documented in the final SOTA document to be prepared by CORI.

## 4.2 Organic-cement interactions

Studies focus on investigating the mobility of selected organic molecules in cement-based materials. Assessment of the mobility of organic molecules includes studies on retention and transport properties. Organics are selected in view of expected relevance and include small $^{14}$C bearing molecules as identified in the previous EC-funded project CAST. Both retentions on individual cement phases and actual cementitious systems are investigated. Analysing the fate of the organics in cementitious environments is a key requirement for understanding and modelling the radionuclide behaviour in single and complex systems.

Sorption properties are measured for various organic molecules (formiate, acetate, oxalate, adipate, glutaric acid, butric acid derivates, phthalate, citrate, gluconate, isosaccharinic acid (ISA), EDTA, NTA and superplasticiser materials) by the CORI partners. Sorption tests are performed on HCP with various cement types. Some studies investigated surface properties, particularly the zeta potential, on pure solid phases such as C–S–H, ettringite or portlandite. The information on surface properties can help to understand the sorption mechanism from a phenomenological point of view.

Figure 7 presents the zeta potential evolution as a function of ISA concentration measured by CIEMAT (Spain). In the range of ISA concentration ($<10^{-3}$ M), the impact of ISA on zeta potential seems not to be significant, in particular for portlandite and ettringite, for which the sorption was found almost zero.

In addition, EDTA, NTA, citrate, gluconate and other low molecular weight organics, such as formate and acetate, are studied in CORI. The general trend points out the notable sorption of EDTA and Gluconate in the cement-based materials, while the low molecular weight organics are weakly sorbed. Selected sorption measurements are performed with selected superplasticisers: polycarboxylate, modified melamine, and polycarboxylate ether (PCE). First tests showed significant sorption on HCP and C–S–H, respectively.

Studies in CORI also include diffusion or electrodiffusion tests for evaluating the transport properties of the various organic molecules in cement-based materials. As the diffusion process is very slow and experiments ongoing, no results are presented at present.

## 4.3 Radionuclide-organic-cement interactions

Processes of radionuclide retention and migration are studied in the ternary system, containing cement and organics, but also radionuclides. The role of organic molecules on the transfer properties of radionuclides is investigated through retention and transport experiments, covering a range of experimental conditions. Selected radionuclides cover a range of chemical characteristics and redox states relevant to the expected conditions in L/ILW disposal.

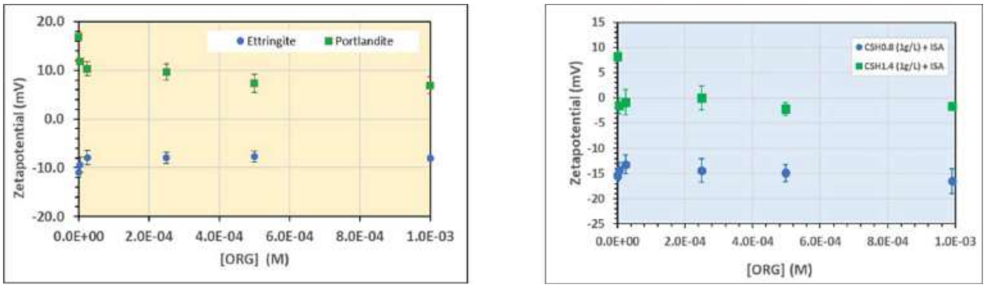


**Fig. 7.** Zeta potential measurements as a function of ISA concentration ([ORG]) on portlandite and ettringite (left) and C–S–H (C/S = 0.8 and 1.4) (right). (courtesy of Missana et al. [CIEMAT]).

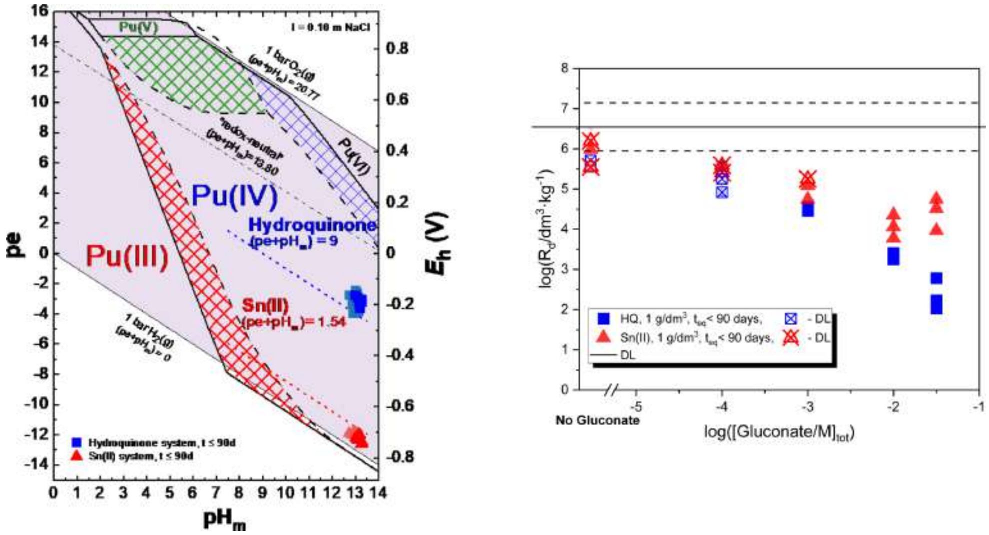


**Fig. 8.** Left: experimental ($pe + pH_m$) values determined for the Pu samples containing hydroquinone (HQ, blue symbols) or Sn(II) (red symbols) as redox buffers. Right: $R_d$ values determined for the uptake of Pu by C–S–H 1.4 in the absence and presence of gluconate at pH = 13.3. All experiments performed at S:L = 1 g dm$^{-3}$. DL stands for detection limit (courtesy of R. Guidone et al. Empa (Switzerland) and KIT (Germany)).

The main radionuclides of interest are U(VI), Ni(II), Pb(II), as well as An(III/IV) and their inactive chemical homologues. The experimental programme is comprehensive and includes studies on solubility/speciation, retention and transport studies in different cement minerals (CSH, CASH, AFm, portlandite) and hardened cement pastes in different degradation stages. Some partners perform selected experiments using the reference cement material (RCM) prepared in CORI. The organics analysed by the different organisations consider a variety of ligands, including chelating agents like EDTA, gluconate (GLU), NTA; cellulose degradation products as isosaccharinic acid (ISA) or homologues; ion exchange resins (IER) or representative degradation products (GTA, HIBA, HBA); carboxylic acids, formiate (FOR), citrate (CIT), adipate (ADI), dioctyl adipate (DOA), phthalate (PHT), dioctyl terephthalate (DOTP), Tri methyl amine (TrMeA) and organic cement additives as superplasticisers (SPs).

Figure 8 shows studies by Empa (Switzerland) and KIT (Germany). The impact of gluconate on the uptake of Pu by C–S–H phases was investigated in the presence of hydroquinone (HQ) and Sn(II), which buffer the redox conditions at ($pe + pH_m$) ≈ 9 and ≈ 1.5. As shown on the left of Figure 8, Pu(IV) is expected to prevail in the mildly reducing conditions set by HQ (blue squares in the figure), whereas the very reducing conditions imposed by Sn(II) result in ($pe + pH_m$) values close to the borderline Pu(IV)/Pu(III) calculated in the absence of gluconate.

The right side of Figure 8 shows that the uptake of Pu by C–S–H decreases at $[GLU]_{tot} \geq 10^{-4}$ M, in line with data previously reported for Th(IV). This observation supports the formation of stable ternary or quaternary complexes (Ca–)Pu–OH–GLU in the aqueous phase. The differences observed for the uptake in systems containing HQ or Sn(II) as redox buffers underpin that the reduction of Pu(IV) to Pu(III) is also feasible in hyperalkaline systems and highlights the need to undertake experiments with plutonium beyond the use of redox-stable analogues such as Th(IV) or Eu(III).

Systems analysed in CORI by the different organisations in radionuclide transport and diffusion studies include several types of hardened cement pastes (HCP). Several degradation stages are investigated, using both through-diffusion (TD) and in-diffusion (ID) tests. The organic ligands and radionuclides match those discussed above.

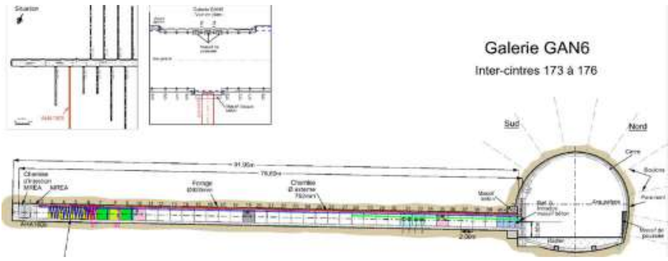


**Fig. 9.** Scheme of the AHA1605 in situ HLW disposal cell demonstrator in Bure URL (Andra).

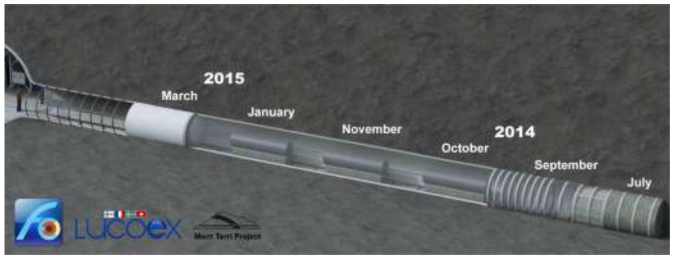


**Fig. 10.** Full-scale Emplacement (FE) Experiment at the Mont Terri URL (Nagra).

### 4.4 CORI expected impact

The specific new scientific results from WP CORI provide new quantitative and qualitative data and process understanding to support RWMD implementation needs and safety. CORI will perform a systematic evaluation of its impact at the end of the project, in close exchange with the CORI User Group and WMOs.

Issues of interest at the repository scale related to *implementation needs* are (i) improved scientific basis for the Safety Case for L/ILW waste repositories featuring relevant organics content, (ii) co-disposal of waste: support decisions regarding the question of whether or not a mix of various wastes (organics, soluble salts, exothermic waste) can be foreseen, (iii) optimisation of vault design in view of limitations on interactions between the vaults regarding their content. CORI provides information on the organic plume by characterising the transfer behaviour in cement-based materials and contributes to the optimization of concrete formulations as regards the potential effect of superplasticisers on radionuclide transfer properties. Regarding *safety*, there are likewise several implications related to (i) characterising the effect of the organic plume on the behaviour of radionuclides in terms of solubility (limitation of solubility increase), (ii) assessing sorption (limitation of retention decrease) in terms of $K_d$ values, and (iii) analysing the retention of potentially $^{14}C$-bearing organic molecules (determined in CAST project) in cementitious environments in the case of specific wastes. CORI research reduces the uncertainties in the current knowledge (mainly based on $K_d$ values) and improves the knowledge of the known organic molecules present in degradation solutions (not considered so far) with their complexing properties. This contributes to a better understanding of the impact of the organic inventory on nuclide mobility (geological and surface repositories).

## 5 MODATS – MOnitoring equipment and DAta Treatment for Safe repository operation and staged closure

The successful implementation of geological disposal of radioactive waste relies on the technical aspects of a sound safety strategy and scientific and engineering excellence, as well as on societal aspects such as stakeholder acceptance and confidence/trust. A key argument in international guidance and national programmes has been that monitoring can significantly contribute to both technical and social aspects of successful repository implementation. Monitoring is a broad subject, and monitoring within a radioactive waste management programme can encompass many different objectives and activities. These objectives and activities include technical and non-technical aspects. Repository monitoring is a more narrow discipline within this wider context and is related to monitoring the features, events and processes (FEPs) affecting the behaviour of a geological disposal facility.

MODATS is working to consolidate the implementation strategy for monitoring systems by developing methods through which confidence can be demonstrated in the data acquired and benefits derived from repository implementation. To develop this ambition, the WP undertakes R&D in data acquisition, data management and presentation, and the use of data in system understanding. This R&D is supported by information from existing case studies, including five reference experiments:

- **AHA1605 (Andra)**, (see Fig. 9): AHA1605 is an in situ HLW disposal cell demonstrator in Andra's Bure underground research laboratory (URL) dedicated to the demonstration and evaluation of the monitoring system for the HLW disposal cells in Cigeo. The experiment was installed in mid-2019. In this demonstrator, 80 m of the liner is instrumented in order to prove Andra's capacity to monitor thermo-mechanical and chemical parameters of a complete HLW disposal cell.
- **FE (Nagra)** (see Fig. 10): the Full-scale Emplacement (FE) Experiment at the Mont Terri URL simulates aspects of the construction, waste emplacement, backfilling and early-stage evolution of an SF/HLW repository tunnel in a clay-rich formation (Opalinus Clay), using heaters in place of SF/HLW canisters. The heating of the experiment commenced in December 2014. The entire experiment implementation and the post-emplacement THM evolution are monitored using several hundred sensors. Some monitoring of gas concentration is also undertaken. The sensors are distributed in the nearfield and the host rock, on the tunnel lining, in the buffer and tunnel plug, and on the heaters. FE is underpinned by extensive THM modelling, several years of monitoring data and a database of monitoring results.
- **POPLU (POSIVA)** (see Fig. 11): the POPLU experiment is a full-scale test of a possible design of a disposal tunnel end plug component of the disposal concept

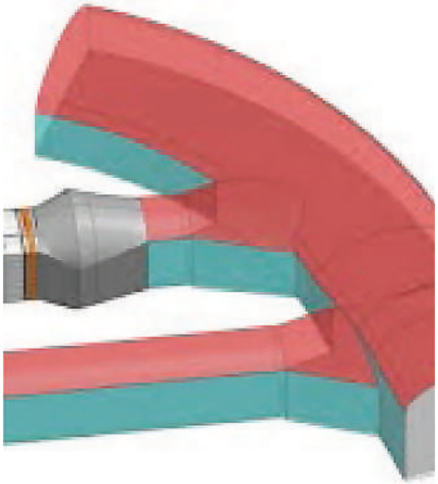

**Fig. 11.** Schematic representation of a full-scale test of a possible design of a disposal tunnel end plug component by the POPLU experiment (Posiva).

for the spent fuel repository in Olkiluoto (Finland) and Forsmark (Sweden). The plug was constructed in 2015, and pressurisation commenced in January 2016. The POPLU experiment was extensively monitored to detect a range of thermo-hydro-mechanical processes.

- **Prototype Repository (SKB)** (see Fig. 12): the Prototype Repository is a full-scale field experiment in crystalline rock at a depth of 450 m in the Äspö Hard Rock Laboratory. The experiment aims to simulate conditions largely relevant to the Swedish/Finnish KBS-3V disposal concept for spent nuclear fuel. The 64 m long experimental tunnel contains six deposition holes and many full-scale copper canisters surrounded by an MX-80 bentonite buffer. The test tunnel was divided into two separate sections. The inner section, with four deposition holes, has been operated since 2001 and the outer section, with two deposition holes, since 2003. Each section was backfilled with a mixture of bentonite (30% by weight) and crushed rock (70% by weight) and finally sealed by reinforced concrete dome plugs. The outer part of the experiment was dismantled during 2010–2011.
- **PRACLAY (EURIDICE)** (see Fig. 13): the PRACLAY experiment is a large-scale experiment designed to study the impact of the heat generated by high-level waste on the host clay formation. It also looks at how excavation affects the behaviour of the clay. The experiment is located in the HADES URL (Mol, Belgium) in a dedicated 40 m long gallery simulating a waste disposal gallery. Heating started at the end of 2014 following construction, ventilation and saturation phases. The target temperature (80 °C at the gallery lining extrados) was reached nine months later and is planned to last for (at least) 10 years. In addition, a gallery seal allows for maintaining the hydraulic boundary conditions. The focus is on the behaviour of the host clay. The most important parameters monitored are temperature and pore water pressure. Numerical modelling complements the experimental part.

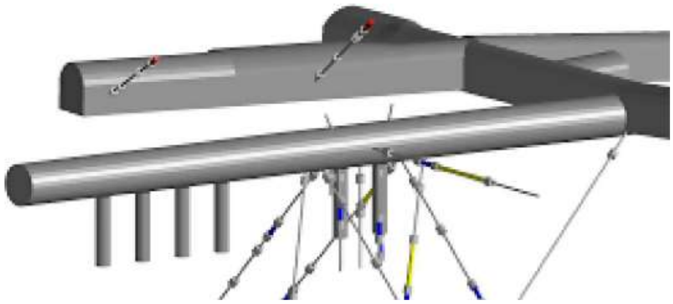

**Fig. 12.** The Prototype Repository is a full-scale field experiment in crystalline rock at a depth of 450 m in the Äspö Hard Rock Laboratory (SKB).

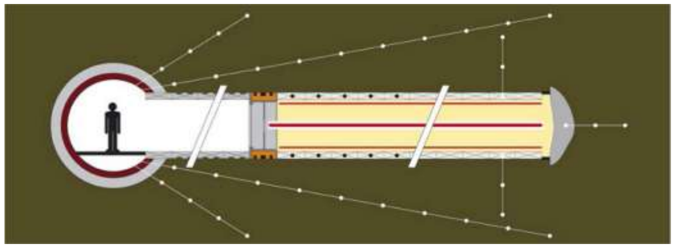

**Fig. 13.** Schematic representation of the PRACLAY experiment located in the HADES URL (EURIDICE).

### 5.1 Data treatment for increased confidence in repository monitoring

The overarching goals of monitoring a radioactive waste repository are to provide information to support decision-making and to strengthen understanding of some aspects of system behaviour. Based on the reference experiments, MODATS wants to address methods to collect, treat and analyse data that will strengthen system understanding, especially since repository monitoring will be spatially and temporally limited. Repository monitoring also presents challenges related to evaluating multi-modal data, i.e. data that is measured by different sensors, resulting in a range of independent parameters, at different locations and at varying spatial and temporal sampling. These data need to be evaluated in a coherent way that considers the specifics of sensors and their spatial relationships and allows for the identification of anomalies related to sensor ageing and malfunction, outside influences, and deviations of the repository system from expected behaviour. MODATS wants to consolidate the implementation strategy for monitoring systems in repository facilities by developing methods through which confidence can be demonstrated in the acquired data and its analysis and benefits derived from repository implementation (see Fig. 14).

### 5.2 Novel and optimised monitoring technology for repository monitoring

The requirements for sensing methods to monitor waste repositories are quite unique. Monitoring must not interfere with EBS integrity and not

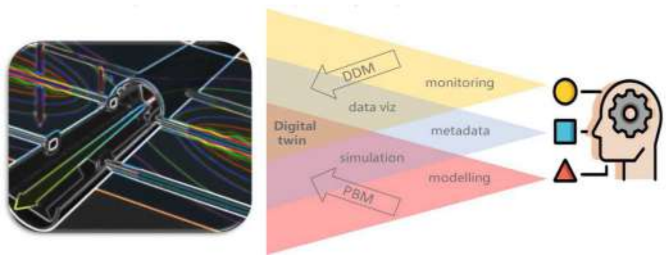


**Fig. 14.** Schematic visualisation of the repository monitoring strategy developed in MODATS with the data-driven model (DDM) and the physics-based model (PBM).

jeopardise the long-term safety of a repository. The MoDeRn Project successfully developed and analysed the capabilities of monitoring technologies for future repository use in the fields of measurement techniques and probes, data transmission methods and energy supply (see [7]). The Modern2020 project accelerated the technological development of a tailored system for geological disposal in a way that was not seen before in order to move from the state-of-the-art to the proof of concept and demonstration phase. With this ambition, Modern2020 explored a large number of innovative methods and techniques for developing useful tools and assessing the monitoring strategies in an appropriate way.

New and emerging sensing methods may change the paradigm of monitoring waste repositories. To push forward what is possible in terms of monitoring, it is crucial to stay abreast with the technological development to apply and adapt emerging technologies to waste repository monitoring and develop new technologies suitable for the specific requirements of repository monitoring. In addition, we develop new methods that extract signals from the data through signal processing, joint inversion schemes and other techniques specific to the monitoring methods. In Task 3 of MODATS, the following actions are ongoing:

- research and further develop innovative sensors and geophysical techniques to measure and infer parameters that are difficult to obtain for long-term monitoring.
- Develop and qualify optical sensors to get them ready to be used in the initial phase of the development of the geological disposal for temperature and strain measurement.
- Develop methods to investigate the impact of monitoring technology on the performance of a range of disposal systems.

## 6 Conclusion

Besides the scientific and technical results and progress discussed above for each of the WPs, general aspects regarding the expected impact of the research performed in CONCORD, FUTURE, CORI, and MODATS are discussed in the following.

The key impact of the research will be the generation of new scientific information. Results provide an improved technical basis for the Nuclear Waste Disposal Safety Case. This includes new qualitative and quantitative data characterising the various systems studied and, in most cases, also significantly improves the scientific process and system understanding. Combining the most advanced complementary of state-of-the-art analytical and spectroscopic tools, key information is derived on a molecular level and up-scaled for performance assessment studies. All WPs include modelling of results and offer potential links to further modelling activities in EURAD and beyond. New materials are tested and evaluated regarding performance and potential usability, and detailed concepts for monitoring repository evolution are developed, evaluated and tested. All the new information generated in CONCORD, FUTURE, CORI and MODATS will support the member states regarding decision-making and planning within their respective national programs.

To ensure high visibility and usability of the research performed in the WPs presented in this contribution, a dynamic dissemination strategy is realised both on a European and international level. The target is to provide information and scientific arguments to support activities contributing to the final disposal of nuclear waste, explicitly addressing different stakeholders. The technical/scientific results are first made available as open access peer-reviewed publications. Results also feed into the State-of-the-Art documents defined as public deliverables in all four WPs, which are currently available in the initial form at the EURAD website for download. The WPs are actively contributing to knowledge management tools established in EURAD, for instance, by authoring State-of-Knowledge documentation, contributing to the population of the WIKI information system currently established or organising joint training events and workshops. The EURAD KM strategy offers a new quality of dissemination to ensure long-term access to the scientific and technical results generated in technical WPs like CONCORD, FUTURE, CORI, and MODATS.

The experimental and modelling work by the EURAD WPs presented here is, to a significant extent, performed by young researchers and within Ph.D. theses. This contributes to the availability of highly trained specialists for implementers, regulators and research entities throughout Europe. EURAD contributes to European integration by bringing together experts from several European member states. The involvement of experts coming from countries at very different stages of implementation likewise poses a positive achievement, for instance, in view of sharing expertise and resources in Europe and integrating new member states.

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## Conflict of interests

The authors declare that they have no competing interests to report.

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## Data availability statement

This overview article has no associated data generated to be disclosed.

## Author contribution statement

All authors have contributed equally to this publication. N. Diomidis has prepared the section on CONCORD, S. Churakov the section on FUTURE, M. Altmaier the section on CORI and J. Bertrand the section on MODATS.

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**Euratom Research and Training in 2022: challenges, achievements and future perspectives, Roger Garbil, Seif Ben Hadj Hassine, Patrick Blaise and Cécile Ferry (Guest editors)**

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Review Article

Open Access

# Modelling of the long-term evolution and performance of engineered barrier system

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**Abstract.** Components of the so-called "multiple-barrier system" from the waste form to the biosphere include a combination of waste containers, engineered barriers, and natural barriers. The Engineered Barrier System (EBS) is crucial for containment and isolation in a radioactive waste disposal system. The number, types, and assigned safety functions of the various engineered barriers depend on the chosen repository concept, the waste form, the radionuclides waste inventory, the selected host rock, and the hydrogeological and geochemical settings of the repository site, among others. EBS properties will evolve with time in response to the thermal, hydraulic, mechanical, radiological, and chemical gradients and interactions between the various constituents of the barriers and the host rock. Therefore, assessing how these properties evolve over long time frames is highly relevant for evaluating the performance of a repository system and safety function evaluations in a safety case. For this purpose, mechanistic numerical models are increasingly used. Such models provide an excellent way for integrating into a coherent framework a scientific understanding of coupled processes and their consequences on different properties of the materials in the EBS. Their development and validation are supported by R&D actions at the European level. For example, within the HORIZON 2020 project BEACON (Bentonite mechanical evolution), the development, test, and validation of numerical models against experimental results have been carried out in order to predict the evolution of the hydromechanical properties of bentonite during the saturation process. Also, in relation to the coupling with mechanics, WP16 MAGIC (chemo Mechanical AGIng of Cementitious materials) of the EURAD Joint Programming Initiative focuses on multi-scale chemo-mechanical modeling of cementitious-based materials that evolve under chemical perturbation. Integration of chemical evolution in models of varying complexity is a major issue tackled in the WP2 ACED (Assessment of Chemical Evolution of ILW and HLW Disposal cells) of EURAD. WP4 DONUT (Development and improvement of numerical methods and tools for modeling coupled processes) of EURAD aims at developing and improving numerical models and tools to integrate more complexity and coupling between processes. The combined progress of those projects at a pan-European level definitively improves the understanding of and the capabilities for assessing the long-term evolution of engineered barrier systems.

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## 1 Introduction

The concept of geological disposal of radioactive waste emerged in the late 1950s [1–4] to ensure long-term containment and isolation of the waste from the biosphere and ensure the safety of future generations. A multi-barrier system of engineered (near field) and natural barriers (near and far field) is foreseen in most of the repository designs. The Engineered Barrier System (EBS) comprises various components, such as the waste form itself, waste canisters, backfill, seals, and plugs. Materials, designs, and safety functions of the EBS depend on the host rock and the concept developed in each country.

The Strategic Research Agenda (SRA; https://www.ejp-eurad.eu/publications/eurad-sra) of the European Joint Programme on Radioactive Waste Management (EURAD; https://www.ejp-eurad.eu/) describes the scientific and technical domains and sub-domains and knowledge management needs of common interest between EURAD participant organizations [5]. The SRA scope is structured by seven scientific themes. Theme number 3 is entitled "Engineered barrier system properties, function, and long-term performance". A list of RD&D priorities and activities of common interest to be addressed within EURAD for theme 3 has been established. Amongst others, the following priorities have to be considered:

- improved understanding of the interactions occurring at interfaces between different barriers, including waste packages in the disposal facility.
- Characterized bentonite/clay-based material evolution under specific conditions to provide data on hydromechanical, thermal and chemical behavior.
- Improved quantification and understanding of cement-based material evolution to improve long-term modeling and assessments.
- Improved understanding of the performance of plugs and seals.
- Improved description of the spatial and temporal evolution of transformations affecting the porous media and degrading materials in the near field of HLW and ILW disposal systems.

Tackling these R&D priorities will help to understand the EBS system evolution and the interactions within the repository near field environment, which support the design and optimization of the EBS system. Independently of the waste package, backfill, and buffer materials under consideration, a need for an improved understanding of the mechanical/chemical evolutions at the interface between the EBS components and the host rocks has been identified in the SRA. Indeed, the EBS properties will evolve with time in response to the thermal, hydraulic, mechanical, radiological, and chemical gradients and interactions between the various constituents of the barriers and the host rock. Therefore, assessing how these properties evolve over long time frames is highly relevant for evaluating the performance of repository systems and for evaluating their safety functions in a safety case. For this purpose, mechanistic numerical models are increasingly being used to make predictive multi-physics assessments at larger time frames (e.g. 10 000 to 100 000 years) and space scales (e.g. hundreds of meters) than the ones covered by laboratory or field experiments. New trends and developments in numerical analysis allow for solving more and more complex problems. Such models provide an excellent way for integrating into a coherent framework a scientific understanding of coupled processes and their consequences on different properties of the materials in the engineered barrier system. Their development and validation are supported by R&D actions within either ongoing HORIZON 2020 European projects or within EURAD R&D work packages supporting its SRA and roadmap. For example, the HORIZON 2020 project BEACON (Bentonite mechanical evolution; https://www.beacon-h2020.eu/) aims to develop, test, and validate numerical models against experimental results to predict the evolution of the hydromechanical properties of bentonite during the saturation process. On the other hand, in relation to chemo-mechanical coupling, WP16 MAGIC (chemo Mechanical AGIng of Cementitious materials; https://www.ejp-eurad.eu/implementation/chemo-mechanical-aging-cementitious-materials-magic) of the EURAD Joint Programming Initiative focuses on multi-scale chemo-mechanical modeling of cementitious materials that evolve under chemical perturbation (including bacterial impact). Integration of chemical processes in models at different scales and of varying complexity (from complex description to their abstraction) is a major issue tackled in the WP2 ACED (Assessment of Chemical Evolution of ILW and HLW Disposal cells; https://www.ejp-eurad.eu/implementation/assessment-chemical-evolution-ilw-and-hlw-disposal-cells-aced) of EURAD. WP4 DONUT (Development and improvement of numerical methods and tools for modeling coupled processes; https://www.ejp-eurad.eu/implementation/development-and-improvement-numerical-methods-and-tools-modelling-coupled-processes) of EURAD aims at developing and improving numerical models and tools to integrate more complexity and coupling between processes. The combined progress of those projects at a European level will definitively improve our understanding of and our capabilities for assessing the long-term evolution of engineered barrier systems and will enhance collaboration between scientific communities.

In this manuscript, first, how the different projects contribute to the EBS thematic is explained. Then the models used to describe some of the most important coupled processes occurring within EBS are discussed in detail, and relevant examples are given.

## 2 Projects contributed to the scientific basis for EBS evolution and modeling of their evolution

The four R&D projects mentioned above contribute to a better understanding of EBS behavior in radioactive waste disposal. It is worth keeping in mind that they do not have the same level of maturity as they did not start at the same time. BEACON started in June 2017 and has finished in May 2022, while ACED and DONUT were launched in June 2019, and MAGIC only in June 2021.

## 2.1 Mechanical evolution of bentonite barriers (BEACON)

The sealing ability is a principal safety function for bentonite-based barriers in all geological repository concepts. Sealing is achieved by the combination of a high swelling potential and low hydraulic conductivity. The swelling potential will ensure self-sealing but may mechanically impact the other barriers in the repository as well. The low hydraulic conductivity ensures that the transport of dissolved species by advection will be very limited. Swelling pressure and hydraulic conductivity can normally be expressed as a function of the dry densities of bentonite materials. The required quantitative values strongly depend on the repository concept and the environment.

The barriers are installed as blocks, pellets, and/or granules depending on the overall repository concept and the required density. Despite the precautions taken when installing these materials, technological voids may occur, and dry density variations may be observed in the structure. Therefore, the bentonite barrier needs to be conceptualized such that these technical voids can be compensated by the swelling of the bentonite and that density variations after hydration are minimized or in the range of expectations.

Despite the high swelling potential of bentonite, full homogenization between the installed components is never expected to be reached. The key question is: “Is the homogenization sufficient to reach the targets for the safety functions after saturation?”. If the answer is yes, then the barrier can be assumed to have its assigned properties in the safety case. If the answer is no, then the effect of a heterogeneous barrier needs to be considered (e.g. advection in the barrier), otherwise, the design and installation of the barrier components need to be improved.

This makes it necessary to have predictive models that can describe the evolution of the properties of the bentonite barriers from “the installed state” to a “saturated state”. The input to the models should be the design specification, including uncertainties, and the site properties, also including uncertainties. In this aspect, uncertainties include variability and tolerances. The output should be the final state of the barrier, preferably expressed in the distribution of dry density and evolution of stresses. The results from the models can then be compared with the indicators/targets for the safety functions to check whether they are fulfilled. The key parameter to check is the dry density, which directly relates to the swelling pressure and the hydraulic conductivity.

The overall objective of the BEACON project has been to develop, test, and improve models that can predict the mechanical evolution of installed bentonite components. Their application is both to support the handling of the barriers in the safety case and to give feedback on the design and the engineering of the barrier components.

## 2.2 Development and improvement of numerical methods and tools for modeling coupled processes (DONUT)

Understanding multi-physical Thermo-Hydro-Mechanical-Chemical coupled processes (THMC) occurring in the EBS is a major and permanent issue supporting the 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, the increasing scientific knowledge acquired for each of the individual components of the EBS. This implies the integration of couplings of different and non-linear processes, covering a wide range of heterogeneous materials with evolving properties in time and space. The development of cutting-edge and efficient numerical methods is thus necessary for the scope of having useful, powerful, and relevant numerical tools for assessments as well as for process understanding. It is also necessary to manage the uncertainties associated with the input data feeding the models, to assess the model responses, and to identify the main parameters and processes driving the behavior of the systems of interest. Managing uncertainties in these complex systems require the improvement and development of innovative, appropriate and efficient numerical methods. According to these needs, a work package called Development and Improvement Of NUmerical methods and Tools for modeling coupled processes (DONUT) has been launched within the EURAD project to develop relevant, performant, and cutting-edge numerical methods that can easily be implemented in existing or new tools, in order to carry out high-performance computing to facilitate the study of highly coupled processes in large systems. These methods and their implementation in tools will be mainly applied to reactive transport, two-phase flow, and THM modeling in porous and fractured media. In addition, numerical scale transition schemes are developed to upscale coupled processes from pore scale to continuum scale in order to support the study of specific multi-scale couplings such as chemo-mechanics. Numerical development is also addressing innovative methods (e.g. surrogate models) to carry out uncertainty and sensitivity analyses. Last but not least, the setup and the achievement of benchmark exercises on representative test cases allow us to evaluate the efficiency of developed methods and tools (robustness, accuracy, time computational).

## 2.3 Assessment of the chemical evolution at disposal cell scale (ACED)

Within a disposal system for intermediate or high-level radioactive waste (ILW/HLW), a particular subsystem is the waste packages and their immediate surroundings (near field), which is the focus of the EURAD ACED work package. These subsystems consist of engineered materials with sometimes distinct different geochemical properties. Depending on the radioactive waste type and the disposal system, the materials considered in ACED consist of vitrified waste, cemented waste, steel, cementitious barriers, and the host rock (clay or granitic rock). Undoubtedly, interstitial pore water of the different porous materials will mix and induce geochemical alterations within the materials leading to, amongst others, dissolution and precipitation of primary and secondary phases with changes in microstructure and transport parameters. Moreover, nonporous material (e.g., steel) may corrode or dissolve as well. Within the perspective of the lifetime of a repository, simulating the chemical evolution is relevant for assessing the durability of different materials and the speciation of the chemical environment as input for radionuclide fate and transport; therefore, its assessment is one of the key elements for the basis of the evaluation of the long-term performance and safety of a repository.

Assessing the chemical evolution is challenging because of the many orders of magnitude in scale to be considered – both in time because, even if geochemical processes are sometimes very slow, they proceed for ten thousand years and in space, with interactions at μm scale, especially at interfaces, influencing the system behavior at scales of several meters. ACED addresses this by considering three scales – interface, waste packages, and disposal cell scale – via dedicated experimental and modeling studies. The experimental studies combine new approaches for studying steel-concrete and steel-clay interfaces under different conditions and enhanced characterization of long-lasting experiments allowing for time scales spanning from one year to a few decades. These studies form the basis for scientific understanding of processes at interfaces between two materials or interactions between two or more materials. In addition, thermodynamic data, specifically for iron phases, and other variables are collected as input for numerical modeling.

The other pillar is numerical modeling from the interface scale to the disposal cell scale. Modeling in ACED is based on so-called continuum modeling, in which the flow and transport of solutes (and possible gases) by diffusion and advection are coupled with thermodynamic and kinetic models to represent the geochemical state. Such models are typically called coupled reactive transport models [6], and although they have already been available for several decades, their recent capabilities now allow them to handle complex environmental and engineering problems, including radioactive waste disposal [7,8]. Beside the reactive transport codes themselves, and the variety of geochemical processes under different conditions (e.g. ionic strength, temperature,...) they can simulate, thermodynamic databases are also a cornerstone for such simulations. Recent relevant databases are e.g., Thermoddem [9], ThermoChimie [10], and CEMDATA [11], amongst others. Models for some kinetic reactions are well-established (e.g. clay minerals [12]), but the incorporation of kinetic models for some engineered barriers, such as steel and glass, in a reactive transport code remains challenging. However, these are essential for the chemical assessment of the disposal cell scale, and approaches are developed in ACED.

ACED describes the processes at different scales but always uses a continuum model. The basic idea is to perform detailed modeling of relevant processes at one scale and extract information as input to a larger scale in which some processes cannot be described with the same level of detail (mainly due to computational time or because it is not a possibility to include sufficiently small timesteps or spatial discretization at a larger scale). By integrating knowledge and information, ACED simulates the chemical evolution at relevant spatial and temporal scales related to the cell disposal scale. The last step is to abstract these complex models to enable sensitivity and uncertainty analyses of the chemical evolution – a key aspect here is that the abstracted models reproduce the aspects of interest of the chemical evolution in a sufficiently accurate way.

## 2.4 Chemo-mechanical evolution of concrete barriers (MAGIC)

Concrete, mortars, and grouts are used for structural, containment, and isolation purposes in high-level and low-intermediate-level radioactive waste repositories. For example, cement-based backfill materials are envisaged for a large number of disposal facilities for intermediate-level wastes across Europe and are already used as liners in disposal cells or as part of waste containers in many Member States' existing facilities for low-level waste near-surface disposal facilities. Knowledge and feedback on concrete durability are available through the return of experience from civil engineering. However, a specific approach during the design and construction of a repository in terms of stringent safety requirements is of paramount importance. In addition, further understanding is required to support their use as a backfill material for high-level wastes under geological disposal conditions, particularly to understand their contribution to the overall system performance during late post-closure time frames. This is especially the case for concrete with low-pH cement-based material formulation, where less knowledge is available.

The mechanical behavior of cementitious materials is strongly influenced by the boundary conditions imposed by the geo-technical system and the host rock (i.e., water saturation, temperature, etc.) during both the operational phase and the post-closure transient period. To assess the performance of the cementitious components, studies must be extended-for long time periods (several years), also considering the operating period in unsaturated conditions. Cementitious materials are planned to be used as disposal barriers (i.e., buffer, plugs, and waste matrices) and structural systems, which require further understanding of their long-term behavior, considering the initial mechanical state and including the impacts of microbes on their degradation. Furthermore, over the long term, ground- and pore waters, with aggressive chemical ions, are a key driving factor for cementitious materials' deterioration. The mineralogical and microstructural changes generated by these aggressive environments might have consequences for the mechanical behavior of the cement matrix.

Cement and concrete are heterogeneous materials containing different constituent phases, pores, cracks, and inclusions at various scales. Their macroscopic thermo-hydro-mechanical (THM) behavior is intimately related to its multi-scale structure. Under THM loading and chemical processes, their microstructures are modified such as porosity variation, calcium dissolution, calcite formation, corrosion product expansion, crack initiation and propagation etc. Consequently, the macroscopic behaviors are affected by such microstructural evolutions. It is crucial to develop multi-scale experimental and modeling approaches to establish inherent relations between short- and long-term macroscopic behaviors of cement and concrete and their microstructural evolutions. On the other hand, there is also a strong spatial variability and uncertainty in the microstructure and the macroscopic properties in large-scale concrete structures. Despite significant advances performed during the last decades, the development of an efficient modeling strategy of concrete materials and structures by considering multi-scale microstructures evolution, uncertainty, and variability is still a pending issue.

The MAGIC WP aims to increase confidence in Chemo-Mechanical numerical models by reducing uncertainties in input data and understanding key coupled processes (for both young (not early-age) and aged materials). Specific conditions for waste disposal (microbial activity, chemical and mechanical stress, variable saturation, etc...) are taken into account by addressing implementation needs and safety aspects, e.g., regarding the selection of materials, dimensioning, and (long-term) behavior of seals and plugs.

This WP is improving the knowledge of the mechanical transformations of concrete in EBS (from the container to the massive plug in the sealing area) exposed to various disturbances (mechanical, chemical stresses, microbial activity...). Several laboratories, mock-ups, and in situ experiments (mainly existing) dedicated to identifying the mechanical behavior of concrete under various stresses are developed/exploited. Furthermore, multi-scale models describing the chemical and microbial impacts on the concrete mechanical properties under real repository conditions are developed.

Particular attention is paid to reinforced concrete. To control crack propagation in civil engineering concrete structures in the short term (during the construction of repository structures and their exploitation phases), steel reinforcement is efficient. The ability of rebars to limit crack openings is well controlled for usual reinforced concrete structures in contact with the atmosphere and the expected service life duration of classical constructions [13]. However, in the context of nuclear waste repositories, the transfer of chemical species into the micro cracks and the localized opened cracks created in the short term could either lead to the healing or the propagation of these cracks, depending on the chemical environment and the mechanical loading. Among the different parameters controlling these phenomena, the two most important ones are the evolution of the concrete matrix mechanical properties and the concrete-rebar bonds (stiffness, strengths, swelling or shrinkage, and creep for both). These aspects are treated experimentally and numerically in the present project to provide homogenized behavior laws for plain and reinforced concrete usable in finite element codes. These codes are then used at the structure scale. The coupling between chemical reactions at the micro-scale, rebars consideration at the meso scale, and loading at the structural scale, enables envisioning a large variety of scenarios by practitioners to examine the safety of these installations during the medium-term (exploitation phase) and the long-term (post sealing phase).

This WP strives for scientific excellence using novel approaches, including microbial effects and nanoscale process understanding under variably-saturated conditions. Moreover, it enhances the quantification and understanding of cement-based material evolution to improve long-term modeling and assessments.

## 3 Examples of EBS modelling performance and evolution

### 3.1 Mechanical evolution of bentonite barriers (BEACON)

The scientific part of BEACON was divided into five actions. The first dealt with the application of the results from the project in safety cases and design. The purpose of the second was to collate and share knowledge on the available information about bentonite mechanical evolution. The third handled the development of models. The objective of the fourth was to provide experimental data to support the model development and testing. The core activities of BEACON were, however, performed in the fifth action, where numerical models describing the mechanical evolution of bentonite barriers were tested, verified, validated, and finally applied in relevant assessment cases. The originality of work performed in this work package was to propose test cases in which heterogeneities in the bentonite-based component were initially present or to revisit large-scale experiments to follow heterogeneities evolution and the capacity of the model to predict the final state. The following section will focus on some of the achievements gathered during BEACON.

At the onset of the BEACON project, there were very few examples of the application of mechanical models of bentonite in a safety case. Many teams had the mechanical formulations included in their THM codes, but the level of testing and verification of those formulations was, in general, rather limited.

To overcome this issue, modeling activities were carried out either in a test case built on experiments performed within BEACON and included a blind prediction of an experiment or on assessment cases proposed by waste management organizations (WMO) based on specific components taken from actual repository designs.

In detail, calibration/validation of the models was carried out using three sets of laboratory tests. These latter were chosen based on the initial heterogeneity of the materials or the introduction of perturbations during the test to induce some heterogeneities. These tests were complementary and represented relevant situations encountered in a repository when installing an EBS. The dispersion of the numerical results was rather large. This was especially true regarding the calculated stresses. For the final

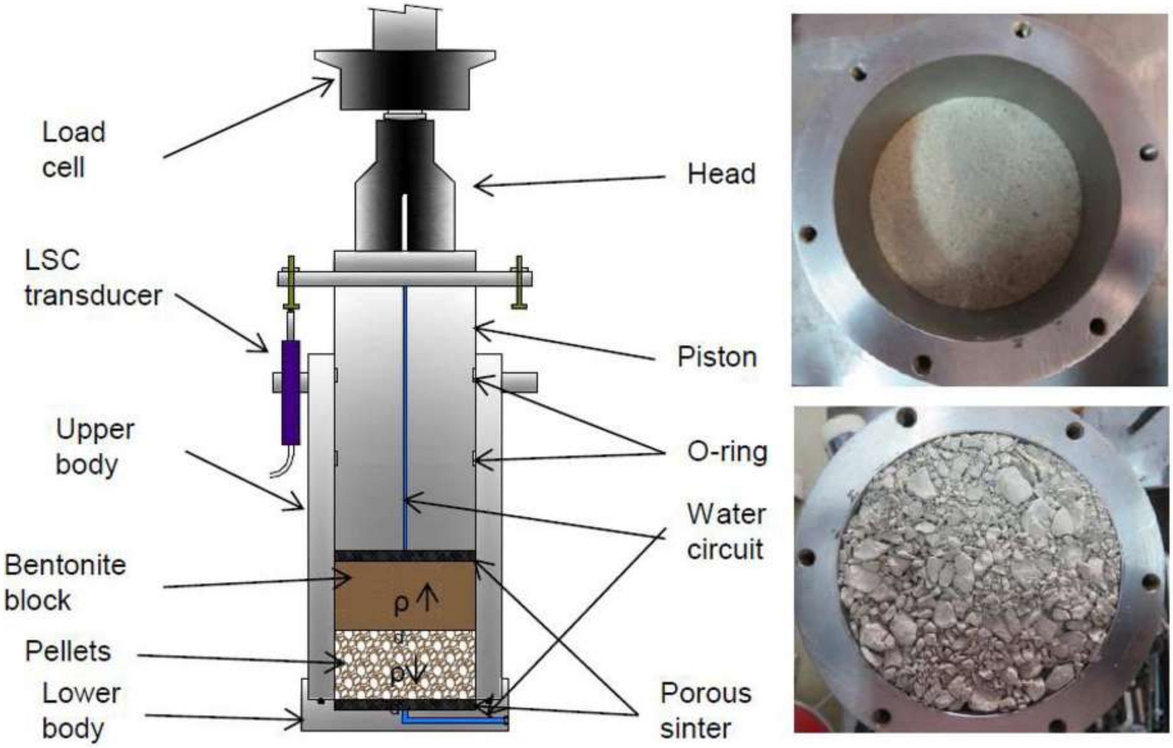


**Fig. 1.** Schematic representation of the test cell and images of the block (upper right) and pellets (lower right). In the predictive test, the block was placed at the bottom of the cell (Villar et al. [14]).

dry density in the test, the calculated values were in better agreement with the measured values. At this point, many teams were also rather inexperienced with this type of issue.

Regarding large-scale experiments, to show the capacity of the models to reproduce in situ experiments, three experiments were selected:

- EB – Engineered Barrier Emplacement Experiment (EB experiment).
- FEBEX – Full-scale Engineered Barrier Experiment in Crystalline Host Rock.
- CRT – Canister Retrieval Test (CRT).

This modeling activity was much more difficult than the previous one due to the complexity of the geometry, the uncertainties on the boundary and initial conditions, and sometimes in the analysis of the information given by the sensors. Moreover, for two of the tests (CRT, FEBEX), it was necessary to consider the temperature and the couplings between the thermal part and the hydromechanical behavior. Despite this, many teams managed to get a rather good estimate of the final state of the barrier in all three tests. One reason for this may be that the uncertainties in the initial conditions allow for more freedom in the setup of the models.

One of the main challenges in modeling swelling materials is the capacity of the models to perform predictive simulations. The presence of initial heterogeneities in these materials or heterogeneities due to external conditions increases the complexity of predicting the evolution of swelling clay materials. Tests performed within the BEACON project were simulated to evaluate the ability of the models to predict the hydromechanical evolution of bentonite. Two tests were already finished at the beginning of the project. All the data available on these tests were given to the partners. The purpose was to have a first calibration step. For these tests, the bottom part of the cell was filled with bentonite pellets with an average dry density close to 1.30 g/cm$^3$ and the top part with a bentonite block with a dry density of 1.60 g/cm$^3$ (Fig. 1). Hydration with deionized water took place through the bottom. In the first case, constant pressure was imposed, and in the second, a constant flow was imposed. One test was

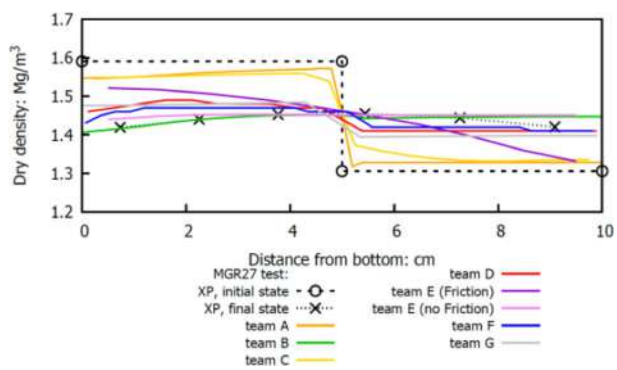


**Fig. 2.** Dry densities at saturation for the experiment used for predictive modelling.

**Table 1.** Mechanical constitutive models used in the benchmark.

| Team | Model |
|---|---|
| A | Bishop effective stress; modified CamClay |
| B | Hysteresis Based Material (HBM) model |
| C | Double-structure hypoplastic model for expansive clays |
| D | ACMEG – TS elastoplastic model |
| E | Internal Limit Model (ILM) |
| F | Modified Barcelona Basic Model (BBM) elastoplastic model |
| G | Elastic with modulus depending on water saturation |
| H | Modified BBM with double structure ICDSM |
| I | Modified Barcelona Expensive Model BExM |

selected for predictive modeling. The results of this test were not given to the participants. The conditions of the test were similar to the first test, except that the pellets layer was located in the upper part of the cell and the block in the lower part. Predictive simulations of water intake, dry densities, gravimetric water content, and stresses were expected on this test case. The results from the predictions of dry densities as well as the experimental results, can be found in Figure 2.

The water intake with time was well modeled by most teams. However, one may observe a number of variations or divergences. Moreover, prediction is less easy for early times of hydration. These globally good results may be surprising considering the large range of permeability used in the simulations by the different teams. As seen in Figure 2, the final (at saturated state) dry densities are well reproduced by many of the models. They do not depend significantly on the mechanical models (including law and friction aspects). It was very difficult to predict the stress's final value and time evolution. Stress evolution showed much variation between teams. Comparing mechanical behavior is not an easy task. Each team has a different conceptual model, and few parameters are comparable. A short synthesis of the mechanical constitutive models used by the different teams is presented in Table 1.

Two teams modeled friction at the cell wall–bentonite interface. These teams managed to satisfactorily blind-predicted the evolution of axial stress in the test.

Direct application to real assessment cases in actual repository systems has also been tackled. A few cases from relevant repository systems were therefore selected as test examples. Three cases were proposed: (1) a tunnel plug based on the Andra design, (2) a disposal cell from the Nagra concept, and (3) the KBS-3 deposition tunnel backfill (SKB, POSIVA). These are representative of the primary areas of uncertainty in density homogeneity. Here, the teams divided the cases, and only 3−4 teams modeled a particular case. The results from the modeling showed a rather strong divergence in results for the final dry density distribution for all three cases. For the Andra and SKB cases, the calculated values were still within the range acceptable for repository performance, but that was less true for the Nagra case. This shows that there are challenges to moving from modeling laboratory and field experiments, where results are available, to simulations of repository performance.

### 3.2 Development and improvement of numerical methods and tools for modeling coupled processes (DONUT)

In addition to the specific R&D work that will be conducted, a specific outcome of DONUT is the definition of a well-described benchmark problem that can be used to validate the newly developed simulator capability. While international benchmarks initiatives exist [15–17], the goal here is to define benchmarks of methods and tools to quantify efficiency and added value in terms of:

- increase of knowledge (e.g., better physical representation, integration of couple processes).
- Accuracy, robustness, computational cost.
- Robustness of scale-transition approaches.
- Ability to manage uncertainty and sensitivity analyses.

Recently, Bildstein et al. [17], in a guest editorial to the subsurface environmental simulation benchmarks special issue, mentioned emerging benchmarking opportunities. Amongst others, machine learning was identified. Indeed, it is considered a recent disruptive technology in the field of reactive transport and will possibly unlock the next generation of simulation that requires highly demanding CPU time [18,19]. The high computing cost associated with chemical equilibrium calculations is typically the most demanding one in comparison to fluid flow or heat transfer. To circumvent this issue, the use of surrogate models is promising, with first implementations providing an impressive speed-up between one and four orders of magnitude without loss in accuracy [20–22]. The observed speed-up depends on the chemical system, simulation code, application, and problem formulation [20–22]. These developments have been possible due to technological and scientific advancements both in terms of the available increasing computing power and the recent breakthrough of machine learning algorithms and relevant open-source software. Therefore, the need for a benchmark that tackles these emerging technologies is timely and will serve as the basis for future developments in the field. Within this context, DONUT defines a benchmark related to machine learning and geochemistry. It aims at mainstreaming and catalyzing the use of machine learning in reactive transport by providing a point of reference for testing and addressing the challenges relevant to (i) producing high-quality training datasets, which will be possible to be used by all available machine learning techniques, (ii) implementing several machine learning algorithms to learn from the generated data such as deep neural network learning, Polynomial Chaos Expansion and Gaussian processes, among others, (iii) testing the accuracy of predictions for geochemical calculations, reactive transport, and uncertainty analysis. Joint efforts across EURAD have resulted in the definition of two nuclear waste management relevant benchmark cases. The first focuses on uranium sorption in claystone, and the second is relevant to the temporal evolution of cementitious systems. While the first one is more related to the long-term/far-field radionuclide migration, the second one tackles the behavior of cementitious materials, which is one of the major construction materials commonly found across all EBS concepts. The test cases are designed with increasing complexity in terms of system dimensions in order to identify the limitations of these techniques relevant to the computational cost of training, efficiency, and accuracy during runtime. The uranium sorption case considers surface complexations. The cementitious system includes the precipitation of CSH-phases and the formation of solid solutions. Both cases will consider the presence of $CO_2$.

The thermodynamic modeling is done using the major geochemical solvers, which are currently used across EURAD (PHREEQC, GEMS, ORCHESTRA), and an excellent agreement between the solvers is observed. The use of open-source software is pursued across the benchmark, and the dissemination of training datasets and the release of the jointly developed algorithms for generating the training datasets and testing the accuracy is foreseen.

### 3.3 Assessment of the chemical evolution at disposal cell scale (ACED)

One of the central elements in ACED is modeling the chemical evolution at the disposal cell scale. This aspect is presented here as an example of the modeling studies in ACED. Although each country program in Europe has its own particularities, some common features in their designs can be identified [23]. Figure 3 shows the four generic disposal cells representing some of the main features of disposal cells throughout Europe. For a high-level waste representative disposal cell, there is a 30 cm Portland-based concrete or a 75 cm bentonite buffer between the vitrified waste (borosilicate glass type) surrounded by a 5-cm thick carbon steel canister and the clay or granitic host rock. The intermediate disposal cell consists mainly of different types of cementitious materials ranging from high-quality functional concrete for waste container walls to backfill mortar. Waste containers are filled with cemented organic waste or bulk steel waste backfilled with mortar. A disturbed excavation zone is considered in the clay host, whereas the granitic host rock has fracturated.

Depending on the disposal cell, some of the following geochemical processes are included: (i) aqueous complexation, (ii) redox reactions, (iii) cation exchange, (iv) surface complexation, (v) mineral dissolution and precipitation (kinetic/equilibrium), (v) solid solutions, (vi) kinetic corrosion of the steel components with the formation of corrosion products and interaction with cement or bentonite, and (vii) kinetic glass dissolution models. In the case of the high-level waste, 2 periods were considered: (i) transient thermal and/or hydric stage assuming an intact canister, (ii) period after canister failure with glass dissolution and interaction with corrosion products.

Simulations were performed with advanced state-of-the-art coupled reactive transport codes such as $CORE^{2D}V5$ [24], iCP [25], HYTEC [26], and the latest version of OpenGeoSys [27].

Because of symmetry reasons, the high-level waste disposal cells are simulated in a 1D-radial geometry (Fig. 4, top left). For the transient stage (Period II) and the period after canister failure (Period III), a base case simulation and sensitivity cases are performed. Figure 4 shows some selected results. Model results for the HLW disposal cell in granite (Fig. 4, top right) show that after 25 000 years before the canister breached, magnetite, siderite, and greenalite precipitated in the bentonite near the canister. Small amounts of siderite and greenalite precipitate 0.1 and 3 dm in the bentonite at 25 000 years. The calculated concentrations of exchanged and sorbed $Fe^{2+}$ in the bentonite increase near the canister interface. After the canister breaching, $H_4SiO_4$ diffuses from the glass into the bentonite, causing the precipitation of greenalite. Magnetite redissolves, and greenalite and siderite precipitate. The pH values are 8.2 in the glass, 8.8 in the canister, and 8 in the bentonite. Figure 4 (bottom left, HLW disposal cell in clay) shows the evolution of minerals and pH in the grout cell next to the canister in case of a transient temperature evolution (purple line) for a sensitivity case considering a thin young cement (5 cm). Temperature influences the effective diffusion coefficient and the solubility of the minerals. In this specific case, complete portlandite dissolution occurs faster compared to a case with a constant temperature at 25°C (100 y compared to 300 y). The modeling of the full system (Fig. 4, bottom right) showed that the driving force is the chemical destabilization of the concrete buffer by the clay rock. This perturbation (decalcification, sulphate attack, carbonation) slowly propagates by diffusion towards the steel overpack with a pH decrease. Overpack water tightness is set as long as the pH is larger than 10.5, then steel corrosion increases significantly, forming magnetite and Fe(II)-silicates. The precipitation of the latter seems to sustain glass dissolution as long as the remaining steel still corrodes.

A two-dimensional model was selected for the intermediate waste simulations in clay rock, although axis symmetry was also applied Figure 5 (top left) to save computational time. Geochemical interactions in a fully saturated system are simulated for $10^5$ y. The model does not consider the waste inside the package but only the walls of the container. However, the geochemical evolution

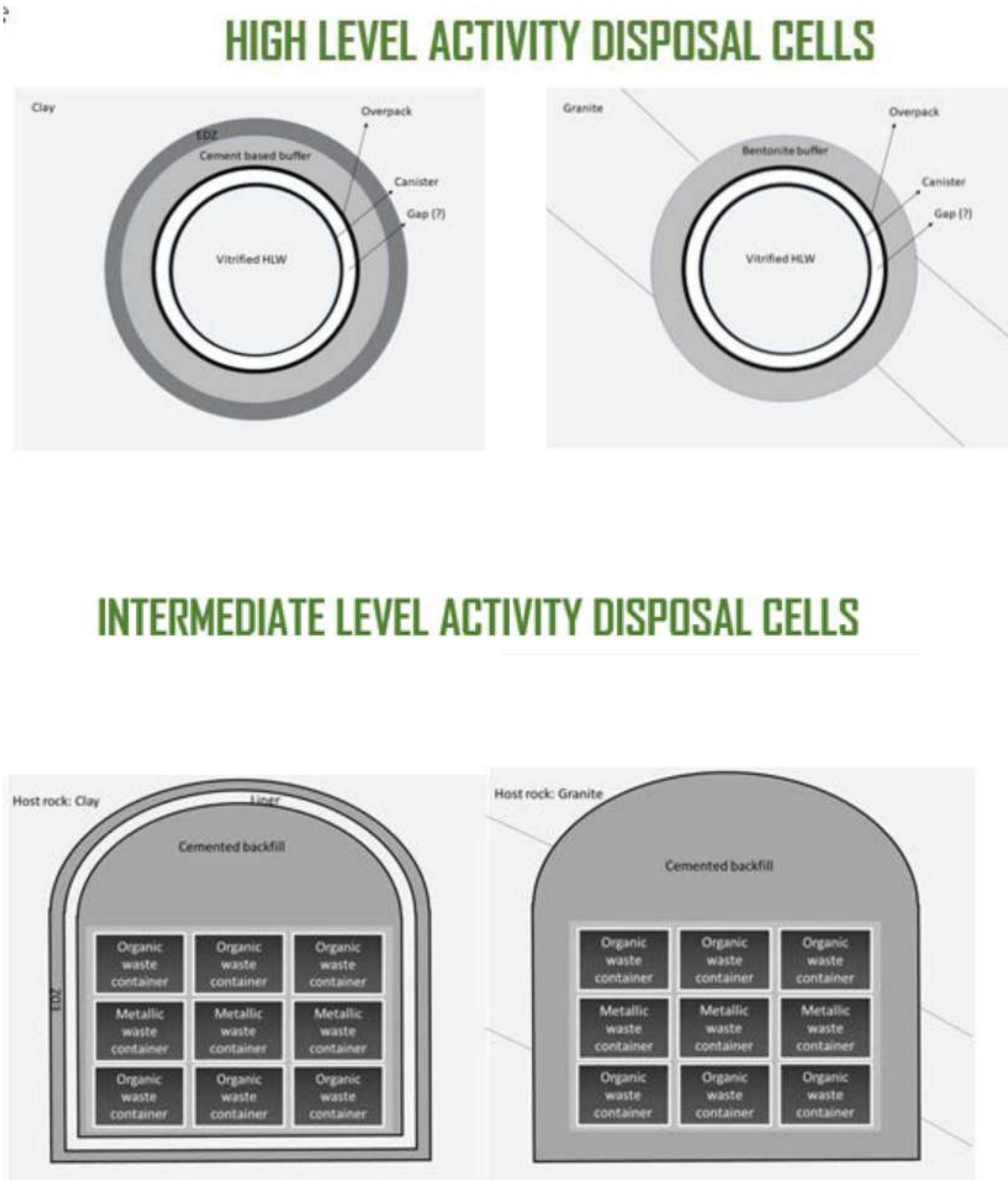


**Fig. 3.** Schematic representations of the four generic disposal cells considered in ACED for high level radioactive waste (top) and intermediate radioactive waste (bottom) in clay (left) and granite (right) rocks.

and gas generation of one organic waste drum inside the container was simulated by Huang et al. [28] for 150 years and open to the atmosphere – this information from the waste package scale will be incorporated at the disposal cell scale at a later stage. Figure 5 (top–right) shows the spatial distribution of portlandite after $10^5$ y. Due to the geometry of the disposal cell, a space-dependent dissolution pattern of portlandite is observed, with significant amounts of portlandite remaining at the concrete walls. On the other hand, precipitation of the calcite at the host rock at the interface occurs more uniformly (Fig. 5); bottom, one observes darker red zones around the disposal cell with increasing interaction time). Also, other geochemical variables (pH, pore water composition), as well as microstructure (porosity), and corresponding transport properties, evolve in a complex space-time manner [29].

In the case of the intermediate waste simulations in crystalline rock, the 1D model considering water inflow to the disposal cell from the left side is assumed at the present moment (Fig. 6) in analogy to the work performed by Idiart et al. [30] which will be extended to a 2D model.

The models illustrated above are cost computing demanding. Therefore, model abstraction will help reduce these complex models to their essential components and processes while preserving the validity of the model for the specific purpose [31]. The following two broad families of abstracted models are envisaged: (i) construction of lower-fidelity numerical models by using (a) a predefined

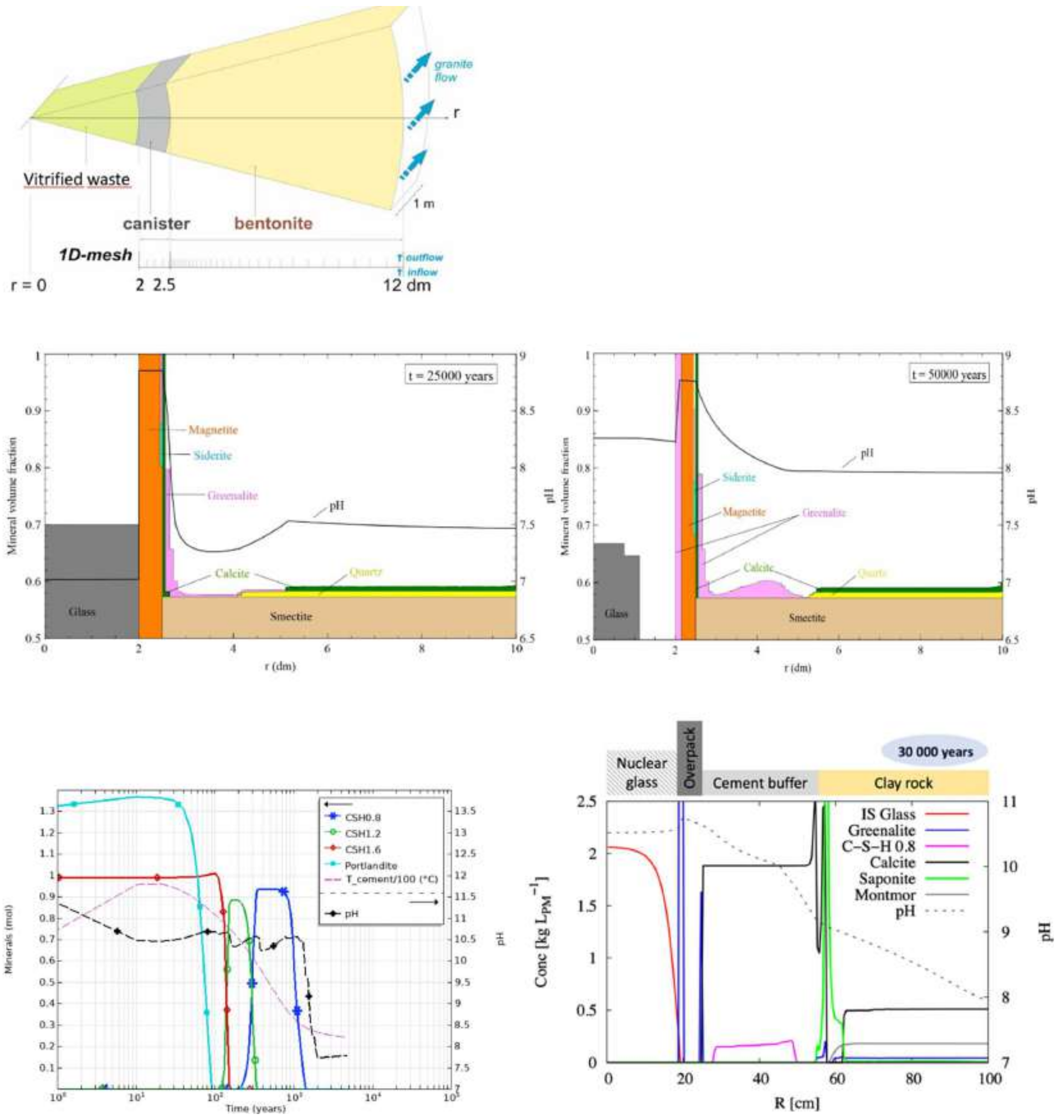


**Fig. 4.** (Top) 1D radial geometry of the HLW disposal cell in granite, (middle) CORE 2D modelling of the geochemical evolution in a HLW disposal cell in granite, (bottom left) HLW disposal cell in clay: transient stage with variable temperature in cement (first cell next to liner), (bottom right) HLW disposal cell in clay: HYTEC modelling of the evolution of the mineralogy of the full disposal cell components after 30 000 years of interaction.

hierarchy of models, (b) delimiting the input domain, (c) scale change by upscaling or aggregation, or (d) reducing numerical accuracy, and (ii) using response surface surrogates of (a) input-output relations of the whole model, (b) the geochemical calculations, or (c) process models.

### 3.4 Chemo-mechanical evolution of concrete barriers (MAGIC)

As MAGIC started recently and results are not available yet, we describe here the strategy in model development in view of the WP objectives. Modeling activities within MAGIC consider all relevant scales from the nano (cement paste) to the safety structure scale (i.e., reinforced concrete). Keeping in mind that the general objective of the modeling activities is to obtain long-term chemo-mechanical models for Portland and low-pH concrete-based material degradation exposed to relevant deep disposal environments.

Concrete degradation, in the time frame of deep disposal, embraces the conjunction of multi-scale coupled processes, occurring from the excavation and construction of the repository until the disposal of the waste for 1 million years (see Fig. 7). Many coupled processes occurring during concrete degradation are inherently multi-scale due to dynamic localization effects (i.e., deformation, reactions, or micro-cracking), which require special constitutive models and numerical methods. Individual processes are often best described on different scales depending on their phenomenology and the scales of their experimental characterization. Consequently, different processes,

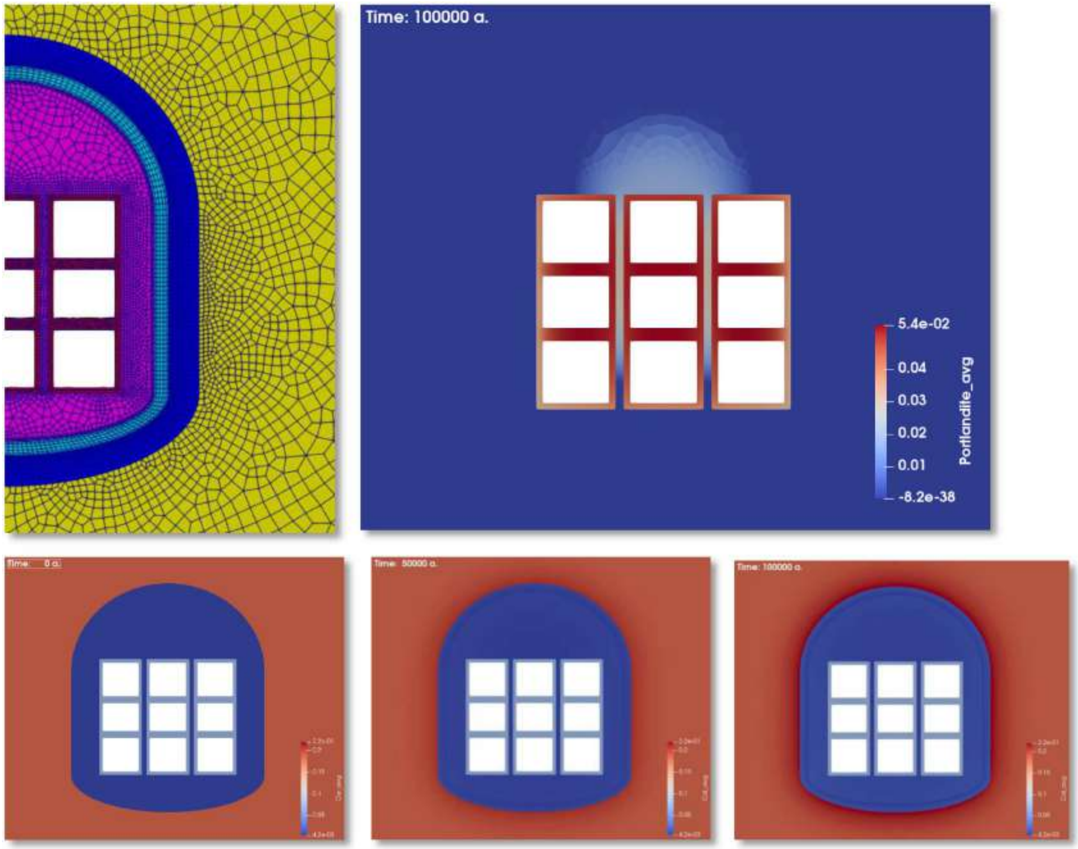


**Fig. 5.** (Top left) Two-dimensional axis-symmetric simulation domain intermediate level waste in clay. Dark blue area is the excavation damaged zone, yellow is the clay host rock, other colors different types of cementitious materials, the height of the disposal cell is about 13 m. (Top right) Portlandite distribution after 100 000 y. (Bottom) Evolution (50 000 yr, and 100 000 y) of calcite precipitation in the host rock.

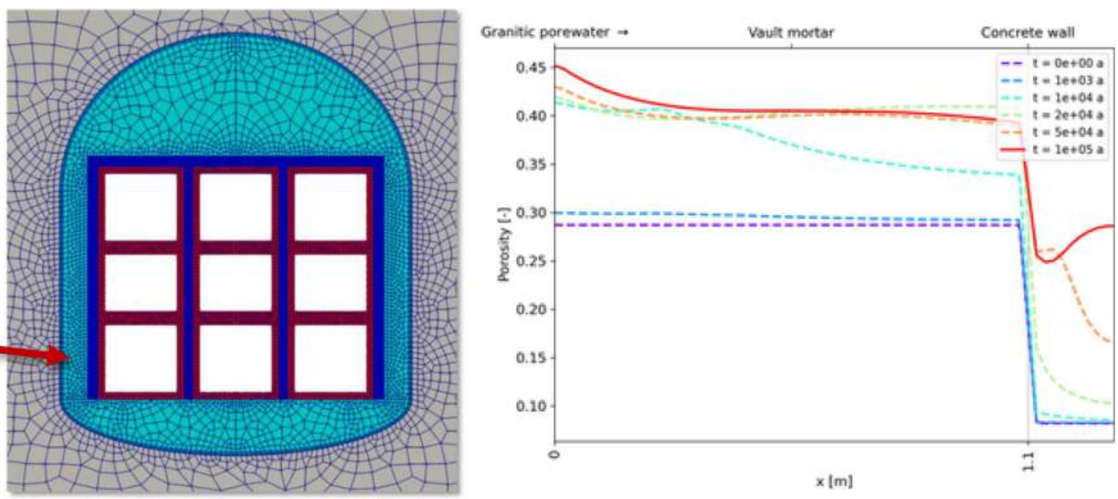


**Fig. 6.** (Left) Disposal cell representation and indication of the water flow (Darcy velocity $(q) = 1.03 \times 10^{-11}$ m/s) direction (red arrow). (Right) Porosity changes as a function of disposal time in the different cemented barriers.

software, and scientific communities have evolved in different directions (i.e., reactive transport and T-H-M modeling). As a result, chemo-mechanical coupling in concrete degradation studies is often neglected despite its importance, not for scientific reasons but due to a lack of technical capabilities and interaction/collaboration between experts in the relevant distinct fields.


| Loading | Construction | Operating phase | Waste disposal | Post-closure |
| --- | --- | --- | --- | --- |
| Thermal (T) | Initial conditions and properties of the damaged zone (EDZ) of the rock | Ventilation | Waste heat | T. stabilization |
| Hydraulic (H) | | Humidity effects | Unsaturated media | Saturated media |
| Mechanical (M) | | Rock convergence | Rock convergence | Rock convergence |
| Chemical (C) | | Atmospheric carbonation | Porewater Interaction | Porewater Interaction |

**Fig. 7.** Scenario of T-H-M-C loading in repository systems.

Within MAGIC, a multidisciplinary team of material scientists, chemists, and engineers is developing the coupling of different reactive transport and mechanical codes (finite element codes). For example, this is the case of chemo-mechanical coupling expansion between the HYTEC reactive transport code [32] and the Finite Element code CASTEM [33] or OpenGeoSys [34]. This later development is also connected to the EURAD DONUT WP. An interface for transferring material parameters from pore scale Lattice Boltzmann simulations into the T-H-M-codes is also under development [22,35]. Regarding the upscaling methods from nano to the representative elementary volume, Reduced Order Models (ROM) and an analytical multi-scale model framework for the aggregate-scale HMC models is being built. The integration between the micro- and large-scale processes and the multi-scale algorithm is being tested against available experimental data at the laboratory scale.

Interdisciplinarity between chemistry, physics, and mechanics can be illustrated on one of the structures that receive the greatest mechanical loading and chemical degradation to know the vault/liner of the low and intermediate-level waste emplacement gallery. Indeed, the liner is exposed to (i) the mechanical loading induced by the surrounding rock, (ii) concrete aging during the long term of disposal, and (iii) chemical disturbance due to the contact with the rock. All these processes increase the risk of fracturing, affecting the integrity of this disposal component [36]. Previous structural chemo-mechanical models decoupled the macroscopic modeling from the mesoscopic phenomena [37]; however, in order to compare concrete made of the different matrices, a non-linear analytical homogenization model for the chemical-mechanical behavior of concrete will be implemented. This model is able to manage the cement paste versus the chemical state of the concrete and will be reflected in the mechanical properties (Young's modulus, compressive and tensile strength, creep rate of concrete, and anchorage of steels). Furthermore, during the chemical damage processes (leaching, carbonation, or chloride ingress in the hydrated cement paste), the model also considers the amount and nature of aggregates on the macroscopic residual mechanical properties. In the case of reinforced concrete, which is the material considered in this structural component, until now, the phenomenon of reinforcement corrosion was decoupled from the chemical state of the concrete [38]; hence the lock to be lifted in this chemo-mechanical model consists in predicting the steel corrosion progress as a function of the concrete chemical state at the interface and in localized cracks; and deducing its effect in term of steel anchorage and their contribution on reinforced concrete mechanical performances [39].

The model implementation is done in a Thermo-Hydro-Chemo-Mechanical finite element code, able to compute the evolution of a tunnel over several thousand years [40]. Once implemented, it shall allow a more accurate prediction of the lifetime of radioactive waste disposal structures, but also the simulation of their very long-term behavior under mechanical loading (induced by rock convergence) and physicochemical degradation caused by porewater (carbonation, leaching, corrosion of the reinforcement bars...). Different cement binders (low pH or ordinary Portland cement based) are under consideration to perform comparative studies of envisioned solutions.

## 4 From individual contribution to complementary added value

While every project by itself will bring novelty and scientific excellence by answering the research questions defined in the project and will integrate knowledge from different scientific communities, they complement each other with the final goal of having a holistic understanding and description of the evolution and performance of the EBS leading to a scientific basis for integrated multiphysic-multiscale modeling of that system, bringing an even bigger added value.

The added value of each individual project should, of course, not be neglected. For example, the BEACON project has made a significant contribution by improving knowledge of bentonite behavior and the simulation of bentonite-based components for the radioactive waste underground repository. While a big part of the project was devoted to modeling and model development, implementing experimental tests using novel techniques such as imaging provided important data to calibrate and feed the models, especially to describe the coupling between micro and macro scales. The modeling teams participating in BEACON have significantly improved the capabilities of their models through the test cases proposed and simulated along the project. As a result of these developments and improvements, 10 teams are now equipped with coupled THM models that reasonably represent the behavior of bentonite-based components in the context of an underground radioactive waste repository. Thanks to this, they were able to model test cases representative of the engineered barrier and sealing concepts proposed by SKB, Nagra, and Andra in the final modeling stage. Teams are generally able to reproduce and predict the mechanical evolution of bentonite in small-scale and large in-situ experiments, particularly the final swelling pressures, dry densities, and degrees of saturation of the bentonite. These are key safety indicators for bentonite used as a buffer or seal in geological disposal facilities for radioactive waste. The progress made throughout the project is illustrated by the improved agreement between models and experiments. This is a consequence of model updates with the inclusion of friction, improved formulations of water retention curves, inclusion of thermal effects, and the development of numerical solvers.

For ACED, DONUT, and MAGIC, it is too early to have a similarly comprehensive and outstanding review of the conducted work. Scientific publications (e.g. [28,41–43]) in a wide scope of journals already exist or are foreseen. Reports generated in these work packages and related scientific publications demonstrate for DONUT a better representation of multi-physical, multi-scale processes of radioactive waste disposal, for ACED a better representation of chemical interaction inside the EBS, for MAGIC integration of multi-scale phenomena in long-term chemo-mechanical models, and all cross-fertilization.

Beyond a better capability to integrate complex interacting processes in a relevant model to decipher the behavior of EBS on a long-term perspective and gain confidence in model abstraction and simplification made either for performance assessment or safety case calculation (see Sect. 5), all four projects actively contribute to knowledge management. Indeed, at the beginning of each project, the state-of-the-art has been gathered and published either as a report for ACED [44], MAGIC, and DONUT [45] or for BEACON as a database integrating a description of experimental tests and the relevant information on the THM models used to represent the behavior of bentonites. As mentioned in the introduction, the different projects respond to a strategic research agenda that meet the priorities of research entities, TSOs, and WMOs. Updated state-of-the-art reports resulting from the research, activities, and joint work in these projects form an important input to adjust the future strategic research agenda. Moreover, documented and archived project data (including computer models) and results are crucial for knowledge transfer across generations and to early-stage national programs.

## 5 Model abstraction and simplification

As detailed by Govaerts et al. [31], performance and safety assessment and supporting models often need to be relatively simple and/or fast to allow computations for large scales and extremely long time scales or to execute it many times with different parameters for sensitivity and uncertainty analysis. Within the above-described projects or work packages, complex (in terms of couplings, concepts, geometries, etc.) and computationally intensive models were developed. To be operational, in the context of a performance and safety assessment, it implies model abstraction as to said, a methodology for reducing the complexity or the computational burden of a simulation model while maintaining the validity of the simulation results with respect to the question that the simulation is being used to address [46].

Within EURAD, a comprehensive review has been carried out for model abstraction [31]. Even though it was oriented towards reactive transport, the principles and guidelines given in the review can be applied to all the models developed in the above-mentioned projects. Firstly, the need for model abstraction should be justified in terms of the saved computational cost. Secondly, the context of the modeling problem has to be reviewed to ensure the objectiveness and comprehensiveness of the model abstraction. Thirdly, model abstraction techniques (e.g. surrogate models) have to be selected to simplify the model. Fourthly, it is necessary to carry out verification calculations to ensure the abstracted model performs sufficiently accurately. Fifthly, the justification, abstraction process, and verification have to be reported in a traceable and transparent way. And last but not least, the benefits of abstraction have to be reaped, for example, in a local or global sensitivity analysis.

## 6 Conclusion

Three work packages (ACED, DONUT and MAGIC) of the EURAD joint programming initiative and an H2020 project named BEACON contribute to improving understanding of and capabilities for assessing the long-term evolution of engineered barrier systems. And last but not least, they support knowledge management and encourage collaboration between scientific communities.

## Conflict of interests

The authors declare that they have no competing interests to report.

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## Data availability statement

This article has no associated data generated.

## Author contribution statement

F. Claret, A. Dauzères, D. Jacques, and P. Sellin discussed and designed the architecture of the papers, checked the consistency of the manuscript, and wrote the paper. B. Cochepin, L. De Windt, J. Garibay-Rodriguez, A. Mon Lopez, L. Montenegro, V. Montoya, J. Samper contributed to the writing of the part dealing with the ACED WP, N. Prasianakis contributed to the writing of the part dealing with the DONUT WP, V. Montoya contributed to the writing of the MAGIC WP and O. Leupin and J. Talendier contributed to the writing of the BEACON project. J. Govaerts wrote the part dealing with model abstraction.

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REVIEW ARTICLE

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# EURADWASTE'22 Paper – Host rocks and THMC processes in DGR

## EURAD GAS and HITEC: mechanistic understanding of gas and heat transport in clay-based materials for radioactive waste geological disposal

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**Abstract.** Deep geological disposal aims to contain and isolate radioactive waste from the biosphere. Repository systems are made of multiple barriers working together, typically comprising the natural geological barrier provided by the repository host rock and its surroundings and an engineered barrier system. Due to their excellent properties for the confinement of contaminants, including low permeability, high sorption capacity, and swelling/self-sealing capacity, clayey materials are considered as engineered and/or natural barriers in most repository designs under development in Europe. During the lifetime of the repository, clay barriers will be exposed to perturbations, among which those are resulting from gas and heat production within the system. It is important to verify that these perturbations will not be detrimental to the good functioning of these barriers. In this paper, it is shown how the two EURAD R&D work packages, GAS and HITEC use a combination of experimental and modelling approaches to increase the understanding and predictability of the impact on clay barriers of the fundamental processes and their couplings related to gas and heat transport respectively, providing building blocks to support the evaluation of the robustness of the repository concepts.

## 1 Introduction

Deep geological repositories for the disposal of radioactive waste generally rely on a multi-barrier system to contain and isolate the waste from the biosphere. This multi-barrier system typically comprises the natural geological barrier provided by the repository host rock and its surroundings and an engineered barrier system (EBS). The EBS represents the man-made, engineered materials placed within a repository, including, among others and depending on the disposal concept, waste canisters, buffer materials, backfill, concrete lining and seals. This multi-barrier principle creates the overall robustness of the system that enhances confidence that the waste will be successfully contained, as the natural barrier provides a stable environment that allows the EBS to function for hundreds to thousands of years, depending on the disposal concept. Moreover, the geological barrier itself can contribute to the confinement of radionuclides that would eventually be released after the degradation of the engineered barriers. Owing to their excellent properties for the confinement of contaminants, including very low permeability, high sorption capacity and swelling/self-sealing capacity, clay-based materials are often considered for use as part of the engineered barriers in about all repository designs under development. Clay formations are also considered as potential hosts for geological disposal in several European countries.

During the lifetime of the repository, clay barriers will be exposed to repository-induced perturbations, which result from gas and heat production within the system. It is important to verify that these perturbations will not be detrimental to the good functioning of these barriers.

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Considerable amounts of gas can be generated in a repository containing radioactive waste. The largest fraction of the gas is expected to be hydrogen produced by the anaerobic corrosion of steel and reactive metals in the waste, their packaging, and the EBS. The degradation of organics and radiolysis also produce gas. Even though the gas production processes are generally slow, it is important to verify that these will not be detrimental to the good functioning of the disposal system. The low permeability of clays that is favourable with respect to the containment function of a repository also limits the evacuation of the generated gas. It is possible that gas could be generated at a faster rate than it can be removed through the engineered barrier components and the host rock by diffusion of dissolved gas, resulting in the development of a pressurised gas phase within the repository and its surrounding. The accumulated gas could then escape from the repository by creating discrete, gas-specific pathways (e.g., fracturing or pathway dilation) through the EBS and/or the host rock. In addition, the potential release to the biosphere of gas containing volatile radionuclides is also an issue that needs to be considered.

The heat produced by radioactive decay in the waste matrix will be transported, mainly by thermal conduction, to the bedrock surrounding the repository. In the beginning, the heat production is high, and therefore most concepts limit maximum disposal container surface temperatures to 100°C to protect clay-based buffer, backfill and host rock materials from undesirable evolution; the temperature gradients will also be high. When temperature increases in a low permeable media like clay host formations, the pore water is pressurised because of the difference between its thermal expansion coefficient and that of the solid skeleton of the clay. In the near field characterised by an excavation damaged zone, this could induce fracture re-opening or propagation, thus increasing the permeability. In the far field, this could induce damage and reactivate fractures/faults. On the other hand, the increased temperature in buffer bentonite may result in changes in buffer material, strong evaporation near the heater and vapour movement towards the external part of the buffer. Accepting higher temperature limits could have significant advantages, such as allowing the disposal of higher enrichment/burn-up spent fuels, shorter interim storage/cooling requirements, easier (re)packaging of the waste and a reduced disposal facility footprint, and so needs to be considered.

The WP HITEC and WP GAS of the European Joint programme EURAD aim to increase the understanding and predictability of the impact on clay barriers of the fundamental processes and their couplings associated with the thermal and gas perturbations. In this paper, the raisons d'être of these two WPs are first presented. It is then shown how the integration of experimental and modelling approaches can provide building blocks that can be used in multiple national programmes to support the conceptualisations of gas and heat transport through clay barriers and evaluate the robustness of the proposed repository concepts.

## 2 The GAS work package

### 2.1 Work package's raison d'être

Work Package 6 of the EURAD European Joint Programme 'Mechanistic understanding of gas transport in clayey materials' (WP GAS) focuses on gas transport in natural and engineered clayey materials. It aims:

- to improve the mechanistic understanding of gas transport processes in natural and engineered clayey materials, their couplings with the mechanical behaviour and their impact on the properties of these materials;
- to evaluate the gas transport regimes that can be active at the scale of a geological disposal system in clayey host formations and their potential impact on clayey barrier integrity and repository performance.

The first raison d'être of this WP is to provide results that apply to a wide range of national programmes in clayey host rock. This is possible because the results of previous efforts on the identification and characterisation of the possible gas transport processes suggest that the mechanisms at play in different clays are generally similar, while the conditions (gas pressure, stresses/deformations, saturations, ...) for the transition from one transport regime (diffusion, two-phase flow, pathway dilation and fracturing) to another strongly depend on the specific properties of a given clayey material.

The second raison d'être of this WP is to transfer knowledge gained from laboratory and in situ experiments to configurations that are commonly found in current repository designs in clays to address key questions from the end-users:

- how could gas be transported throughout the clayey disposal system, and which water-soluble and volatile radionuclide transport could be associated with it?
- how and to what extent could the hydro-mechanical perturbations induced by gas affect clayey barrier integrity and long-term repository performance in clayey host formations?

This WP builds strongly on the return of experience, results and conclusions from the past FORGE EC project [27]. The experimental investigation of gas transport in clayey materials in FORGE revealed complex mechanisms, e.g., the development of discrete, unstable pathways controlled by the mechanical behaviour of the porous media. However, it was also suggested that this complexity could be addressed if one can bound the effects of these mechanisms using simpler and robust descriptions for evaluation purposes. The WP GAS of EURAD aims then at increasing the confidence in the overall understanding of gas behaviour in clayey materials gained from FORGE and improving its integration in the conceptualisation process for the different clayey components of a disposal system. This should, in turn, support and justify the use of robust evaluation approaches and confirm the expert judgment at the end of FORGE that gas is not a showstopper for geological disposal but a question of managing uncertainties [22].

### 2.2 Key objectives and work programme

The Work Package GAS aims to increase the understanding and predictability of gas transport in different clayey host rocks (Boom Clay, Callovo-Oxfordian claystone and Opalinus Clay) and clayey engineered barriers (MX-80, BCV and FEBEX bentonites) of geological disposal systems. It also aims to support the stepwise integration of the knowledge on gas transport and its effects in conceptualisations of the functioning of a disposal system in support of the safety case.

To reach these objectives, the work programme of the WP is defined through three scientific tasks: a first dealing with the 'transport mechanisms' of gas, a second dealing with the 'Barrier integrity' and a last dealing with 'Repository performance aspects'.

The WP GAS produces new data and develops new process-level models to improve mechanistic understanding of transport processes in natural and engineered clayey materials, including couplings with mechanical behaviour and impact on the material properties. Experimental work that is carried out determines, for each identified gas transport regime, the conditions under which that regime is possible in clay materials representative of host formation and clayey EBS components. Data obtained are pertinent from low (diffusion) to high (advection) gas transport rates.

This WP also illustrates how knowledge gained from laboratory and in situ experiments can be integrated into the conceptualisation of gas transport through different clayey components of a disposal system and how gas could affect (or not) the performance of the system. This work carried out involves (i) the development of phenomenological descriptions of gas transport and of its likely consequences at the relevant scale and (ii) the testing of different approaches to represent the effects of gas at the repository scale and bounding its consequences in terms of repository performance.

## 3 The HITEC work package

### 3.1 Work package's raison d'être

The Work Package 7 of the EURAD European Joint Programme 'Influence of Temperature on Clay-based Material Behaviour' (WP HITEC) aims to develop an improved thermo-hydro-mechanical (THM) understanding of clay-based materials (host rocks and bentonite buffers) exposed at high temperatures (>100°C) or having experienced high-temperature transients for extended durations. The WP's raison d'être is to evaluate whether or not elevated temperature limits (up to 150°C) are feasible for various geological disposal concepts for high heat generating wastes (HHGW). HITEC studies clay host rock formations, document and establish the possible extent of elevated temperature damage in the near and far field (e.g., from over-pressurisation of water due to temperature increase) and also indicates the likely consequences of any such damage. The WP also looks at bentonite buffers and determines the temperature influence on buffer swelling pressure, hydraulic conductivity, erosion, or transport properties and see where the buffer safety functions start to be unacceptably impaired.

For the disposal of HHGW, it is important to understand the consequences of the heat produced (temperature and temperature gradients) on the properties and long-term performance of the natural and engineered clay barriers. Most safety cases for disposal concepts that involve clay currently consider a temperature limit of 100°C [33]. Being able to tolerate higher temperatures while still ensuring an appropriate performance would have significant advantages, e.g., shorter above-ground cooling times, more efficient packaging, fewer disposal containers, fewer transport operations, and smaller facility footprints. This WP has the potential to effectively integrate with the parallel SFC R&D WP (i.e., interrogate the validity of the currently applied thermal limits and also the importance of the accuracy of the assumed radiological waste properties) and consequently is the first step toward optimisation of the design architecture of the deep geological disposal.

### 3.2 Key objectives and work programme

The overall objective of HITEC is to evaluate whether an increase in temperature is feasible and safe by applying existing and work package produced novel knowledge about the behaviour of clay materials at elevated temperatures:

- to improve understanding of the THM behaviour of clay rock and engineered clay material (buffer) under high temperature and provide suitable THM models both for clay host rock and buffer,
- to better assess the effect of water overpressures, build-up induced by the heat produced from the radioactive waste on the THM behaviour and properties of the clay host rock, and
- to identify processes at high temperature and the impact of high temperature on the THM properties of the bentonite buffer material.

In the host clay formation task, the aim is to deploy new knowledge of the mechanics of clay in order to better evaluate and model possible damage evolution during the temperature transient phase and better assess the consequences of possible damage. This includes experiments, model development and model benchmarks.

In the buffer bentonite task, the aim is to deploy new knowledge on the mechanical behaviour of the buffer at high temperatures. The temperature impact on important processes is measured either after a high-temperature exposure or while the clay is at a high temperature. Processes that may have a temperature dependence are swelling pressure, hydraulic conductivity, erosion properties and transport of solutes.

Finally, HITEC aims to document all the above to be utilised in Safety Cases studies.

# 4 Conceptualisation of gas and heat transport trough repository in clayey host formations as considered in Europe

From past evaluations, it is known that gas generated by corrosion and/or radiolysis in large quantities may result in the development of a gas phase within the existing porosity of the EBS, within the excavation damaged zone (EDZ) and, to some extent, within the host formation. Experimental evidence suggests that discrete, transient, gas-specific pathways may also, or alternatively, form through (or between) EBS materials, the EDZ and the clayey host formation in the form of subcritical (pathway dilation) or supercritical (fracturing) cracks. The transient nature of such phenomena is to be emphasised.

Desaturation of the existing porosity because of gas invasion can have a significant effect on soluble radionuclide migration: it may limit the extent of diffusion of soluble radionuclides but may also result in advective transport of radionuclides if groundwater is displaced one way or another by gas as a consequence of pressurisation or suction. High levels of desaturation may even affect the gas source term by decreasing the availability of water for gas production processes. Continuous gas-specific pathways, possibly evolving and unstable, may form from the deposition zones to the repository access. Even though most of the gas flowing through these pathways would be inactive, it could also carry volatile radionuclides. Finally, high gas pressures may possibly result in mechanical damage to the clayey engineered and natural barriers, including the host formation. It is important to assess if this could occur in practice and if such damage would be transient only or would have a lasting effect and how this would affect (or not) the global functioning of the repository.

Most high-level waste types, spent fuel or reprocessed fuel, produce heat during the early post-closure phase of the repository life. The heat production typically decreases quickly so that the highest temperatures occur in the nearby field only decades after closing the (part) of the repository. The highest temperature in most concepts is limited to about 100°C at the surface of waste canisters. This temperature requirement has a big impact on the dimensioning of the repository and, therefore, not only directly affects the size and costs of the repository but also sets requirements for interim storage before final disposal. Therefore, accepting higher temperatures has many benefits, e.g., shorter above-ground cooling times, more efficient packaging, fewer disposal containers, fewer transport operations, and smaller facility footprints. However, applying higher temperatures even during the short period of time at the beginning of final disposal might have detrimental effects on the material properties of EBS and/or change the mechanical behaviour of those materials.

To guarantee that the migration of radionuclides will be delayed as long as possible for each type of waste, no alteration of the properties of clay host rock or clayey materials of the engineering barrier has to be induced by either the gas production & evacuation or by the temperature increase. To that goal, most concepts adapt the general architecture of the repository to:

i. have a sufficient expansion volume available in the porosity of the EBS, buffer & backfill for the gases generated after closure and a continuous release and evacuation through dissolution and diffusion or along existing pathways through the EBS, EDZ or interfaces by visco-capillary two-phase flow;
ii. limit temperature increase and its impact on the EBS in the near & far field host rock by adjusting the spacing between disposal packages and between galleries, respectively.

The current conceptualisations of gas and heat transport through repositories as considered in Europe are detailed in [17] and [32], respectively by the radioactive waste management organisations (WMO) and the regulatory technical safety organisations (TSO) working with the clayey host formations and/or bentonites considered in the WPs GAS and HITEC. Communication of these conceptualisations developed in several national programmes is based on ‘storyboards’. The storyboard elements are then compared to highlight the commonalities and explain the rationale for differences between the repository development approaches and the expected evolutions considered by the end-users within their respective national programmes in relation to gas and heat generation and transport. All these aspects are summarised in the following.

## 4.1 Comparison of repository design approaches

Unlike in crystalline and halite host rocks, there is still no geological disposal facility in operation or even in construction in a clayey host rock in Europe. For the moment, only France has selected a site in a clayey host rock, so it has been possible for Andra to define a complete repository concept for that site [2]. National programmes of other countries considering clay host rocks are at various stages of searching for a site and/or pre-design of a repository concept (e.g., [25,31]). Nevertheless, all those countries are targeting clay layers at a depth of a few hundred metres in their search for a site, and all participating WMOs are planning single-level disposal with separate zones for high-level waste disposal and long-lived intermediate-level waste disposal.

For all participating end-users, the concepts are different for high-level waste and long-lived intermediate-level waste. These differences relate mainly to (i) the geometry of the primary waste packages, (ii) the management of the thermal phase for high-level waste and (iii) the need to delay the migration of radionuclides as long as possible for each type of waste [17].

All participating WMOs include in their repository concept for high-level waste a disposal overpack made of steel. To delay the release and attenuate the migration of radionuclides out of the waste, two main approaches are envisaged:

- placing the steel overpack in a highly alkaline environment for as long as possible to slow down generalised corrosion and to guarantee the longest possible tightness of the overpack. The counterpart is that once the

tightness is lost, in the case of disposal of vitrified high-level waste, the glass containing the waste may degrade more rapidly if the alkalinity of the water is still elevated and release all the radionuclides over a relatively short period of time.
- Guarantee tightness only during the operating phase (possible safe handling of the waste packages, includes reversibility/retrievability period) and maintain the pH of the water around the packages at values that guarantee, in case of disposal of vitrified high-level waste, slow degradation of the glass once the tightness of the package is lost. The counterpart is that these low-alkaline waters imply faster corrosion of the steel of the packages and thus an earlier loss of tightness.

As far as gas generation is concerned, the first approach rather implies a lower gas source term (low corrosion rate) but longer in time, whereas the second approach implies a higher gas source term (higher corrosion rate) but of shorter duration.

Regarding long-lived intermediate-level waste, the primary waste packages that have to be dealt with in all national programmes generally have a wider variety of geometries (e.g., [23]) than primary packages of high-level waste, which are generally cylinders of about a few decimetres in diameter and between one and a few metres in length (e.g., [24]). In contrast, for long-lived intermediate-level waste, the primary packages may be drums of more diverse sizes. More than this, for high-level waste, considerations like criticality and thermal criteria have to be considered. As no damage to the clay host formation should be caused by thermal loading, it results in:

- high-level waste disposal cells are generally smaller in diameter, and the waste disposal packages are disposed of horizontally with only one package per cell section;
- long-lived intermediate-level disposal cells are generally larger in diameter, and waste disposal packages are disposed of either horizontally or vertically, with several waste packages per cell section, the optimal arrangement being partly driven by cost consideration.

In addition to the above elements that are important for the general architecture of the repository and, therefore, the expansion volumes available for the gases generated after closure, the following points related to the repository concepts are directly related to the generation of post-closure gases and are common to all programmes:

- high-level waste overpacks are made of steel, which represents an important source of hydrogen generation by anoxic corrosion.
- The lining of the galleries includes metallic elements, mainly reinforcing bolts and/or concrete reinforcement.
- Some long-lived intermediate-level waste contains (mainly or partially) metallic elements.
- Some long-lived intermediate-level waste (e.g., organic waste) may produce significant quantities of gas by radiolysis and/or (bio-)chemical degradation processes.

The sealing system is also an important component concerning gas migration after repository closure. For most participating WMOs and TSOs, it is dimensioned (usually by the definition of a water permeability below a certain value) to limit the flow of water containing dissolved radionuclides but with an induced effect on the transport of gases which are also fluids and for which it may represent a bottleneck for gas transport across the system. Therefore, some designs take explicitly into account the gas component in the dimensioning and choice of materials of the components of the sealing system [21].

### 4.2 Common phenomenological representations of the hydraulic-gas transient and the THM processes in clays

Regarding gas production mechanisms, other gases than hydrogen are produced in the repository, but the latter represents the main source term and evaluations are conducted assuming that only this gas is produced (except possibly in some sensitivity analyses).

The main mechanism producing hydrogen after the closure of the repository is corrosion of metals (principally steel) under anoxic conditions [7,26]. Radiolysis of organic matter and/or water is a secondary mechanism but not a negligible source term of hydrogen. Other production mechanisms (e.g., alpha decay which produces helium, or bacterial activity, which may produce additional gas or convert part of the hydrogen into methane) are studied but currently neglected in practice (except possibly in some sensitivity analyses). Gas consumption processes (like bacterial activity or pyrite oxidation) have been addressed in generic studies for gas-related repository optimisation, indicating a certain potential for reducing the build-up of gas overpressures in the backfilled repository structures [15]. However, due to the complexity of the associated microbiological processes, gas consumption is generally neglected for the sake of robustness of the assessment (except possibly in some sensitivity analyses).

The main mechanisms of transport of hydrogen at the repository scale (including the host rock) are advection for the part expressed in gaseous form and diffusion for dissolved gases. As detailed in [17], the main mathematical formulation used for advection is the Darcy formulation generalised to the water-gas two-phase flow. The relative permeability and retention curves are generally represented by van Genuchten/Mualem type relationships [20,30], but sensitivity analyses with other relationships are common as summarised in [17]. The main mathematical formulation used for diffusion is that of Fick generalised to water-gas two-phase transport. The impact of porosity and water saturation on diffusion coefficient is generally represented by Millington-Quirk type formulations [19]. Gas exchanges between the liquid and gas phases are generally represented by a Henry-type formulation (linear relationship between dissolved concentration and gas partial pressure, [14]).

Studies are in progress to increase support for using these gas transport process representations and refine these where needed, particularly in connection with phenomena associated with hydro-mechanical couplings (gas capillary thresholds, pathway dilation, degradation of concrete over time due to corrosion of the rebars, etc.) or hydro-chemical coupling (alkaline plume, effect of bacteria, etc.). The WP GAS of EURAD is expected to contribute to these efforts by extending the scientific bases about possible transport modes and couplings in clayey materials and gathering additional data in conditions relevant to the repository configurations considered in clayey host formations.

The thermal transient has been exhaustively investigated these last decades. For the clay host rocks and bentonite, previous knowledge indicates that an increase in temperature due to the presence of heat-emitting wastes will induce strong and anisotropic THM coupled responses within the clayey materials [18]. Although the effect of temperatures higher than 100°C has been studied concerning, for instance, mineralogical transformations of bentonites [16,28,29], less is known with respect to HM properties of clayey materials for this range of temperatures, mainly because of the testing experimental issues.

This relative scarcity of scientific bases at high temperatures has led to geological repository concepts for heat-emitting wastes that often limit maximum disposal container surface temperatures to about 100°C [33]. Higher temperature limits could have significant advantages, such as allowing the disposal of higher enrichment/burn-up spent fuels and shorter interim storage/cooling requirements. The WP HITEC of EURAD is expected to contribute to these efforts by extending the scientific bases on the THM behaviour of clays at high temperatures. Although the purposes and requirements of clay host rock and bentonite in repository concepts differ, their mechanical behaviour is studied both experimentally and numerically in a similar way.

### 4.3 Analysis of long-term gas-related repository transient

For countries that already have, if not a site, at least data on the two-phase behaviour of the target geological layer and that have carried out numerical evaluations of the long-term transient evolution of a repository under the action of gases, the overall evolution of the geological disposal facility with time includes similar structuring elements as detailed in [17] and illustrated in Figure 1 based on Andra concept.

At the time of closure, the remaining gases from the operational period are rapidly dissolved and diffused through the groundwater infiltrating the host rock (gas transport number 3 in Fig. 1).

After a certain period of time, which varies according to the repository concept and the properties of the host rock, dissolution and diffusion may no longer be sufficient to evacuate all the gas that is produced by anoxic degradation processes (mainly corrosion of metals) and a gas phase may develop in part or all of the repository (gas transport number 4 on Fig. 1).

This gas phase generally remains confined to the repository's system of disposal cells and galleries while the host clay layer remains almost saturated with water due to at least one of the following elements: very high gas entry pressure, high capillarity gradient once gas desaturates the media, very low permeability. Desaturation of the host rock, if it is considered to happen, would be restricted to the immediate vicinity of the galleries (metre scale), and saturation would not decrease by more than a few per cent in that zone.

The gas migrates towards the repository access structures (transport galleries, ramps, shafts) mainly by convection but also continues to dissolve into the surrounding groundwater along the way.

Along the way, gas flow is slowed down by the repository closure system, mainly by the seals.

While migrating, the gas is not expected to displace large quantities of water along the galleries mainly (i) because a limited desaturation of the EBS/EDZ is sufficient to obtain high enough transmissivities for gas and (ii) because water can be more easily pushed into the surrounding clay by gas than displaced along the galleries.

In some evaluations, a significant portion of the gas generated in the repository may reach the geological layer above the host rock under gaseous form through the shafts, ramps and/or the surrounding EDZ (gas transport number 6 in Fig. 1).

The duration of these phenomena linked to gas generation in the repository is of the order of several tens to several hundred thousands of years.

It cannot generally be excluded that gas pressure may reach values such that the transfer of gases will be controlled by hydro-mechanical couplings. This would materialise initially as an expansion of the connected pores ('dilatant pathway') and then possibly in the fracturing of the clay barrier material (in particular if this pressure exceeds the local minor mechanical stress). These effects are investigated in terms of gas transfer and material permeability.

In the frame of the WP GAS of EURAD, UPC/CIMNE geotechnical laboratory studies, for instance, the consequences of the passage of gas in Boom Clay and Opalinus Clay by analysing gas injection tests performed in oedometer cells at constant vertical stress [11,12]. They show that the bedding plane orientation plays a fundamental role in the volume change behaviour during gas migration (Fig. 2). Samples with bedding planes orthogonal to flow are less constrained and consistently displayed more significant expansions than samples with bedding planes parallel to flow. Estimation of the effective permeability to gas flow during the dissipation stages is, in general, higher than the measured for water flow, which indicated a possible opening of preferential pathways for the gas flow that controls the permeability. This opening of fissures or discontinuities due to gas transfer is confirmed by the pore size distributions obtained from mercury intrusion porosimetry (MIP) tests before and after the gas injection experiments.

As the host rock has self-sealing properties due to its high clay content, if a fracture occurs, it is expected to close as soon as the gas pressure decreases and the effects on dissolved element transfers are weak. To assess the self-sealing capacity of clays after the passage of gas, UPC/CIMNE geotechnical laboratory compares the water permeability

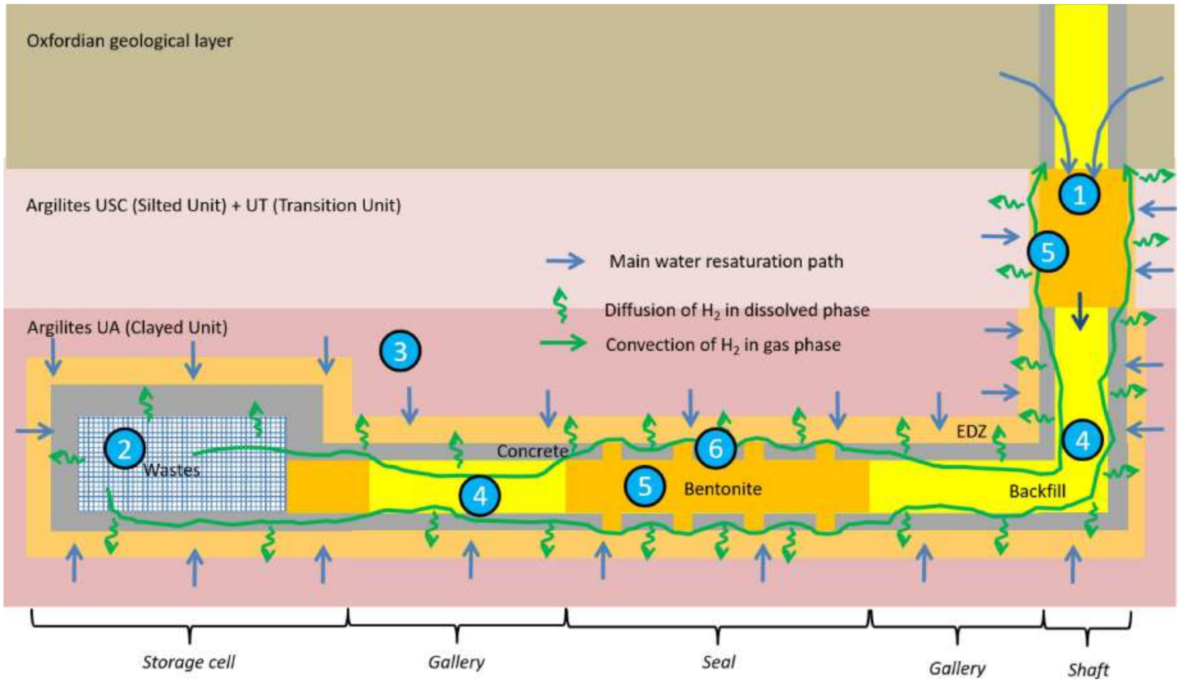


**Fig. 1.** Schematic representation of the Andra repository concept and the main phenomena structuring the hydraulic-gas transient [17]: 1 – resaturation of the shafts and ramps seals; 2 – gas production; 3 – diffusion of dissolved gas in clay host rock; 4 – transfer of gas by the components of the repository; 5 & 6 – low permeability of the bentonite of sealing cores favouring the transfer of gas by concrete annular rings, the EDZ and interfaces between the different materials.

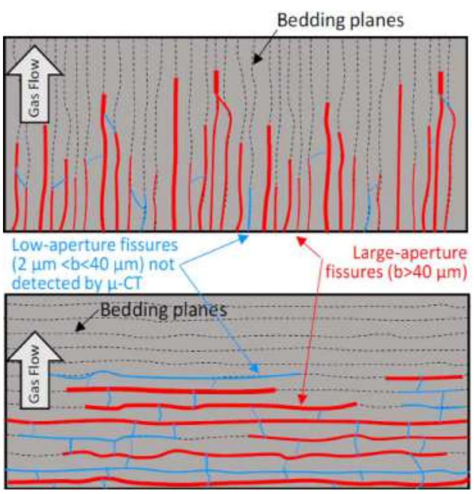


**Fig. 2.** Schematic representation of expected gas flow at different orientations of bedding planes: parallel to flow (top) and orthogonal to flow (bottom). Dashed thin lines represent bedding planes. Solid lines depict the volume occupied by gas: apertures larger than 40 µm and detected by µ-CT (in red); and apertures between 2 and 40 µm detected by MIP but not by µ-CT (in blue) [12].

before and after gas injection. Their experiments on Boom Clay indicate a progressive recovery of water permeability after re-saturation, which pointed to a good self-sealing capacity. The preferential pathways developed along the bedding direction after the gas injection was not observed on µCT images after the re-saturation. Nevertheless, a small pore volume at the macro-porosity scale was still detected by MIP and the gas permeability after re-saturation is slightly high, which could imply some memory of the previous gas pathways [13].

Such assessments at the scale of repository sub-systems are a good illustration of how experimental and modelling results of the WP GAS programme can help to determine whether hydro-mechanical couplings and possibly associated damages play a role in the functioning of the global repository system.

### 4.4 Analysis of temperature effects on repository

#### 4.4.1 Clay host rock

The characterisation of in situ THM behaviour of the clay host rock is significant for the design and the long-term safety of the deep geological disposal facility. Obviously, the heat generated by the waste must not affect the favourable properties of the host rock, especially its chemical, mechanical and transport properties.

The temperature rise in a low permeability porous medium such as Callovo-Oxfordian (COx) claystone, Opalinus Clay or Boom Clay generates pore pressure increase essentially due to the difference between the thermal expansion coefficients of water ($\sim 10^{-4}\,K^{-1}$) and one of the argillaceous rock skeleton (e.g., $\sim 1.28 \times 10^{-5}\,K^{-1}$ for COx). Thermal pressurisation is the key mechanism for the potential damage induced by the waste emitted heat. There is a competition between excess pore pressure

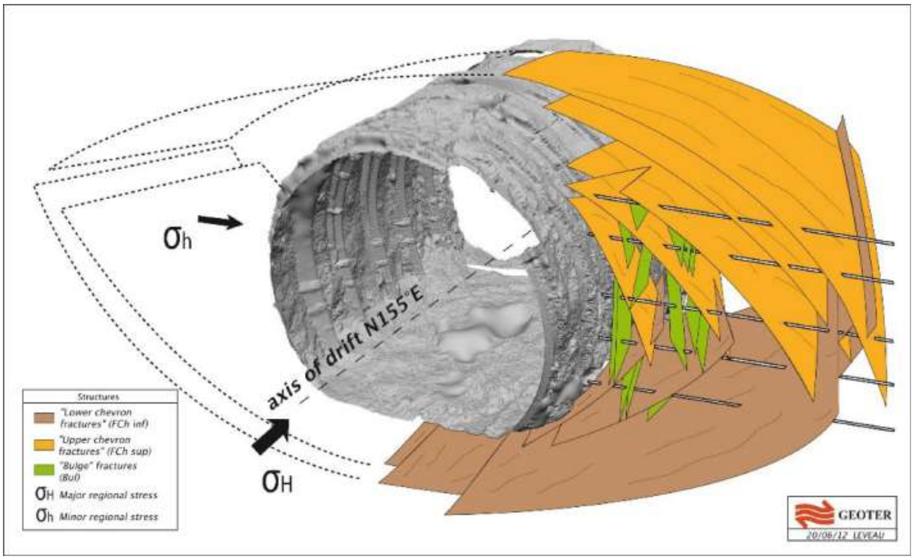


**Fig. 3.** Conceptual model of the excavation-induced fractures network in Callovo-Oxfordian claystone (Meuse/Haute-Marne URL, [32]).

due to thermal pressurisation and drainage due to pore pressure gradient increase. With the periodic distribution of an important number of similar parallel cells and their lengths, it can be expected that the induced pore pressure between cells could not be dissipated in the horizontal direction. In the near field, the excavation of micro tunnels induces a fractured zone around them ([3]; Fig. 3). In the far field, the pore pressure induced by the temperature increase leads to a decrease of the mean effective stress which can reach the tensile strength of the rock and induce damage, e.g., it could reactivate fracture/fault. The evolution of the effective stress field in the vicinity of the cell due to the temperature rise can induce the fracture opening or propagation in this fractured zone. The effect of the temperature on the behaviour of the excavation-induced fracture network around the HLW cell will affect the load evolution on the casing (emplaced for retrievability purposes) [4].

When modelling a nuclear waste repository, horizontal displacement, thermal flow and fluid flow are set to zero on the lateral boundaries of the model due to the symmetry conditions. The periodic distribution of parallel cells prevents lateral expansion of the rock and thus provokes compression thermal stresses in horizontal directions. The decrease of the total stress sets off the effect of the pore pressure build-up on the horizontal components of the effective stress tensor. However, the vertical effective stress increases and can, in some cases, reach the tensile strength of the rock (i.e. potential appearance of sub-horizontal cracks). One of the objectives of HITEC is to better assess the behaviour of clays under such stress path, and determine the potential damage appearance and the effect of a macro cracking over the pore pressure field and the permeability.

In that context, ULorraine studies, for instance, the effect of temperature on the behaviour of the Callovo-Oxfodian claystone. To achieve that goal, they perform short-term triaxial compression tests and long-term (creep) triaxial tests at different temperatures and confining pressures. The first results obtained from short-term triaxial compression tests [9] suggest that the peak strength decreases with the increase of temperature up to 100°C for both orientations, parallel and perpendicular to the bedding plane (Fig. 4).

Modelling the interaction between a structure, the casing and the rock mass is always a complex task (as illustrated in Fig. 5 by a schematic representation of coupled processes associated with vapour transport). Around the canister and the casing, the increase of the thermal stress and change in pore pressure increase the complexity of interaction between the rock mass and the structure. The higher temperature is reached in the surrounding of the casing/heater, meaning that the heat could affect the behaviour of the excavation fracture network around the cell. It is important to assess if clay host rock thermal compaction could affect the near field and far field.

### 4.4.2 Bentonite buffer

Although the effect of temperatures higher than 100°C has been considerably studied concerning mineralogical transformations (unfortunately not always in clearly representative conditions), less is known concerning hydro-mechanical properties for this range of temperatures, mainly because of the testing experimental issues. It has been shown that the effect of temperature on hydro-mechanical properties of bentonite has been systematically studied for temperatures of up to 100°C and is quite well established with respect to safety functions: temperature modifies some properties, but they keep in values acceptable for complying with the safety functions. Although temperature increases the hydraulic conductivity, the effect on swelling capacity seems to depend on the predominant exchangeable cations [6,34]). Less work has been done on the effect of temperature on the water retention curve and thermal conductivity. Likewise, most

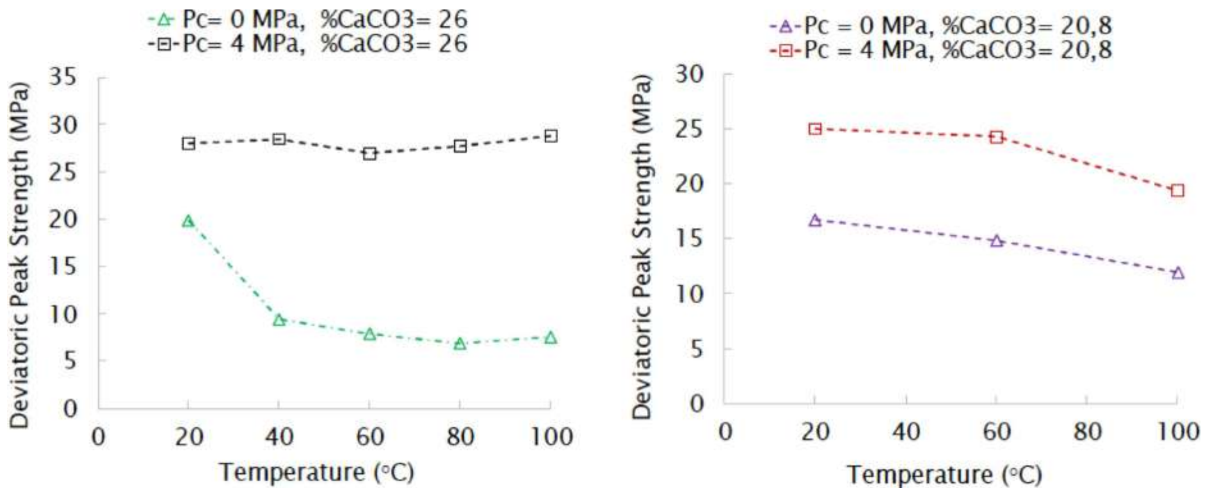


**Fig. 4.** Evolution of the peak strength of COx claystone as a function of temperature: at left the parallel orientation, at right the perpendicular orientation (from [9]).

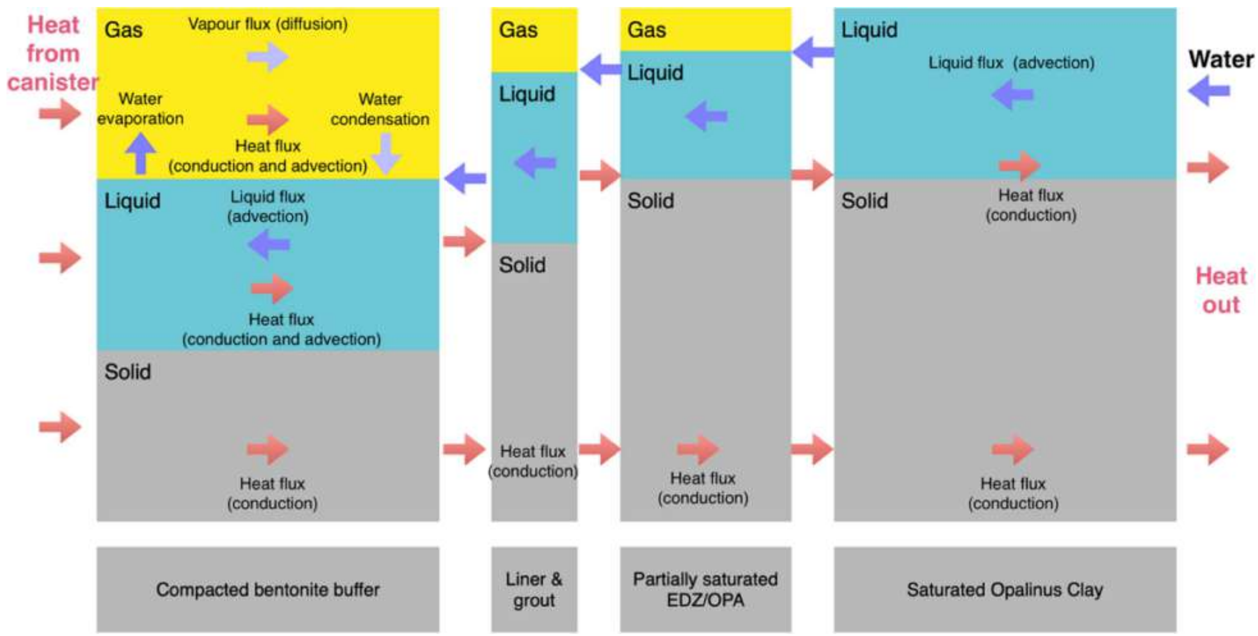


**Fig. 5.** Simplified schematic illustration of coupled processes associated with vapour transport [32].

laboratory studies have focused on compacted bentonite; therefore, it cannot be stated if the effect of temperature on some properties is affected by the initial fabric (compacted powder, grains, pellets) or not. Concerning the modelling of the buffer behaviour, it is considered that the THM formulations developed and validated for temperatures below 100°C can be extended without large modifications to temperatures above that value [10].

In the frame of the WP HITEC of EURAD, a Czech consortium consisting of the CTU, CU, and UJV is focusing, for instance, on determining changes in the hydro-mechanical, geochemical and mineralogical characteristics of Czech BCV bentonite due to elevated temperatures. The initial results of the analysis of the dry-treated bentonite show a slight degradation with a temperature higher than 100°C in terms of hydraulic conductivity and water retention capacity, while the effect of temperature on the swelling pressure is not significant. Similar tests carried out on wet treated material did not allow to put in evidence of such changes. [5,8].

### 4.5 Accounting for gases and temperature in performance assessments

Total system performance assessment models in most national programmes considering clayey host formations and/or barriers do not currently directly represent the effects of gases on radionuclide transport – at least on soluble radionuclide transport – and thus their potential radiological impact. Indeed, it is assumed that the transport rate of solutes, among which soluble radionuclides, is higher if the 'repository/host rock' system remains saturated with water. It is thus deemed conservative in estimating the transport of radionuclides in water-saturated conditions.

It is also recognised that inactive gas produced in large quantities in a repository (essentially $H_2$) and transported through it could act as a carrier for radionuclides that would be present in gaseous form. This can be taken into account via a numerical evaluation based on the two-phase phenomenological conceptualisation, which is currently used as a reference (Darcy and Fick laws generalised for water and gas transfers and Henry's law for exchange between liquid and gas phases). Alternatively, gaseous radionuclides might be represented as dissolved in the pore water but with specific hypotheses concerning their transport (increased migration parameters values and privileged passage via the interfaces between materials, instantaneous transport from the galleries up to the accesses, etc.).

As far as gas fracturing is concerned, if this mechanism is considered, it is generally under the form of an altered evolution scenario or even under the form of a low probability or 'What-If' type scenario. This kind of scenario generally assumes that the system is fully saturated but incorporates the presence of a drain (local or more extensive) connecting the repository galleries to the nearest aquifer above and/or below the clayey host rock.

For the disposal of HHGW, performance assessment models require to well understand the consequences of the heat produced on the properties and the long-term performance of the natural and engineered clay barriers. For now, most of those developed for disposal concepts that involve clay consider a temperature limit of 100°C. In such conditions, it is known that the performance of the system in clay host rock should not be affected negatively by the thermal evolution of the EDZ around a radioactive waste repository. However, in the case of higher temperatures, process understanding is currently insufficient to guarantee that this will still be true.

Being able to tolerate higher temperatures while still ensuring an appropriate performance would have significant advantages in terms of repository optimisation. The WP HITEC contributes to assessing how higher thermal loads, changes in canister pitch and/or tunnel spacing affect the likely performance of geological barriers. This includes an assessment of the consequences of locally surpassing the threshold criteria that are now put forward to ensure the integrity of the geological barrier in safety cases.

Thanks to its excellent properties for radionuclide containment and confinement, clays are exploited in developing most geological disposal systems in Europe either as host rock or as materials for engineering barriers. One of its particular favourable properties is its self-sealing capacity which allows fractures to close rapidly. The impact of temperature or gas on the self-sealing capacity of clays is one of the key questions addressed by both WP HITEC and GAS of EURAD. ULorraine investigates, for instance, the self-sealing capacity of the Callovo-Oxfordian claystone with the same test configurations after both thermal loading and/or gas passage. Their first self-sealing tests performed on the Callovo-Oxfordian claystone under triaxial condition and at various temperature shows that the self-sealing process significantly reduces the fracture permeability [1]. This mechanism is faster for samples oriented in parallel to the bedding plane than samples oriented perpendicularly to the bedding plane. Similar tests are ongoing in the frame of the WP GAS after gas injection to characterise all the (T)HM(-C)(+gas) processes associated with self-sealing mechanisms in clayey materials.

## 5 Expected impacts and key challenges of these two WPs

### 5.1 Expected impacts of the WP GAS

During the course of the WP GAS, conceptualisations of gas transport through repositories in clayey host formations will be improved by the integration of the findings of the tasks on transport mechanisms and barrier integrity. The phenomenological description improvements will be evaluated for transfer to the repository scale via updates to the storyboards. Uncertainties about which gas transport modes will effectively be active or about other gas-related aspects of the evolution of the system will be identified and evaluated in terms of possible scenarios to be investigated. This task will also benefit from recent advances in phenomenological understanding from the CAST (CArbon-14 source term and fate) and BEACON (bentonite mechanical evolution) EC projects allowing respectively (i) a better understanding of potential release mechanisms of carbon-14 (in the form of methane, for instance) from radioactive waste materials under conditions relevant to geological disposal facilities in clayey host formations and (ii) a better characterisation of hydro-mechanical coupling in swelling clayey materials (from the installation of materials to their evolution over the long term).

In that sense, the WP GAS is expected to provide building blocks to implementers that may inspire their storyboards and, in turn, design measures that further reduce the gas impact on the disposal system and/or the uncertainties associated with the gas flow through engineered and natural clayey barriers in geological disposal systems. It will allow testing of various approaches for the treatment of gas in repository-scale models, identifying the inherent strengths and limitations of each approach and assessing its suitability in different contexts, as this may depend on the disposal system that is being evaluated (host formation/concept) or even the advancement of the (national) programme.

### 5.2 Expected impacts of the WP HITEC

While both clay host rock and bentonite materials have a long history of studies, investigations of thermo-hydro-mechanical behaviour at elevated temperatures have not been common. Carrying out experiments at higher than 100°C requires typically large modifications in the equipment and measuring system. The same is true for models, which might require rather many modifications (parameters and constitutive relations) to be functional at higher temperatures. In that sense, the WP HITEC is expected to increase the scientific and technical knowledge of the mechanical behaviour of clay host rocks and bentonites at temperatures higher than 100°C.

This knowledge will interest radioactive waste management, implementation, and safety cases. Being able to better accommodate higher temperatures than presently accepted 100°C while ensuring similar safety standards can have significant advantages with respect to disposing of higher enrichment/burn-up fuels, interim storage requirements, (re)packaging of the waste and reducing the footprint of the disposal. It could also allow for evaluating limits of temperature and the overall impacts higher temperatures cause to materials and systems. In addition, proving temperatures higher than presently considered acceptable is very relevant even for current concepts: it increases safety margin and gives greater credibility to the design.

### 5.3 GAS and HITEC common challenges

The main challenges of the two R&D work package, GAS and HITEC of the European Joint Programme EURAD, lies in the stepwise integration and contextualisation of experimental results and modelling approaches. On the one hand, it sought to increase the understanding and predictability of the impact on clay barriers by studying fundamental mechanisms and their couplings related to gas and heat transport, respectively, observed at the lab scale or via past and present in-situ experiments. On the other hand, models of different complexity are built to support the understanding of the observed mechanisms and transfer it to the configurations and conditions of the different clayey components and the context of the functioning of a disposal system. To that aim, it is also essential to be transparent about the context in which any piece of data has been collected, or any model has been developed, key uncertainties, and clearly communicate all elements of scientific consensus.

These two WPs strongly build on the results, return of experience and conclusions from past EC projects, for instance, FORGE, TIMODAZ, BELBaR, and BEACON. These projects revealed complex mechanisms but also hinted that these could probably be addressed using a combination of simple and robust (e.g., bounding) approaches. By providing the end-users with a collection of data, tools and building blocks for storyboards that may be of use in the conceptualisation of the functioning of their specific geological disposal system, GAS and HITEC will contribute to the development of such approaches and support the justification of their use.

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## Conflict of interests

The authors declare that they have no competing interests to report.

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## Data availability statement

This article has no associated data generated and/or analyzed / data associated with this article cannot be disclosed due to legal/ethical/other reason.

## Author contribution statement

Séverine Levasseur: conception, execution, interpretation, writing. Xavier Sillen: interpretation, revision. Paul Marschall: interpretation, revision. Jacques Wendling: Paul Marschall: interpretation, revision. Markus Olin: conception, execution, interpretation, writing. Dragan Grgic: interpretation, revision. Jiri Svoboda: interpretation, revision.

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**Euratom Research and Training in 2022: challenges, achievements and future perspectives, Roger Garbil, Seif Ben Hadj Hassine, Patrick Blaise and Cécile Ferry (Guest editors)**

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REVIEW ARTICLE — OPEN ACCESS

# Spent nuclear fuel management, characterisation, and dissolution behaviour: progress and achievement from SFC and DisCo

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**Abstract.** SFC is a work package in Eurad that investigates issues related to the properties of the spent nuclear fuel in the back-end of the nuclear fuel cycle. Decay heat, nuclide inventory, and fuel integrity (mechanical and otherwise), and not least the related uncertainties, are among the primary focal points of SFC. These have very significant importance for the safety and operational aspect of the back-end. One consequence is the operation economy of the back-end, where deeper understanding and quantification allow for significant optimization, meaning that significant parts of the costs can be reduced. In this paper, SFC is described, and examples of results are presented at about half-time of the work package, which will finish in 2024. The DisCo project started in 2017 and finished in November 2021 and was funded under the Horizon 2020 Euratom program. It investigated if the properties of modern fuel types, namely doped fuel, and MOX, cause any significant difference in the dissolution behavior of the fuel matrix compared with standard fuels. Spent nuclear fuel experiments were complemented with studies on model materials as well as the development of models describing the solid state, the dissolution process, and reactive transport in the near field. This research has improved the understanding of processes occurring at the interface between spent nuclear fuel and aqueous solution, such as redox reactions. Overall, the results show that from a long-term fuel matrix dissolution point of view, there is no significant difference between MOX fuel, Cr+Al-doped fuel, and standard fuels.

## 1 SFC

Eurad is a large European Commission project aiming to joint programming of nuclear waste management in the European Union. The project consists of many work packages, of which Spent fuel Characterization (SFC) is the largest. SFC, in turn, consists of four tasks: Task 1 – S/T coordination, State-of-the-art and training material, Task 2 – Fuel properties characterization and related uncertainty analysis, Task 3 – Behavior of SNF pellets under interim storage conditions, Task 4 – Accident scenario and consequence analysis.

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SFC investigates issues related to the properties of the spent nuclear fuel (SNF) in the back end of the nuclear fuel cycle. Decay heat, nuclide inventory, and fuel integrity (mechanical and otherwise), and not least the related uncertainties, are among the primary focal points of SFC. These have very significant importance for the safety and operational aspect of the back-end. For example, the thermal situation is most often the limiting factor in the various parts of the back-end. Important parts of the back-end include cooling, transportation, intermediate storage (wet and dry), encapsulation, reprocessing (for some countries), and final disposal. One consequence is the operation economy of the back-end, where deeper understanding and quantification allow for significant optimization, meaning that significant parts of the costs can be reduced. The results are relevant for countries with small as well as large and advanced nuclear waste management programs. Great care has been put into doing research complementary to research already done or done elsewhere, not repeating previous efforts.

In this paper, SFC is described, and examples of results are presented at this point in time, which is about half-time of the work package; it will finish in 2024.

### 1.1 SFC Task 2: fuel properties characterization and related uncertainty analysis

The main objective of this task is to produce experimentally verified and validated procedures to determine reliable source terms of SNF, including realistic uncertainties. The focus is on source terms which are of primary importance for safe, secure, ecological, and economical handling, transport, intermediate storage, and final disposal of SNF [1]. The main source terms of interest are neutron emission rates, $\gamma$-ray emission spectra, decay heat rate, and the 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 ($^{241,243}$Am, $^{242,244}$Cm). The inventory of fissile nuclides is needed for nuclear safeguards requirements and reactivity calculations to prevent criticality. To avoid overly conservative criticality margins, a burnup credit approach can be applied. Such an approach requires the inventory of strong neutron-absorbing fission products and actinides. The inventory of activation products and long-lived FP is important to study the impact on the biosphere. Some of the FP (e.g., $^{148}$Nd) are used for burnup determination.

The complete list of source terms is hard to be measured directly, in particular during industrial operation. Therefore, they are estimated based on a combination of calculations and results of non-destructive analysis (NDA) measurements to verify the calculations. It requires the calculation of a complex inventory of nuclides with strongly varying characteristics. The calculations involve neutron transport and nuclide creation and depletion codes. The results of such calculations strongly depend on nuclear data (including cross sections, FP yields, neutron emission probabilities and spectra, decay data etc.), fuel fabrication data (design, composition), and reactor operation and irradiation conditions (burnup, neutron spectrum). The design, composition, production, operation, and irradiation conditions will be referred to as "fuel history".

#### 1.1.1 SFC Subtask 2.1: theoretical study of SNF source terms

The goal of subtask 2.1 is to provide recommendations in terms of neutronics transport and decay calculations for estimating the SNF composition (nuclide inventory) and its decay heat. Such recommendations should lead to well-justified best estimate values, with uncertainties and biases, later used in subtask 2.4. To reach this ambitious goal, a number of PIE samples were selected either from the SFCOMPO database [2] or from proprietary descriptions available within the EURAD SFC project. These samples were selected to cover the characteristics of a large number of existing SNF in terms of assembly types (for BWR or PWR), burnup values, initial enrichment, and fuel type ($UO_2$ or MOX). They help compare calculated nuclide concentrations with measured ones within the context of specific calculation tools, nuclear data libraries, and modeling assumptions. Such comparisons lead to the estimation of biases for the nuclide concentrations and finally to recommendations. Additionally, if uncertainties were considered for the model description (e.g., fuel temperature, void fraction, but also nuclear data), it would also be possible to provide a calculated uncertainty for the nuclide concentrations based on the input variations. Another source of uncertainty can be estimated if different partners independently analyze the same PIE sample. Such overlap will most likely lead to different calculated concentrations, thus indicating the user effect, which is also considered an uncertainty.

The second calculated quantity, the SNF decay heat, can be analyzed in a similar manner. This will also lead to best estimate values, uncertainties, and biases. Naturally, these two quantities (nuclide concentrations and decay heat) are connected, at least from the calculation aspect. One additional constraint on the decay heat, at least from the user's point of view, can be the necessity to use standards such as the ANS (see `www.ans.org` for details) or the DIN (see `www.din.de` for details) standards. A deviation between the results from dedicated simulations and standards will necessitate understanding and justification, which can be backed up by the present project. To illustrate such possibility, an example for a specific PWR assembly is presented in Figure 1. In this example, differences between measured and calculated decay heat can be observed, but also differences between standard values (ANS and DIN) and both CASMO5 and SNF calculations. If successful, explanations will be provided by the present project.

In total, 17 PIE samples were analyzed, some of them by different participants. For decay heat, the calorimetric measurements from CLAB (Swedish Central Intermediate Storage Facility), GE-Morris, and HEDL (Hanford Engineering Development Laboratory) were considered, leading to more than 250 cases. To support the recommendations of this subtask, some studies were already published, see references [3–15]. A global review of the

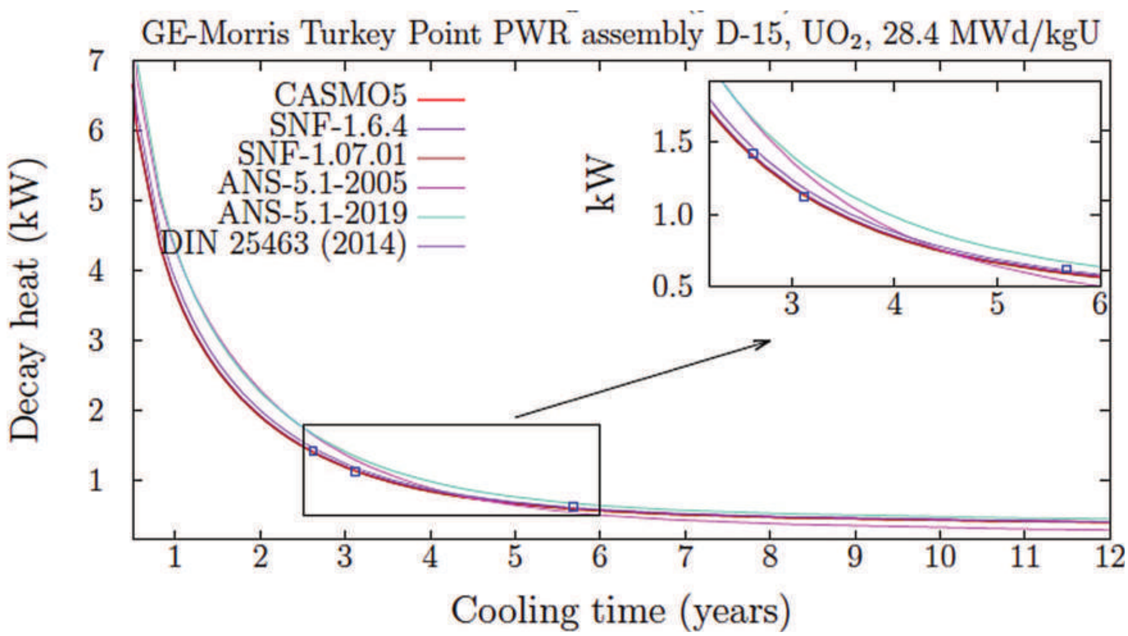


**Fig. 1.** Comparison of the measured and calculated decay heat for a specific PWR assembly from the GE-Morris facility.

work performed in this subtask is expected for the end of 2022.

### 1.1.2 SFC Subtask 2.2: develop, improve and demonstrate NDA methods/system for SNF characterization

The aim is to produce NDA systems that can be used to provide experimental data to validate the performance of the codes (including nuclear data) and to verify the declared design and operational history of the assemblies. Within this task, the performance of current NDA methods used to characterize SNF is assessed and improved. In addition, innovative neutron and gamma-ray detectors and NDA systems are developed. Two types of measurement systems are investigated: systems to characterize small SNF samples (including pellets) and systems to characterize entire SNF assemblies. The focus is on NDA methods based on the detection of gamma-rays and neutrons and calorimetric systems determining the decay heat rate.

A procedure to measure the neutron emission rate of a spent nuclear fuel segment sample by an NDA method without any calibration using a representative sample was developed, validated, and demonstrated. A standard neutron well-counter designed for routine nuclear safeguards applications was applied. The method relies on a transfer procedure adapted to the hot-cell facilities at the Laboratory for High and Medium level Activity of the SCK CEN. The sample was a segment taken from an SNF rod that was irradiated in the Tihange 1 PWR reactor to a burnup of 50 GWd/t. The composition and design specifications of this fuel rod and the irradiation conditions are fully documented. The method and procedures are described in detail in [16]. The results of these measurements will be used in subtask 2.4 to validate codes.

A large effort is being made to perform a full uncertainty evaluation of the NDA systems that were used at the CLAB facility as part of the SKB-50 measurement campaign. This includes the gamma-ray spectroscopic scanning system and calorimeter, which are installed at CLAB for routine use, and the Differential Die Away Self-interrogation system (5DDSI) that is developed at the Los Alamos National Laboratory. For the gamma-ray measurements, a study of systematic effects due to the determination of the net peak area and the positioning of the assembly with respect to the detector was carried out and reported in reference [17]. In addition, a model was developed to determine the ratio of the inventory of some key nuclides absolutely without the need for additional calibration measurements or transport calculations. A paper describing the use of this method on the SKB-50 data is in preparation.

### 1.1.3 SFC Subtask 2.3: determine the inventory of activation and fission products in cladding material

Although the cladding seems free of fissionable nuclides, impurities are introduced into the cladding during the fabrication. Moreover, by inserting the pellets within the cladding, traces of fuel are adherent on the inner surface of the cladding. The existence of uranium on the inner surface means the generation of fission products and actinides on and within the cladding during reactor operation, which has a direct impact on the long-term disposal characteristic of the cladding. In view of the current situation, where fuel assemblies are about to be stored for much longer periods than foreseen, the feasible, but not necessary, failure of the cladding within the dry storage cask could become a large obstacle in handling the fuel rods later on for the final disposal. Evidently, the ability to quantify the radioactive nuclides, particularly those that cause radioactive defects in the cladding via high-energy alpha particles, is of high importance. Furthermore, the exact material composition of the cladding itself is a key issue for the sustainability of the irradiated mechanical and thermal loaded cladding. One of the goals of this subtask is to combine the confirmed simulations with the measured activated materials and by a reverse process to identify the original “real” material composition, which will allow estimating the failure time of the cladding (if at all) in the future, evidently determining the technical allowed temporary storage period.

In view of the above, the objective is to analyze the inventory of fission and activation products present in irradiated Zircaloy. The inventory of these products comprises the fraction that is formed during irradiation within Zircaloy and the fraction that is deposited on the inner surface of the cladding. The importance of this analysis lies in the assessment of the integrity of the cladding, in particular within the dry storage period, which could reach, as mentioned above, 100 years or more. Dedicated simulations are ongoing to compare and validate codes and their burnup procedures. The next step after code-to-code validation is the comparison with experimental results to depict the manufacturing effects (defects) on the cladding material composition as explained above. In that sense, primary calculations have shown that for the same Monte Carlo codes, the inventory of the main nuclides is very similar, which is, for an amount of roughly seven orders of magnitude lesser than the values within the fuel pellets, very encouraging.

For the experimental studies, two kinds of samples were prepared:

– cladded fuel pellets of $UO_2$ (50 GWd/tHM) irradiated in a pressurized water reactor (PWR).
– A plenum cladding obtained from a $UO_2$ fuel rod segment irradiated in a PWR.

Subsamples of these highly active claddings were analyzed by means of different (radio-) chemical analytical methods e.g., gamma-spectrometry, alpha spectrometry, LSC, and ICP-mass spectrometry.

The comparison between the experimental data and the simulation results will allow for the estimation of the adherent fuel on the inner surface of the cladding and, as said above, a reliable determination of the cladding sustainability under changing radiation conditions, as well as heat and pressure changes within the storage containers.

#### 1.1.4 SFC Subtask 2.4: define and verify procedures to determine the source terms of SNF with realistic uncertainty limits

Within this task, validated state-of-the-art procedures will be defined to determine the SNF source terms with realistic uncertainty limits. This task combines the results of the other tasks. The final procedures will be validated based on the SKB-50 data. The main objective is to obtain statistically relevant statements (about the bias and uncertainty of source term calculations) by applying the standard, recommended calculation procedures to a large set of data. Calculations will be performed both with an established code like SCALE6 and a more sophisticated code like EVOLCODE2.

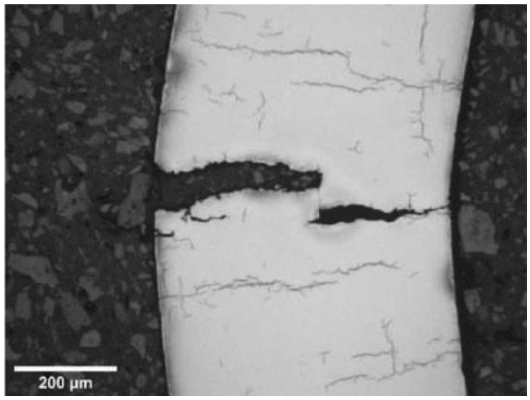


**Fig. 2.** Brittle failure of a pre-hydrided unirradiated ZIRLO(R) cladding sample with radial hydrides subjected to a ring compression test.

Source term calculations are influenced by many factors whose uncertainties are often insufficiently comprehended: initial material and geometry conditions, irradiation power history, spectrum influences from neighboring fuel assemblies, control rod history, and measurement procedures, for example. By evaluating many samples, the influence of these factors can be minimized. On the other hand, uncertainties from microscopic nuclear data are the same for all samples, and they manifest themselves as a bias in all calculations. Hence the determination of the latter allows conclusions about the improvement potential of cross sections and fission yields.

Finally, comparing results from different codes will allow assessing the impact of different methodological approaches for source term determination.

### 1.2 SFC Task 3: behaviour of nuclear fuel and cladding after discharge

The main aim of SFC Task 3 is progress regarding spent nuclear fuel (SNF) characterization and performance with respect to pre-disposal activities. In particular, the behavior of irradiated cladding, the phenomena ruling the potential SNF degradation, the fuel/cladding chemical interaction (FCCI), and aging effects under conditions of extended interim storage, transport, and emplacement in a final disposal system are investigated through experimental as well as modeling studies.

The understanding of spent fuel performance during dry interim storage is indispensable both for analyzing the failure probability and to characterize the state of the cladding, so that fuel management can be conducted with accurate knowledge of the fuel conditions. The main interest is in cladding degradation mechanisms, as it is the first physical barrier between fission products and the environment (Fig. 2). A description of the key phenomena governing the fuel rod state during dry storage can be found in the gap analysis carried out by Hanson et al. [18].

### 1.2.1 SFC Subtask 3.1: thermo-mechanical-chemical properties of the SNF rods and cladding

Subtask 3.1 investigates the thermo-mechanical-chemical properties of the spent nuclear fuel rods and cladding. In this subtask, experimental and simulation activities are taking place. Some highlights are given below.

At JRC-Karlsruhe, a ring compression test (RCT) was performed in an irradiated duplex cladding sample (from the upper plenum, average burnup 67 GWd/tHM) [19]. This test was modeled by BAM using finite element analysis and an inverse method with an iterative approach.

At the Hungarian Centre for Energy Research, creep tests on as-received and hydrogenated E110 cladding samples were performed. Samples with 1100 ppm hydrogen content showed a significantly lower thermo-mechanical creep rate than the as-received samples.

At UPM, a newly developed device was used to perform a hydride reorientation treatment in pre-hydrided unirradiated ZIRLO(R) cladding samples. RCTs were performed in samples with a significant fraction of radial hydrides at different temperatures. Failure was brittle at room temperature and 135 °C, with cracks initiating at radial hydrides (Fig. 2).

NAGRA (National Cooperative for the Disposal of Radioactive Waste in Switzerland) validated its three-dimensional static finite element analysis of 3-point bending tests at JRC-Karlsruhe, a sensitivity analysis on different beam implementations in finite element modeling, and a derivation of appropriate rod failure criteria.

At CIEMAT, the code FRAPCON-xt has been used to validate the initial conditions for fuel rod behavior assessment at dry storage, applied to a specific PWR fuel rods dataset with burnups ranging from 45 to 65 GWd/tHM. The results show that practically 90% of deviations might be explained by uncertainties in the estimate, as shown in Figure 3.

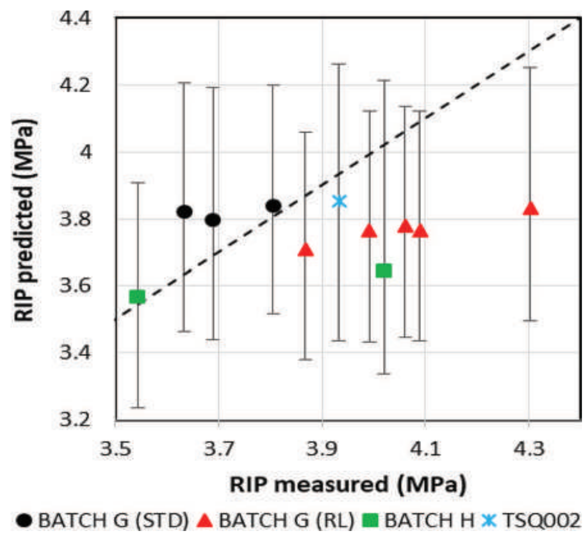


**Fig. 3.** Best estimate plus uncertainties of rod internal pressure (RIP) at EOL for different rod designs (distinguished by symbols and colors).

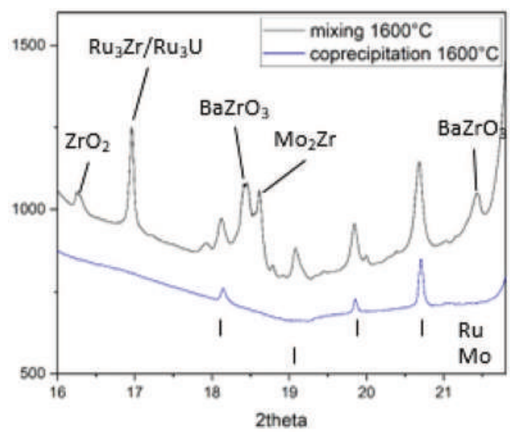


**Fig. 4.** Synchrotron XRD of SIMFUEL manufacture by solid (mixing) and liquid (co-precipitation) routes.

### 1.2.2 SFC Subtask 3.2: behavior of SNF pellets under interim storage conditions

In a strategy of long-term interim storage, it is required to evaluate the SNF evolution over long periods and to quantify the consequences of non-standard conditions such as aging or defective cladding. An accurate understanding of SNF performance during dry interim storage is indispensable for ensuring the safety of all relevant operations. If the fuel pellet is exposed to an oxidizing environment during dry storage due to fuel management operation issues and an undetected defect in the cladding, $UO_2$ oxidation can occur. The main concern is that if oxidation develops up to the formation of $U_3O_8$, it results in a volume expansion, which may involve a fission gas release and fuel grain de-cohesion.

The objective of subtask 3.2 focuses on the performance of irradiated fuels and simulated SNF pellets both under (ab-)normal dry interim storage conditions and under conditions of water contact, i.e., container or cladding failure scenarios, respectively, and extended storage prior to their transport, during the transport and emplacement in a disposal system. The main goal is to provide new insights into the aging and degradation mechanisms of the SNF (e.g., He build-up, oxidation of the SNF, influence of the various fission products, etc.). The potential evolution of the SNF in case of mal operating conditions (e.g., moisture, aqueous dissolution of the $UO_2$ matrix, corrosion of the SNF, etc.) is also considered. Various compositions of simulated SNF are used as lanthanide Ln (La, Nd, Ce, Gd, Eu)-doped $UO_2$, and SIMFUEL pellets doped with metallic particles (Ln–PGM–Mo–$UO_2$ ceramics) to be tested under conditions relevant in the back-end of the fuel cycle (dry and wet). Morphological and chemical/spectroscopic analyses of the fuel behavior are performed by means of conventional techniques (i.e., ICP-MS, SEM-EDX, ESEM, TEM, XRD, Raman spectroscopy). Cutting-edge synchrotron methods at the Rossendorf beamline (i.e., high-resolution diffraction, x-ray absorption spectroscopy, and x-ray emission spectroscopies) are also applied. The results provide degradation performance and mechanisms at a multi-scale level ranging from the atomic scale to the macroscopic scale (Fig. 4).

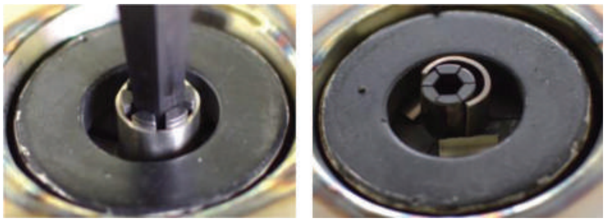

**Fig. 5.** The mandrel test performed with a ductile (left) and a brittle sample (right).

### 1.2.3 Subtask 3.3: pellet-cladding interaction under conditions of extended storage, transport, and handling of SNF rods

During normal operation, the gap between the fuel pellet and the cladding closes. In case of sudden changes in operating conditions or in accidents, the thermal expansion of the pellet can rupture the cladding wall. Air ingress during high-temperature dry storage can oxidize the fuel pellet resulting in volumetric expansion; this also can result in cladding rupture. Hence, the ductility of the cladding is an important parameter under transport and storage conditions.

In subtask 3.3, the mandrel test simulates the pellet-cladding mechanical interaction (PCMI) by expanding segmented dies (mandrels) inside cladding samples (Fig. 5). This setup represents the mechanical conditions of the cladding under internal pressure. The result is the maximum force, the force-displacement curve integral, the maximum diameter, and the mode of failure, which all give important information about the ductility of the sample.

The tests were performed with samples from E110 and sponge-based E110M cladding tubes. Some rings were pretreated with hydrogen and heat treated at high temperatures. The hydrogen content was between 300 ppm and 3000 ppm. The tests were performed at 20 °C and 300 °C in air. The cladding samples behaved gradually less ductile as the hydrogen content in the samples increased. The minimum ductility was reached at 2000 ppm absorbed hydrogen. Above 2000 ppm hydrogen content, the ring samples failed in brittle mode after minimal plastic deformation at higher force compared to the as-received samples.

## 1.3 SFC Task 4: accident scenario and consequence analysis

Task 4, coordinated by CIEMAT, was set up to study SNF performance under potential accident conditions, which might lead to a loss of confinement during storage, transport, and predisposal activities. The investigation to be carried out was split into two subtasks. The first one (4.1), coordinated by NAGRA, is specifically focused on thermo-mechanical aspects of fuel behavior under dry interim storage. The second one (4.2), coordinated by the Chernobyl Research and Development Institute (ChRDI), pays attention to the consequences of potential accidents. In the next paragraphs, a synthesis of the progress made in each of them since the inception of EURAD is to be described.

As for Task 4 as a whole, coordination has managed three major achievements:

- communication with Task 3. Any accident analysis requires an accurate description of the SNF at the time of the accident. This, in turn, needs a thorough characterization of SNF properties evolution during irradiation, which is the main purpose of Task 3. After exploring different ways of communication with Task 3, the one that has resulted in more efficient under the circumstances has been the bridge built by the participation of some partners in both Tasks 3 and 4. This is now well settled through CIEMAT and NAGRA.
- Consolidation of the program of work. The research activities initially identified were diverse and have been consistently distributed so that each subtask addressed a specific aspect of interest in fuel performance, as described above. Deliverables to be released have been better accommodated as for their scope and, no less important, due dates. Additionally, several technical reports will be issued concerning accident scenarios and methodologies, Source Term in Vault systems, and criticality studies in accidental configuration.

### 1.3.1 SFC Subtask 4.1: fuel thermo-mechanics

Subtask 4.1 aims to provide a synthetic analysis of identified accident scenarios in different stages of the back-end spent nuclear fuel cycle (i.e., storage, transportation, and handling). The core topics include the identification and analysis of potential accident scenarios in interim storage and/or packaging facilities and, consequently, the assessment of the fuel performance. Therefore, the work related to this subtask is closely linked to the experimental and numerical activities performed in the other tasks with regard to the fuel properties characterizations and related uncertainty analysis, as well as to the behavior of nuclear fuel and cladding after discharge. The development of a methodology trying to link degradation mechanisms to fuel performance and possible accident scenarios would be beneficial to support future specific National Programs in relation to the safe management of SNF. The work in this subtask is a synthesis of individual studies performed by five contributing participants and will be summarized in deliverable 8.11.

In particular, the development of a methodology for the evaluation of the SNF performance under accident scenarios is being done by Nagra (National Cooperative for the Disposal of Radioactive Waste in Switzerland) and CIEMAT (Center for Energy, Environmental and Technological Research in Spain). For this purpose, two different approaches are being followed: Nagra is working on a methodology based on numerical investigations with Finite Element Analysis; and CIEMAT is relying on an engineering methodology capable of assessing the fuel performance with considerably less computational cost and by utilizing fuel performance code (i.e., FRAPCON-xt). These developments, though, are not fully independent from each other, as CIEMAT plans to use some of the findings from NAGRA's research.

The identification and analysis of possible accident scenarios will be performed by IDOM (Spain) and TUS

(Technical University in Sofia). IDOM already summarized a list of all accident scenarios, including potential initiating event and their associated risks (probability and consequences). In addition, they are reviewing multiple studies to identify the types and magnitudes of the different loads that SNF assemblies might undergo in different scenarios. By doing so, they foresee identifying the main fuel parameters and related degradation mechanisms involved in every accident scenario. In the future, TUS plans to support IDOM by studying and reviewing information sources related to the possible phenomena and the consequences that could appear during SNF long-term storage in case of an accident.

Finally, CEA (French Alternative Energies and Atomic Energy Commission) has already started the detailed mechanical characterization of SNF that underwent fuel matrix oxidation due to defective rods in dry storage and off-normal conditions, i.e., air ingress inside a defective rod. The work includes annealing spent fuel rodlets (with Zr4 cladding) until fuel crack failure, followed by a series of experimental investigations (3D FIB/SEM).

#### 1.3.2 SFC Subtask 4.2: accident management and consequences

The general objective of subtask 4.2 is to study SNF behavior under accident conditions with the intention to assess the current capability of consequence analysis and to support national programs for safe management during back-end activities. The main focus of the subtask is the writing of Deliverable 8.13, “Analysis of the conditions of the state-of-emergency radioactive wastes packages containing SNF, FCM (Fuel-Containing Materials) or HLW/LLW generated due to ChNPP accident”, as it is considered that the experience gained in the aftermath of the accident might be instrumental in building accident management guides elsewhere. Presently, the report is being drafted, and a final version will be released soon to partners other than ChRDI. Additionally, two studies are planned to explore the analytical capabilities of the Source Term in a vault system undergoing a postulated leak from an SNF and the criticality values that might be reached in accident arrangements within a storage cask. The former has already been started; the latter sets a bond between Tasks 2 and 4, in this case through CIEMAT participation in both tasks.

## 2 DisCo

The disposal of new and unconventional fuel types was identified as a high-priority topic in the Strategic Research Agenda of the IGD–TP (Implementing Geological Disposal–Technology Platform). The DisCo project was initiated to test the hypothesis that modern fuel types, such as doped fuel, will dissolve in a way that does not significantly differ from standard conventional nuclear fuels. Specifically, the DisCo project focused on Cr-, Cr+Al, and Gd-fuels. The project aimed to provide data from leaching experiments of spent nuclear fuel, model materials (analogs), and models are describing the chemical system expected in the failed waste container. Two main objectives motivated the project: (1) to improve understanding of spent fuel matrix dissolution under relevant repository conditions and (2) to assess the dissolution behavior of modern types of fuel (MOX, doped) compared to standard fuel.

The DisCo project was based on three main parts: experiments with real spent nuclear fuel, experiments with model systems, and chemical modeling. To allow comparisons between the parts and to ensure the modelers received the required data in the right format, a specific work package was dedicated to synchronizing sample synthesis, characterization, and experimental systems. The idea was to provide a well-defined initial state of the system before the dissolution experiments. Synthesized model $UO_2$ included additions with Cr, Al, Gd, Th, and Pu, either as sole dopants or in a combination of two dopants. Studied spent fuel samples included UOX fuel doped with Cr and, Cr+Al, and spent MOX fuel, as well as standard UOX fuels. In addition, failed fuel recovered from fuel ponds was characterized, and data was used as input to the modelers. Most of the spent fuel experiments were performed using simplified, synthetic granitic groundwater with bicarbonate, while some used synthetic cement water with Ca – this water has a high pH and more complex chemistry. In the model materials experiments, four different water types were used: simple bicarbonate water and young cement water to mimic the experiments performed with real spent fuel; simulated Callovo-Oxfordian groundwater relevant for clay-based geology, and real granitic groundwater from the Olkiluoto site in Finland. Most spent fuel experiments were performed in anoxic and/or reducing environments (with hydrogen in the gas phase), and this was also the aim for most model systems experiments. In some model systems experiments, however, the oxidative dissolution of doped $UO_2$ was investigated by using hydrogen peroxide as a simulant for the expected radiolytically produced oxidants. Samples were taken from the systems at various intervals, and the fluids were analyzed with mass spectrometry to provide dissolution data. When available, these data were used in the modeling activities, including models developed using different tools and approaches. The presence of near-field materials, such as iron components, was taken into account in the models.

### 2.1 DisCo results

The main outcome from the different work packages providing results from SNF, model systems, and modeling are provided below.

#### 2.1.1 Experiments using spent nuclear fuel

Samples from the following spent nuclear fuels were prepared and characterized before starting the dissolution experiments: standard UOX with average burnup of 50–59 MWd/kgU, doped fuel (Cr, Cr+Al) with average burnup of 57–58 MWd/kgU, and MOX fuel with average burnup of 38–56 MWd/kgHM. By also using different chemical conditions, the data produced was used to assess the effect of various parameters:

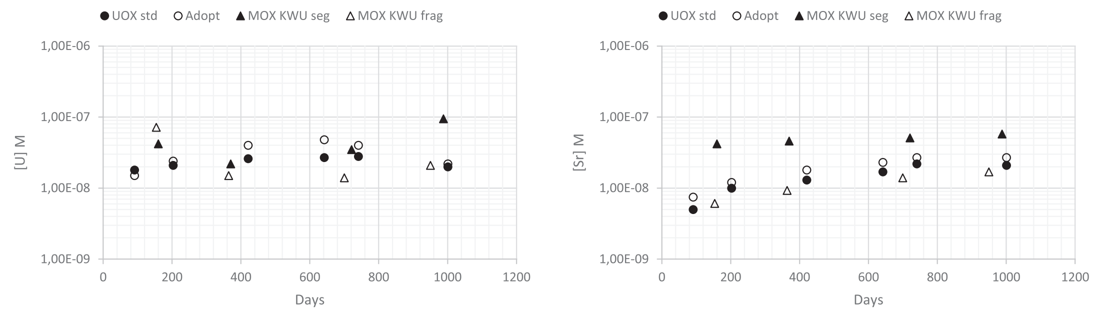


**Fig. 6.** Concentration in aqueous solution vs. time for standard fuel, doped fuel (Adopt), and MOX. Experiments with hydrogen overpressure (Studsvik: initially 50 bar hydrogen. KIT: initially 40 bar with 3,2 bar hydrogen). NB Only data after 90 days are shown on this plot. Data produced by Studsvik and KIT in the DisCo project.

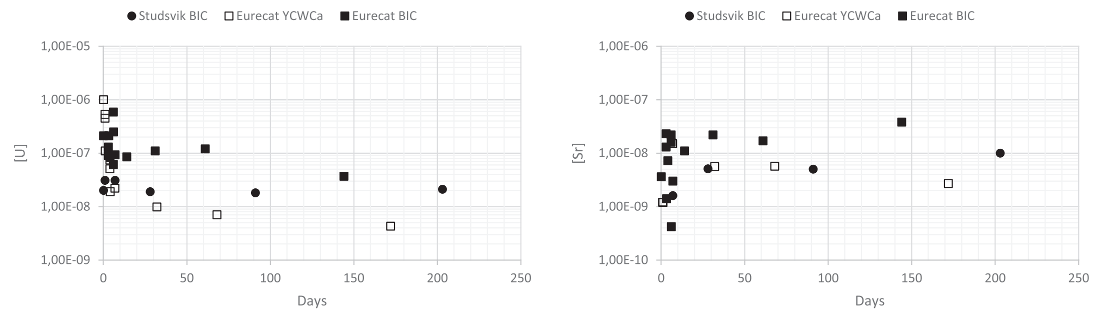


**Fig. 7.** Concentration in aqueous solution vs. time for standard fuel leaching in bicarbonate (BIC) water and Young cement water with Ca (YCWCa), both with hydrogen overpressure (Studsvik: initially 50 bar hydrogen. Eurecat: initially 35 bar with 1,7 bar hydrogen). NB for the Studsvik dataset, only data up to ~200 days are shown. Data produced by Studsvik and Eurecat in the DisCo project.

(1) fuel type;
(2) hydrogen overpressure;
(3) aqueous solution;
(4) sample preparation.

The release of actinides (uranium plutonium americium) and other radionuclides commonly show some scatter in all experiments during the first year of dissolution [20–22]. This makes it hard to draw clear conclusions from those data with regard to matrix dissolution and the effects of different parameters. To assess the effects on matrix dissolution, data from experiments that were run longer than one year are presented in Figure 6 ([22]; data from Studsvik and KIT)). In experiments using bicarbonate water and hydrogen overpressure, the U and Sr release is quite similar. Release data from other radionuclides (not shown) are also similar, indicating that neither doped fuel nor MOX exhibit any significantly different dissolution behavior compared with standard UOX. For the three fuel types studied here, the hydrogen clearly inhibits the oxidative dissolution and the release rate approach but have not yet reached, zero. Experiments without hydrogen display much higher uranium concentrations due to the oxidation of uranium in the spent fuel matrix. To assess effects of chemical conditions, datasets using the same fuel type, but different aqueous solutions are compared in Figure 7 ([22]; data from Studsvik and Eurecat). When writing[1], data from experiments using young cement water (high pH) under hydrogen are provided for up to ca 200 days. Therefore, interpretations with respect to the effect on matrix dissolution should be made cautiously. One may observe, however, that using the young cement water appears to lower the concentrations of some radionuclides (Pu, Am).

### 2.1.2 Experiments using model systems

In the DisCo project, experiments were performed using the following types of model materials: pure $UO_2$ and $UO_2$ with one additive (Cr, Gd, Th, or Pu) and two additives (Cr+Al and Cr+Pu). Adding Pu as $^{238}$Pu adds alpha radiation to the system, and the amount is adjusted to mimic spent fuel with an age of ca 10 000 years. The effect of alpha doping was also investigated using $UO_2$ doped with $^{233}$U. These model materials were exposed to both oxidizing and reducing conditions and different aqueous solutions with compositions mimicking those used for spent fuel experiments (see Sect. 2.1.1). In addition, real Finnish (granitic) ground waters were used in a few experiments.

The work performed during the preparation of model materials provided essential information and knowledge concerning the uranium dioxide solid-state characteristics. The preparation method chosen affects the resulting product: the microstructure, as well as the amount of Cr that is soluble in the $UO_2$ matrix, is controlled both by the oxygen potential and the amount of Cr available during sintering [23,24]. It was shown that the solubility limit of Cr is between ca 700 and 1000 ppm. Above the solubility

[1] January 2022. More data will be available later in the year.

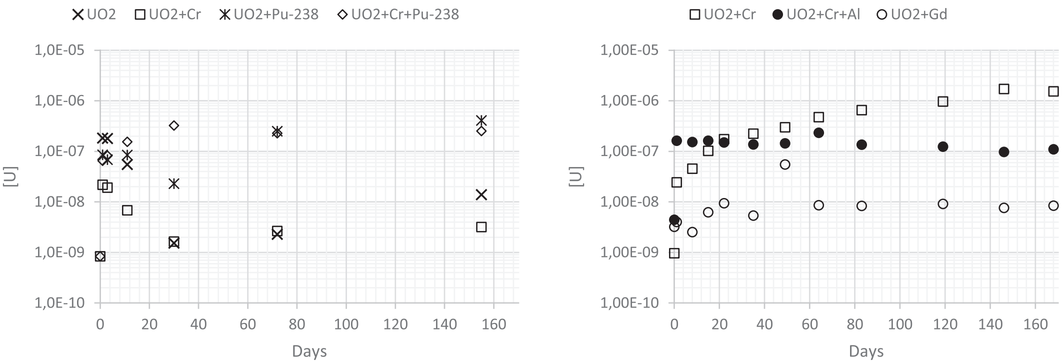


**Fig. 8.** Uranium concentration in aqueous solution vs. time for undoped and doped $UO_2$ in experiments with hydrogen in the gas phase. Left: data from SCK CEN (10 bar hydrogen). Right: data from Ciemat (initially 8 bar with 5% hydrogen; NB, some air contamination noted).

limit, Cr, which acts like a sintering agent, will precipitate long grain boundaries. Detailed studies of the defect concentration and Cr oxidation state revealed how the potential formation of oxygen vacancies influences the Cr incorporation into the uranium dioxide lattice [25,26].

Unirradiated Pu-rich MOX was already available at the start of the project, however, two sets of Th-MOX were produced: heterogeneous and homogeneous samples were needed to compare with previously available data from unirradiated Pu-MOX as well as data produced in this project [27].

Dissolution experiments in oxidizing conditions show that Cr-doping may affect the dissolution rate – however, in these systems, it appears to be more related to the microstructural (e.g., grain size, porosity) effects of the doping rather than the chemical effect of Cr. The differences observed are mainly related to the initial stages of dissolution, and in the long run, the differences are smaller, and the Cr-doping appears insignificant. Another important observation is that when the sample is repeatedly exposed to hydrogen peroxide, the dissolution rate of uranium is reduced. It appears a second phase is produced that affects the surface reactivity of the uranium dioxide, even if the aqueous solution contains bicarbonate [28].

Model materials dissolution experiments with hydrogen present aimed to investigate U dissolution in strongly reducing conditions. However, in some of these experiments, there may have been traces of oxygen (from the air). Oxidants were also available in systems with alpha-doped material [29]. In most cases, data indicates no effect of Cr-doping on the U dissolution rate. Only in a few cases an effect of doping with Cr are seen (Fig. 8). It seems Cr may have some anti-oxidation effect, but it is small and only apparent when the conditions are weakly oxidizing. The Gd-doped material produces less oxidized U, however, the combination of Cr and Al may also be inhibiting U oxidation.

Unirradiated MOX systems were investigated using simulated Callovo-Oxfordian water. For these systems, it appears the added Pu and Th have a protective effect regarding uranium oxidation. However, the most obvious is the effect of iron on the systems. Even in a system with relatively high alpha-radiolysis, U is kept at the level of $UO_2$ (am) solubility, and Fe precipitates are found both on the Pu-MOX-pellet as well as on the corroding iron. This corroborates the results from an alpha-doped sample in natural groundwater and iron – the U concentrations in these systems are very low. Overall, in the experiments performed in the DisCo project, iron appears to have a more pronounced effect on U concentrations than hydrogen for both doped and undoped systems.

### 2.1.3 Modeling the dissolution of spent fuel in repository conditions

The modeling work considered experimental data produced before the project and data generated along Disco. To this aim, an experimental Excel database was generated, including all experimental details needed by modelers to incorporate into the numerical models. The concept of this database constituted an important outcome of the project.

The main question relating to the potential effect of dopants is how the oxygen potential of the irradiated fuel changes due to the elements added to the uranium dioxide lattice. Thermodynamic modeling using the GEM-Selektor code was employed to explore this. The development of the model went through different stages to account for the solubility of Cr in the lattice and the effect of irradiation, implying modeling a complex system including fission products and Cr. The final results show that above a burnup of ca 20 MWd/kgU, Cr-doping has a negligible effect on the oxygen potentials [30]. The model results also confirmed that zirconium alloy oxidation at the pellet-cladding interface might locally reduce the oxygen potential.

Important improvements were incorporated into the Matrix-Alteration Model (MAM) during the DisCo project. The MAM model has now been implemented with the iCP (Comsol-PhreeqC coupling interface) tool, including modeling the effects of metallic aggregates and hydrogen. The model is able to reproduce data from the experimental systems studied in the DisCo project [31]. For example, the possible effect of combining Cr and Al in the spent fuel has been modeled. The experimental results indicate that the Cr+Al combination may have a more pronounced catalytic effect with regards to the hydrogen effect than if only Cr is reproduced by the model.

The MOX experimental system, corresponding to the French repository system with the Callovo-Oxfordian groundwater, was modeled using the CHESS-HYTEC approach, using geochemistry and reactive transport. The results clearly show that iron in the system is very efficient in reducing oxidants, and the U and Pu concentrations are very low [32]. Thus, the corroding iron in this groundwater system appears to be enough to keep the actinides in their reduced form, keeping the dissolution rate low.

#### 2.1.4 Failed fuel in ponds

As an additional study, the DisCo project also involved characterization and modeling of fuel exposed to pond water for ca 40 years. The data from the characterization of this fuel (gamma spectrometry, visual inspection, and optical microscopy) were used in the efforts to model the fuel behavior using electrochemical modeling. The so-called Mixed-Potential-Model, the electrochemical model, previously used and developed in Canada [33], was further developed and improved in the DisCo project. However, the results were not encouraging due to a large number of unknown parameters, which forces estimations and thus increases the uncertainty level. Therefore, the electrochemical approach is suggested to be abandoned in [34].

### 2.2 Discussion of DisCo results

The combined results presented in section 3 show that even though grain size and microstructure are affected by synthesis procedures and doping with Cr (or Cr+Al), the effect on irradiated fuel is insignificant with regard to oxygen potential and radionuclide release patterns. In some cases, there is an effect of the doping – especially Gd seems to be able to reduce the redox reactivity of the $UO_2$ matrix. This corroborates with previous results from [35].

The spent nuclear fuel and model systems data used in modeling has improved the understanding of the systems; results indicate that a three-valent additive may protect the uranium dioxide from oxidation. Even though only Cr may not be so efficient in this respect, combining Cr with Al makes the reactivity towards oxidants in the presence of hydrogen seem to be diminished. This supports the hypothesis that dopants do not affect the dissolution of spent fuel negatively – it rather seems to have some protective effects. The weaker effect of Cr compared with Gd may perhaps be related to the possibility that the valence of Cr is not always (III).

The chemical environment in which $UO_2$ dissolution takes place has the most pronounced effect. Clearly, if the oxidation of U can be avoided, the dissolution rate is slow and is controlled by the release of U(IV). The results show that hydrogen does inhibit the U oxidative dissolution, but in these experiments, the spent fuel matrix seems to continue to be very slowly dissolved even after ca two years. In at least one case (Studsvik), some answer to this may lie in a strong pre-oxidation of the sample. There are other recently published data where hydrogen overpressure has completely stopped oxidative dissolution [36,37].

Finally, the results from model systems show that the presence of corroding iron in groundwater (both natural granite and simulated clay water) can efficiently remove oxidants and minimize the rate of oxidative dissolution. The systems have very low Eh and U concentrations equal to (or lower) than that expected from equilibrium with $UO_2$ (am).

Even though much has been learned from the new results produced in the DisCo project, some questions remain. There is a need to further understand the hydrogen effect – e.g., reactions involving hydroxyl radicals at the fuel surface and potential countereffects from groundwater constituents – and the relative effects of iron and hydrogen in a repository setting. The impressive effect of Fe on the MOX system means we need to further explore the effects of various expected Fe concentrations in the different repository settings. With regards to the effects of dopants, there is some remaining uncertainty regarding the valence of Cr in the uranium dioxide matrix that still requires some attention. In general, the influence of dopants with a predominant valence other than +3, for example, Th, is not satisfactorily understood and requires further study.

### 2.3 Conclusions from the DisCo project

The results from the DisCo project show that the matrix dissolution behavior of MOX, doped fuels (with Cr and Al as dopants), and standard fuel types are similar. This indicates that the modern fuel types studied in this project can be included in the plans and safety assessments for spent nuclear fuel repositories without any detrimental effects. Project results have confirmed that a reducing environment and the presence of corroding iron in the repository can keep the dissolution rate of spent nuclear fuel low. The mineral chemistry and microstructure of the uranium dioxide matrix are better understood due to efforts in producing the model systems, and a tangible outcome is the actual samples available for further studies. The modeling of spent fuel dissolution and radionuclide release and transport performed in the DisCo project has also improved understanding of the repository systems, from the thermodynamics of the spent fuel to the effect of a redox front on the radionuclide transport in the repository. The models developed are ready to be included in the safety assessments. The DisCo project has thereby contributed importantly to the safety case for spent fuel repositories in a range of different settings. Uncertainties in critical parameters are reduced and important for the performance assessments, but the outcomes are also useful for developing waste acceptance criteria for spent fuel repositories, an important issue closely connected to the licensing process.

## Conflict of interests

The authors declare that they have no competing interests to report.

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## Data availability statement

Data from experiments performed in DisCo are found in project deliverables available via https://cordis.europa.eu/project/id/755443/results.

## Author contribution statement

All the authors were involved in the preparation of the manuscript. All the authors have read and approved the final manuscript.

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# SESSION 2: STRATEGIC RESEARCH STUDIES IN RADIOACTIVE WASTE MANAGEMENT

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# SESSION 2- SUMMARY

# REFLECTIONS ON ACTIVITIES AND EMERGING ISSUES OF STRATEGIC NATURE WITHIN THE CURRENT AND FUTURE EURATOM RTD PROGRAMME ON RADIOACTIVE WASTE MANAGEMENT

**Piet Zuidema**

## Scope of this note

This note looks at issues of strategic nature related to the currently on-going EURAD Joint Programme and the PREDIS project and at emerging issues based on discussions within EURAD and PREDIS and in the broader waste management community. This note also points to issues of potential relevance for a future European Joint Programme (EJP) on radioactive waste management.

The note looks mainly at the development since the last EURADWASTE conference three years ago and is mainly based on material presented during the strategic and other sessions of EURADWASTE'22 and/or discussed in connection with the conference . The note also considers insights of the author based on his role as Chief Scientific Officer (CSOff) of EURAD. To better capture the context, sometimes also older issues are mentioned.

The structure of this note is as follows:

- Scope of the note (this chapter)
- Implementation and structure of EURAD and PREDIS
- Topics of strategic importance to radioactive waste management (RWM) and contributions by EURAD and PREDIS
- Looking ahead
- Summary and conclusions

# 1 Implementation and structure of EURAD and PREDIS

## EURAD

EURAD – the joint programme on radioactive waste management - started in 2019 and consists of ten work packages (WPs)[23] on RDD and two WPs[24] on strategic studies and has a strong Knowledge Management programme with 3 WPs relying on a roadmap produced and managed by the Project Management Office (PMO). Joint programming takes place through the involvement of three colleges (Waste Management Organisations (WMO) in charge of implementing disposal solutions, Technical Support Organisations (TSO) supporting regulatory activities and Research Entities (RE)) and the participation of Civil Society (CS) representatives and is managed by a coordinator, the PMO and the Bureau representing the three colleges. The Chief Scientific Officer (CSOff) reports to the General Assembly (GA) of EURAD and participates in important meetings, including management meetings. With its WPs and the governance structure, EURAD covers a broad range of issues that are either of scientific-technological or of strategic relevance (see chapter 3 and e.g. Beattie et al., 2022a).

EURAD involves 51 mandated actors[25] from 23 countries (20 Member States and 3 associated countries) that are supported by 62 linked 3rd parties and 3 international partners. Furthermore, CS representatives and end-users are also involved. With the 23 countries, a broad range of waste management programmes are involved – from advanced programmes with large inventories to early-stage programmes with small inventories, with the complexity of waste inventories varying significantly between the different programmes.

The steps towards implementation of EURAD were strongly supported by EC co-financed activities that started several years ago. This included:

- The implementation of the three colleges: (i) the waste management organisations with IGD-TP founded in 2009, (ii) the technical support organisations started with SITEX its activities in 2012 that did lead to the foundation of the SITEX network in 2018 (iii) the European research entities with EuradScience founded in 2019. Thus, all three colleges are formally organised and have their procedures to form common views, e.g. through position papers.

  It should be noted that regulators are not directly involved; this decision was made to maintain the independence of the regulator. However, the regulators

[23] The current RDD studies are related to (i) the source term, the engineered barriers, the nearfield; (ii) the geosphere barrier & the performance clay material barriers (e.g. buffer, seals, …); (iii) perturbing effects; (iv) methods, strategies and tools

[24] Current strategic studies are related to methods, strategies, tools and interactions

[25] WMO: 19 organisations; TSO: 13 organisations; RE: 19 organisations

can participate as end-users or indirectly by becoming a member of SITEX – however, regulators will not be fully involved as mandated actors.

- The EC co-funded project JOPRAD investigated the options of a European Joint Programme and supported the planning and development of the corresponding material to submit a proposal for a European Joint Programme on Radioactive Waste Management (EURAD) to the EC in 2018.
- The well thought out structure of the call for a EJP by the EC allowed to develop and submit a proposal with a suitable framework for the successful implementation of a European joint programme.

The experience and findings up to now indicate that the foundation documents are very suitable for Joint Programming and would also be a good starting point for a new EJP (with some small adaptions). Experience, however, shows that the preparation of a EJP with the WPs for a first phase being fully developed, will need considerable time. This should be kept in mind for a follow-up EJP of EURAD.

EURAD is a step-change compared to earlier EC co-funded projects:

- EURAD provides a platform that ensures the structured and efficient interaction between key actors in RDD that have a formal responsibility to support the implementation of radioactive waste management activities, including disposal, in their respective member states / programs. The interaction within EURAD takes advantage that the actors are organized in colleges with each college having its distinct functions (see e.g. Detilleux, 2022b (presentation)).

- The ability of the 3 colleges and the representatives of CS to constructively work together within EURAD increases trust and mutual understanding between the partners and will eventually lead to a 'common' culture.

- EURAD leads to increased cooperation and enhanced information exchange to assess specific issues (e.g. supported by strategic studies and position papers prepared by the colleges) with the possibility to form common opinions within EURAD (not yet fully exploited):

– EURAD is an excellent platform for early-stage programmes to learn about state-of-the-art, to have access to the most recent information and to develop personal contacts.

– EURAD allows advanced programmes to discuss and share information and through that support the early-stage programmes in advancing their projects.

– EURAD is of significant value for the interaction between SIMS (small inventory member states) and LIMS (large inventory member states) with the possibility to learn from each other and to identify potential synergies.

- EURAD is more efficient in the administrative management of the work than the earlier EC co-funded projects; it makes better use of resources (economy of scale).

- EURAD allowed to define the needed work upfront by the members of the EJP and thus by the member states. This gives the flexibility to the EJP to define and/or adapt the detailed program of work (see e.g. the identification of the themes and the development of the 2nd wave WPs, the possibility for small modifications in individual WPs, etc.). Thus, it is now the members of the EJP that define what needs to be done (within certain bounds) and not anymore the EC.

- EURAD ensures that the impact of new findings and experience on future RDD is periodically evaluated by updating the Strategic Research and Knowledge Management Agenda (SRA), see Detilleux et al. (2022a).

- EURAD shows the importance to have a knowledge management programme as integral part of the EJP that ensures that KM actually takes place, and that the needs of the broad spectrum of EURAD-participants are taken into account. With the approach chosen (using the roadmap to provide structure and context), it is expected that the KM system will be easier to use than other systems as it provides not only the 'what', but also the 'when', the 'why' and the 'by whom'. It is envisaged that on the longer run, the KM programme will also allow active networking through 'communities of practice' - this is of special relevance to young professionals entering the field of RWM.

- The combination of RDD (10 WPs), strategic studies (2 WPs to discuss / network on emerging issues) and knowledge management activities (3 WPs, roadmap and 'lunch & learn' also for networking) within one EJP leads to significant synergies.

- The strong participation in EURAD with 23 countries being involved with 51 mandated actors, 62 linked 3rd parties and 3 international partners ensures that the information produced is known, will be directly accessible and used by a broad community.

- The involvement of the IAEA and NEA already in the preparation of EURAD and the current cooperation are beneficial for both sides; IAEA and NEA are important partners of EURAD (and PREDIS). Through 'learning-by-doing' a working mode is established between EURAD and the international organisations that ensures that no duplications will occur (see e.g. Mayer et al., 2022).

- To summarize: The EJP concept is a very powerful instrument to support the implementation of radioactive waste management activities in the member states and associated countries. With EURAD and PREDIS being at interface between RDD and implementation, they can be very efficient. This, however, requires an efficient interaction between the Member States and EURAD/PREDIS.

### PREDIS

PREDIS - the project on the pre-disposal management of radioactive waste - is complementary to EURAD and provides many of the detailed aspects of theme 2 (pre-disposal) of EURAD. The main emphasis of PREDIS is on L/ILW and consists of 7 WPs with 4 of them looking at specific waste streams and the other related to management, to strategic issues and to KM. With this, PREDIS is able to provide an integrated view on the management of the different pre-disposal issues and to maintain a link towards disposal (see Holt et al., 2022).

PREDIS has 47 partners from 17 countries and profits from the strong involvement of end-users (waste producers) and with integrating the SNETP side of the community. Finally, PREDIS also provides a sufficiently close link to decommissioning.

### Concluding remarks

EURAD and PREDIS are well underway and have already produced a considerable amount of valuable information and allowed the development of a lively interaction between the different participants, allowing some of them to experience a strong learning-curve. EURAD's mid-term review took place early in 2022 and the final report of the experts is available. The experts came to rather positive conclusions about EURAD.

Besides their current work, both EURAD and PREDIS use their network to maintain an up-to-date view on issues for potential future collaborative projects by updating their strategic research and knowledge management agendas. This is done in close cooperation between EURAD and PREDIS.

## 3 Topics of strategic importance to radioactive waste management, their status and current and possible future contributions by EURAD and PREDIS

Below, topics of strategic importance to radioactive waste management are briefly described and the contributions of EURAD and PREDIS to these topics discussed.

### 3.1 Waste management strategy at the highest level

**Elements of a waste management strategy**: The waste management strategy at the highest level defines the endpoints of waste management for the different waste streams. It defines the path towards the envisaged endpoints - a roadmap with milestones and decision-points with the needed activities in between. It also defines in broad terms the Governance (the 'who', 'for whom', 'what', 'when' and 'why') and describes the needed RDD, taking the available knowledge into account. At a more detailed level it also defines what is done within the country itself and what could be done through shared solutions or by 'out-sourcing' with relying on service providers external to the programme. Then, it also discusses existing alternatives for the topics to be covered by each country on its own.

These issues are described in the national programme by each of the member states as required by the waste directive (EC, 2011). Progress is reported every 3 years in a report to the Commission on the implementation of the directive. The waste directive also states that geological disposal is at this time at the technical level accepted to represent the safest and most suitable option as the end point of the management of SF and HLW; this is also true for LL-ILW. For LLW and short-lived ILW, disposal in surface or near surface facilities is the typical concept; however, in some countries these wastes are also disposed in geological repositories, though sometimes at more shallow depth than SF/HLW.

EURAD contributes to the issues related to the waste management strategy through the ROUTES work package. In ROUTES, key issues and open questions about the **waste management strategies and options** (*'from cradle to grave'*) are being discussed (Leoni et al., 2022). The interactions in ROUTES between Large Inventory Member States (LIMS) and Small Inventory Member States (SIMS) are important for knowledge transfer to SIMS for them to develop an understanding on the options available to manage their waste streams. The interaction between all the participants also contributes to knowledge exchange on challenging waste streams (small amounts of difficult to treat wastes). These interactions also include the identification and discussion of options to optimize waste management. These issues are also of technical and economic relevance and thus, methods are being developed that may have the potential to systematically investigate alternative options (see e.g. Bourdon et al, 2022).

Looking at the evaluation of the waste management programmes (EC, 2019), one sees that **shared solutions** for waste management activities (including disposal) are envisaged as an option by a significant number of countries, especially for those without a nuclear power programme. This is also reflected by the ongoing joint activities by a range of countries within ERDO (see Vuori et al, 2022). The use of shared solutions requires that the chosen facility is suitable for the disposal of the envisaged waste stream. For this, waste acceptance criteria play an important role and thus, the development of adequate WACs for situations with no disposal solution available yet is also a topic within EURAD (WP ROUTES) and PREDIS (see e.g. de Bock et al., 2022). There, a 'no regrets' approach is suggested (see poster of de Bock et al., 2022).

Besides the technical aspects, also regulatory and legal issues can hinder shared solutions. An initiative (project HARPER) is underway that analyses these obstacles and that eventually may lead to more favourable conditions for shared solutions (see Szoke et al., 2022).

Besides the technical aspects of the envisaged solution, also the **pathway for implementation** is essential. Implementing disposal solutions is a highly interdisciplinary undertaking that changes its nature from one phase to the next, needing in each phase special capabilities – with integrators needed in each of the phases. The phases and their goals are addressed in the EURAD Roadmap (Beattie et al., 2022b) which describes in a generic manner the different thematic issues that need to be addressed in the different phases of developing, operating and closing disposal facilities. Although primarily addressing geological disposal of HLW and LL-ILW, the roadmap can also be used for planning the implementation of disposal facilities for all other waste streams.

**Timing of the start of operation of disposal solutions** depends upon several factors. On the one hand, the time needed to perform the technical work, e.g as described in the EURAD roadmap (Beattie et al., 2022b) but also policy issues (including political and societal issues and decision-making) can be very influential for the start of construction/operation, with the latter potentially also including financing issues.

## 3.2 Pre-disposal issues

Pre-disposal is in all programmes with L/ILW a very important issue to achieve an optimal situation for interim storage and eventual disposal in relation to safety (operational safety, radioprotection, post-closure safety) and economy. To ensure acceptability of waste packages for storage and disposal, waste acceptance criteria should be available at least in a preliminary format to allow to perform the necessary activities in a suitable manner. This includes the characterisation and classification of raw wastes in view of their segregation as well as the treatment/conditioning and packaging of the waste (incl. characterisation and quality assurance of the final product, including its documentation). The end point of these steps forms the waste acceptance process to ensure the suitability of the waste package for interim storage and disposal.

In some programs, the implementation of disposal solutions is that far away, that no waste acceptance criteria are available at all. This can lead to difficult situations as the discussions within the EURAD WP ROUTES show (Leoni et al., 2022).

The work done on pre-disposal issues within PREDIS is devoted to L/ILW; in EURAD, some work is done on Spent Fuel (see Sjöblom et al., 2022). For **Spent Fuel** (and HLW and LL-ILW in case of a closed fuel cycle) it is important to consider disposal issues very early in the path towards disposal, ideally already in the phase of designing new reactors and in the phase of developing advanced fuels. In that sense, it is very beneficial that the FISA/Euradwaste conferences take place at the same time; unfortunately, however, the programs are made such that hardly any discussion/interaction on scientific-technical issues can take place at the conference (Forsström, 2022a, summary).

Within PREDIS, different issues related to **waste characterisation and treatment of L/ILW** are addressed. This includes segregation of raw wastes and their classification that may benefit from refined characterisation methods (see e.g. Plukiene et al, 2022). For some of the challenging waste streams (e.g. certain liquid organics) new materials and technologies for conditioning / solidification are being developed that are expected to be more efficient/economic and/or lead to better quality and are also assessed with respect to environmental impact (see e.g. Poster of Hamadache et al, 2022).

Also for waste streams that are since many years solidified in an industrial manner, it is worthwhile to investigate new processes that are expected to have advantages over currently used procedures (see. e.g. Galluccio et al. 2022).

For those cases where disposal will only take place in the more distant future, **evolution of the waste properties during interim storage** can become an issue of relevance. For SF, this might be related to changes in cladding properties during dry storage as investigated in the EURAD WP SFC (see e.g. Sjöblom et al., 2022). The potential degradation of L/ILW waste packages may make it advisable to implement specific monitoring activities (see e.g. Niederleithinger et al, 2022).

### 3.3 Implementation of geological repositories for SF/HLW

**Progress with implementing SF/HLW repositories**: With the implementation of SF/HLW repositories, significant progress has been made over the last years by the advanced programmes, e.g.:

- Finland: The operation license application was submitted by the end of 2021
- Sweden: The license was granted by government at the end of 2021
- France: The process of submitting the construction license is underway
- Switzerland: The announcement of the site selected for implementing the repository took place in autumn 2022
- Canada: Currently, two sites are under investigation; the announcement of the site selected for implementation is expected towards the end of 2023
- China: The excavation of a URL at the potential site in crystalline (Beishan region) started in 2022
- Germany: In 2021, a broad range of regions were proposed for further evaluation, considering three different host rocks (salt, clay stones, crystalline)

United Kingdom: The WMO (NWS) is in dialogue with several communities about potential siting with starting some field work (seismic survey) in the near future

The progress described above indicates that the **scientific and technological basis and knowledge** for implementing geological repositories for SF/HLW has reached an advanced stage as demonstrated by the licence applications / granted licenses for repositories in crystalline rock (Posiva, SKB), the prepared licence application for a repository in claystone (Andra) and the corresponding regulatory reviews and governmental decisions. This shows that for these host-rock types no fundamental open issues exist and that the scientific-technological basis and knowledge is available for licensing of HLW repositories with these types of host rock for well-chosen sites and repository design tailored to the site conditions and the properties of the waste.

However, it is important to note that the corresponding licensing process can be complex and involve **not only nuclear safety but also environmental issues** (see e.g. Abbadie, 2022).

With this recent progress, a big step has been made towards **achieving the vision of IGD-TP from 2009** (IGD-TP, 2009) *'Our vision is that by 2025, the first geological disposal facilities for spent fuel, high level waste, and other long-lived radioactive waste will be operating safely in Europe.'*

The **advanced programmes** will now face the transition from developing of a pilot project to the industrialized routine process of construction and operation – this is expected to be a considerable challenge and will take some time. The corresponding IGD-TP vision for 2040 calls for moving *'towards industrialization of radioactive waste disposal in Europe'* that puts highest priority on safe operations, on optimization and industrialization of planning, construction and operation and that acknowledges the need to tailor solutions for the implementation of additional repositories in Europe (IGD-TP 2022 and Jalonen, 2022).

From a purely technical point of view, implementation of repositories for SF/HLW is feasible within reasonable time scales. Therefore, in an **EC-taxonomy document** (EC, 2022) implementation (start of operation) in 2050 is mentioned as a reasonable time point to envisage for the start of operation of SF/HLW repositories.

The very strong national **RDD-programmes of the advanced programmes** were essential to reach the current status of implementing HLW repositories. However, also the EC co-funded RDD projects over the many years made very significant contributions to the recent advances. The value of the **EC co-funded RDD** is manifold: it allows to interact and learn from each other, cooperative activities are less costly for each of the participants and the work done in international projects is often perceived as 'highest standard'.

Despite the progress made, **RDD will also continue for the advanced programmes** for SF/HLW during implementation, e.g. to optimize implementation and to address some safety-related issues (including the management of uncertainties and making the safety arguments more convincing):

- The management of uncertainties includes the identification of uncertainties (including the issue of completeness), to analyse their potential impact on overall system behaviour and performance and, depending upon the importance of the uncertainties, identify options to manage them (possibilities to avoid them or to mitigate their effects and/or to reduce their likelihood of occurrence e.g. through design measures; accept uncertainties because of their limited significance and/or their low likelihood of occurrence, etc.). These issues are addressed within the WP UMAN (see Diaconu et al, 2022).

- Within the EURAD WPs contributions are made to reduce uncertainties and to make the safety arguments more convincing and are related to the source term/engineered barriers/ near field performance (SFC, ConCorD, ACED, MAGIC), the geosphere & performance of clay material barriers (FUTURE), perturbing effects (CORI, GAS, HITEC) and methods/strategies, interactions and tools (ROUTES, UMAN, DONUT, MODATS) with summaries in respective WP SotA-documents.

- Some of the RDD contributes besides improved understanding also to optimisation of repository design and operation (alternative canister materials (ConCorD), optimise heat loading (HITEC), monitoring (MODATS), etc.) and through reduction of uncertainties in waste properties (e.g. heat output, see SFC).

- To optimize the implementation through innovations. In view of the envisaged industrialisation of implementation (construction, operation, closure) by the advanced programmes, it is expected that RDD will in future also address technological innovations for industrialization of implementation to improve efficiency (time and finances).

- Finally, it is important to mention that a review of each of the finalized RDD WP is essential to see where we are and whether anything else is needed in future. For this, the remaining uncertainties should be discussed in the final report in a manner that their meaning and importance can be assessed quantitatively or at least qualitatively by the end-user for their specific application. A contribution to this are the planned updates of the SotA-documents.

Also the **less advanced programs will need some specific RDD**, as each disposal system is to some extent a prototype (differences in geology, waste inventories and legal/regulatory requirements) and thus, the adaptation of the existing scientific and technological basis to the specific system at hand may require some specific focussed development work (*'tailoring of disposal solutions'*). Also for the areas with no need for specific adaption, a good understanding is needed to use the scientific and technological basis in a correct manner.

For these scientific-technical issues, some of the less advanced programmes take advantage of the experience of the advanced programmes – currently, the interactions takes mainly place through commercial contracts.

In the earlier-stage programmes with a significant NPP-programme, progress with implementing their HLW repositories is often not hindered by open RDD issues but much more by the **limited progress in political/policy-related decision-making** (also influenced by societal aspects). One extreme example is e.g. the USA where after abandoning the YMP not much has been done towards implementation.

Most programmes with only very limited HLW e.g. from R&D (no NPP-programme) are still at an early stage looking at different options for managing their HLW (mined repository, borehole disposal, shared solutions) to find a feasible solution with respect to safety, economy, timing, human resources, etc.

Directing future R&D will profit from the ongoing update of SRA within EURAD (together with PREDIS) that allows all partners (from both the advanced programmes and the early-stage programmes) to influence the content of a new EJP on waste management by providing their input through their respective college, see Detilleux et al. (2022b).

### 3.4 Implementation of disposal solutions for L/ILW

**Progress with implementing L/ILW disposal solutions**: The implementation of L/ILW repositories is established already since quite a long time. In many programmes with a significant amount of waste, implementation of the needed repositories occurred already many years ago, with extensions of some of these repositories taking place (e.g. SFR) and with optimization continuing.

In some countries, implementation is still under development and operation has not yet started for a range of reasons (incl. political / policy reasons).

As already mentioned for SF/HLW, also for L/ILW the implementation of RWM activities is for **'small inventory member states'** (SIMS) without a NPP-programme each on its own often a challenge – for SIMS, **shared solutions at least for part of the RWM activities** is an important issue. Many of these programmes follow the dual-track approach (both a solution on its own and a shared solution (with different models in principle possible)), see e.g. the corresponding national programmes. The option of shared solutions is also considered by some programmes with a small NPP-programme. (Vuori et al., 2022)

However, there are challenges with shared solutions: First of all, countries have to be found that accept to host facilities that are also used by other countries. Then, the differences in legal and regulatory requirements in the different countries must be handled. Additionally, there exist difficulties of trans-boundary transfer of waste. Finally, waste acceptance criteria and disposal suitability have to be clarified. An initiative outside of EURAD/PREDIS is underway to identify possibilities to **reduce the legal & regulatory hurdles** for implementing shared solutions (Project HARPERS, see Szoke et al., 2022)

The different strategic options (from cradle to grave) for these programmes are discussed within the EURAD WP ROUTES (see Leoni et al., 2022). The options to identify the optimal strategy include also shared solutions for the different RWM activities, including disposal. Within that WP also very practical issues are discussed (e.g. management of poorly understood legacy waste).

Also for L/ILW RDD is ongoing to improve the scientific-technological basis and to improve the detailed understanding for safety. RDD WPs and Strategic Studies WPs of relevance for L/ILW in EURAD are ACED, CORI, DONUT, FUTURE, GAS, MAGIC, UMAN.

### 3.5 Knowledge Management

Implementation of disposal facilities for radioactive waste covers a period of up to 100 years or more and will involve several generations of actors requiring specific knowledge for operational issues but also for post-closure issues (e.g. addressing emerging issues (by science/technology, public, etc), periodic safety report updates, etc), the latter requiring both specific expertise and the capability to integrate. This is true for both the implementer (WMO), the regulatory side (regulator and TSO) and research entities (RE). Thus, knowledge management is an important issue. Knowledge management has to address the following elements:

- **Availability of capabilities**: Knowledge management has to ensure that the capabilities needed are and will remain available for the implementation of the disposal facilities with the corresponding activities up to (and beyond) closure of the disposal facilities. The capabilities include:

– **competences** (people (individual competences) acting in a team (collective capacity) with networks to interact – the 'human capital') with the tacit knowledge to use existing information and the ability to develop new knowledge when needed. This includes both specialist domain experts and integrators / generalists,

– **specialist infrastructure** needed to perform the necessary activities (e.g. labs),

– **external supply chains** to cover all external needs (e.g. special services and products).

Sufficient knowledge (information and capabilities) has to be available within each programme, as each disposal facility is, to some extent, a 'prototype'.

When discussing the availability of capabilities, it may be useful to distinguish between:

- Areas of general interest, where **broad scientific and technological communities exist**, independent of waste management activities. In these areas, capabilities will be available independent of waste management and disposal; however, it is essential to stay connected with the community at large to be able to hire qualified specialists from the market and to properly integrate them in the team. Furthermore, one has to have the ability to make links to specific waste management activities / issues to be aware of and emerging issues.

- To be sufficiently knowledgeable, this will also require in these areas some activities within each disposal programme with the possibility of some coordinated joint activities.

- **Areas specific to waste management and disposal**. In these areas, capabilities will only exist if specific measures are taken. This may include some R&D that educates people, that supports the activities of the 'communities of practice' (for networking between specialists), that maintains specialist infrastructure and that also helps to stay connected with neighbouring scientific communities, also to be aware of any new developments that offer some opportunities or may need some corrective actions (emerging issues). Thus, international cooperation and some joint activities in these areas are important.

For both areas it is critical to **attract bright scientists and engineers already today**, as the age profile of people working in the nuclear field is at a critical level - 35% of the workers are at an age of 55 years and more (Najder, 2022). Thus, disposal projects must be visible in their full dimension to demonstrate their attractiveness; this requires some activities to stay connected with the scientific community. Training and mobility are specific additional measures that may be useful for educating young scientists entering the field in specialist areas. Finally, for some topics it may also be useful to develop some guidance documents that facilitate the start of newcomers in the area (see e.g. Ormai et al,, 2022), combined with the transfer of tacit knowledge through networking (creation of 'communities of practice').

- **Availability of information and the knowledge needed for its further use:** Knowledge management has to make existing and newly developed information 'durable', visible and accessible to those that need it. In combination with adequate competences (people providing tacit knowledge), this leads to knowledge to support the implementation of disposal facilities.

- For DGRs for SF/HLW and LL-ILW, a large body of knowledge (information and competences providing the needed tacit knowledge) has been **developed by the advanced programmes** and through **European Commission co-funded research** over a period of about 40 years, leading to the currently licensed DGR projects.

  The scientific and technological basis for these facilities (as documented in the licence applications and in supporting documentation) will be used to **further develop and optimize the advanced projects**, to perform the needed periodic safety case updates up to closure of the DGRs and to address emerging issues. These activities will continue over a long time, meaning that this work will sooner or later be done by younger generations not yet in the field. For them it is important to have the current information available in an understandable form to ensure its correct use in their future work. This also requires that the younger generations receive the needed knowledge, including the rationale for choices made.

  The information available from advanced programmes is also **very valuable for the earlier-stage programmes** for further developing their own disposal projects. This may, however, need some **adaptation of the existing information** to the specific situation at hand. Both the correct use of existing information and the partial adaptation of the information to the specific situation at hand will require knowledge within these programmes that needs to be built up. To some extent, it may be necessary to rely for this on the **support by the organisations that developed the knowledge** to be used, e.g. through commercial contracts. As soon as the earlier-stage programmes become more advanced, they will also face the same issues as mentioned above for the advanced programmes.

- **Transfer of knowledge between generations**: Knowledge management has to assist in the transfer of information and tacit knowledge between generations within the organisations responsible for the disposal facilities, including the regulator. This needs specific measures within each organisation and requires a corresponding organisation culture.

Within **EURAD and in close cooperation with PREDIS**, a knowledge management programme is under development. It addresses the points mentioned above through the following elements:

- It has several RDD work packages and two work packages on strategic issues. Besides **generating new knowledge**, these WPs also **educate young scientists** and thus contribute to maintaining a body of experts over the many years to come. The education of scientists is supported by a work package that provides training and supports the mobility of young scientists.

- It has a work package that collects information to provide an **overview on existing guidance** in areas of importance for waste management. In some areas of interest to several European waste management programmes where no suitable guidance is available yet, **new guidance** is being developed. The guidance documents are an important element for knowledge transfer.

- It has a work package to **capture the state-of-knowledge**. This work is linked to the **EURAD roadmap that provides the structure and context** for organising the information in a hierarchical manner. This again is an important element of maintaining and transferring knowledge.

- For the early-stage programmes, the **EURAD roadmap** provides a **suitable tool to support the planning of implementation** of disposal solutions (5 generic phases, with for each of the phases a description of the key activities for the 7 broad themes needed for implementation). This is complemented by guidance documents (currently under development within EURAD). Finally, also training is provided.

- The **EURAD roadmap provides a framework** for national disposal programmes to **identify the knowledge needed** in the different phases of implementation. With this, it becomes visible whether all knowledge areas needed in the near future are already covered or if there is a need to acquire additional knowledge, including competences, networks, infrastructure and supply chains / external service providers.

- EURAD provides a **platform for interaction**. This platform should, on the long term, develop into a range of **'communities of practice'** that allow systematic networking and provide the opportunity to newcomers to become fully familiar with the relevant areas and develop their personal network. Such networks are important for both subject-matter experts and integrators / generalists. Especially for the integrators, it is important to be involved in a broad range of communities of practice.

Finally, it is important to recognize that a knowledge management programme can only be effective when it **continues over a significant period of time** – thus, it would be very beneficial if the work started within EURAD could continue in follow-up European Joint Programmes on Waste Management. Such activities within European Joint Programmes would be complementary to the ongoing activities within the IAEA and the NEA that are already in place for many years.

### 3.6 Importance of society

Societal support is a pre-requisite for implementation of RWM activities. This requires sufficient **mutual trust and understanding**. Also in EURAD the involvement of CS was foreseen from the beginning on. The active involvement of CS in EURAD works well with the main involvement of CS in EURAD's strategic studies but some involvement also in the other WPs. However, it still needs to be seen in how far this beneficial interaction within EURAD can be transferred to the national programmes to support the constructive cooperation of society in implementing disposal solutions.

To get a better understanding of societal involvement, it might be useful to find out why societal involvement worked in some countries and why it did not work in other countries. Furthermore, it would also be interesting to investigate how repository projects are perceived in the different countries and if differences are seen, to investigate the reasons for these differences.

## 4 Looking ahead – experience with EURAD as input for developing a new European Joint Programme on radioactive waste management

There are clear signals from the EC that a follow-up EJP on RWM to EURAD is envisaged where pre-disposal issues would be integrated within waste management at large (the current EURAD).

Experience within EURAD can and will be used as input for shaping a future EJP on RWM. This could include:

- Use the experience made with the **basic structure** (founding documents with some modifications) and **instruments** (type of WPs & activities) used in EURAD

- The on-going **updates of the SRA** of EURAD and PREDIS (with 'characterised' activities by 'drivers'). In this update or complementary to this update, the following issues are considered important: (i) for areas with RDD for many years, the questions 'how good is good enough for implementation?' and 'where is a continuation for what reason justified?' should also be addressed; (ii) sufficient thought should be given on which new areas might deserve more attention in future. This should also include areas related to optimisation of implementation.

- The interactions through EURAD stress the importance of having a detailed **understanding on the needs of the member states** in implementing radioactive waste management activities, including disposal, as an EJP on RWM is at the interface between RDD (DG RTD) and implementation (DG ENER) – remember: the main motivation for a EJP on RWM is to support all member states in implementing radioactive waste management activities, including disposal. For this, the specific needs of each the following types of programmes should be assessed:

- advanced programmes (with significant NPP-programme)
- early stage / medium stage programmes (with significant NPP-programme)
- early-stage small inventory programmes

This indicates the importance to take the findings of evaluation of the national programmes of member states into account, see the ARTEMIS reports and the reporting by DG ENER

- Ensure inclusiveness
  - by making the boundary conditions such that all member states (and associated countries) with a waste management programme can participate in a new EJP
  - by finding possibilities to include regulators & waste producers in a new EJP through appropriate mechanisms
  - by giving the opportunity to newcomers in RDD to become partner in RDD projects to get 'hands-on' experience with RDD and develop a network
  - by ensuring a sufficiently broad SRA that should include some novelties
- Ensure the **active engagement of advanced programmes** in the **continuation of the KM programme** by providing adequate economic boundary conditions for their participation e.g. for the following contributions:
  - development of KM sign-posting documents (domain insights, SoK's, …)
  - development of guidance documents
  - becoming 'drivers' within 'communities of practice'
- Develop position papers and use other measures to provide information to the public to allow them to develop a balanced perception of disposal of radioactive waste as the endpoint of RWM.

## 5 Summary and conclusions

- European Joint Programming for Radioactive Waste Management offers many benefits in comparison to the earlier EC co-funded projects that were developed through competitive calls:
- Joint programming allows to develop **balanced views and approaches**, taking the needs of European radioactive waste management programmes into account. With the instrument of **mandated actors**, the member states have a clear handle on which organisations represent them in the joint

programming, in deciding on which work to do and in the detailed organisation of the programme of work and to make changes if needed.

- A European joint programme allows to **jointly decide on future RDD projects, strategic studies and knowledge management activities**. The programme should also allow and encourage participation of partners from outside of the EC.

- A European joint programme provides an **excellent platform for interaction** between colleges and civil society organisations and between the different types of programmes (advanced programmes vs. early-stage programmes, large inventory programmes vs. small inventory programmes) to exchange information and learn from each other, to address emerging issues, to decide on the details of the programme of work, incl. the periodic update of the strategic research and knowledge management agenda (SRA), to form common opinions, to develop position papers and to enhance mutual understanding and trust.

- With the **different types of projects** implemented in EURAD (RDD WPs, Strategic Studies WPs and KM WPs), experience has been made on the power of each of these instruments and on how to use them.

- Especially the instrument of 'strategic studies' allows to investigate novel ideas and emerging issues through networking. It is encouraged to use this instrument more strongly in the current phase of re-orientation, taking the need for optimisation (materials, design, …) / industrialisation of implementation (novel technologies & methods) in the advanced programmes into account.

- A European joint programme also provides an ideal **platform for knowledge management**. It has a direct link to knowledge providers and to those that need knowledge and thus ensures efficient transfer of knowledge. For this, experience with a range of instruments (roadmap to provide structure & context, SotA's, SoK's, theme overviews, domain insights, guidance, first steps towards 'communities of practice', etc.) have been made and future improvements are expected.

- Through a European joint programme there are the means to ensure the longevity of the now implemented knowledge management programme; the EC has to provide adequate structure and financing for this.

- A European joint programme has the instruments to allow for strong **participation of end-users**; this also allows the participation of regulators, waste producers, etc. The participation of end-users is important to ensure that the results produced will meet the expectations of those that want to use them.

- Finally, a European joint programme allows a more efficient way of managing a big programme than a fragmented number of individual projects for several reasons (easier interaction, synergies, economy of scale, etc.).

- Overall, a European joint programme is a **very powerful instrument to support the implementation of radioactive waste management activities in the member states**, being at interface between RDD (DG RTD) & implementation (DG ENER).

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EURADWASTE'22

30 May - 3 June 2022
Lyon, France

SITEX.Network

## Key activities and upcoming challenges

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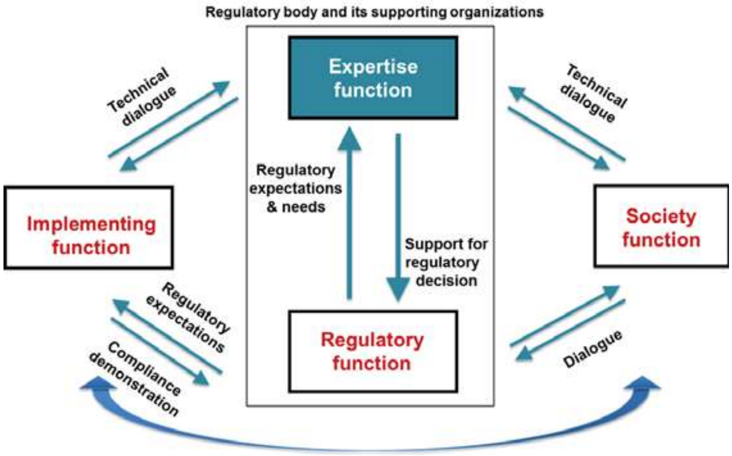
## Context of the SITEX initiative (1/3)

*Main functions interacting in the RWM*




SITEX.Network focuses on the Expertise Function
and its links with the other Functions.

# Context of the SITEX initiative (2/3)

*The role of the Expertise Function*

- Key mission of *Expertise Function* is to provide the technical and scientific basis for supporting the decisions made within the *Regulatory Function*.
- Article 6 of EC Directive 2011/70/Euratom (addressing safety of RWM) states notably:
  - Member states shall establish and maintain a competent regulatory authority;
  - Regulatory authority is functionally separate from Waste Management Organizations (WMOs).
- Independence and competence of the *Regulatory Function* calls for the support of a competent *Expertise Function*, independent from the *Implementing Function*.
- Typical activities of the *Expertise Function* include:
  - Contributing to the establishment of regulatory requirements;
  - Developing guidance for meeting these requirements;
  - Evaluating Safety Cases related to RWM facilities;
  - Develop and maintain its knowledge and skills.



# Context of the SITEX initiative (3/3)

*Develop and maintain the knowledge and skills of the Expertise Function*

- For complex issues such as those associated to operational and long-term safety of disposal facilities, following activities are essential:
  - Performing and/or overseeing R&D activities;
  - Exchanging between expertise function organizations on practices;
  - Organize and/or participate in training activities to transfer knowledge;
  - Interacting with the civil *Society Function*.
- These activities are essential to build the expertise and a mutual trust with the stakeholders (e.g. the civil society) of the *Expertise Function*.
- For instance, Article 8 of the EC 2011/70/EURATOM directive requires *all parties* (i.e. *Expertise Function* included) *to carry out education, training and R&D activities*.
- Concerning R&D, IAEA safety guides stresses that *the Regulatory Body* (and thus its supporting organizations) *may need to conduct or commission R&D in support of regulatory decisions* (see IAEA GS-G-1.1 and IAEA GS-G-1.2).

# From SITEX projects to SITEX.Network (1/3)

*The born of the SITEX initiative*

- In this context, several organizations fulfilling an *Expertise Function* and Civil Society Organizations (CSOs) started the "**SITEX** initiative" in 2012.

- What does SITEX mean ?
  - **S**ustainable network for **I**ndependent **T**echnical **EX**pertise of Radioactive Waste Management

- What is the overall objective?
  - Enhance and foster cooperation at international level to achieve a high quality *Expertise Function.*
  - Independent from Waste Management Organizations (*Implementing Function*).
  - Aiming at supporting the *Regulatory Function* and the *Society Function.*
  - In the field of radioactive waste management (including disposal).

- The start of this « SITEX initiative » was funded by the European Commission.



# From SITEX projects to SITEX.Network (2/3)

*SITEX projects paved the way to the SITEX.Network*

**SITEX project**
2012-2013

**SITEX-II project**
2015-2017

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 References and action plan for establishing SITEX.Network.

# From SITEX projects to SITEX.Network (3/3)

*SITEX.Network foundation*

- Purpose of the SITEX.Network association:

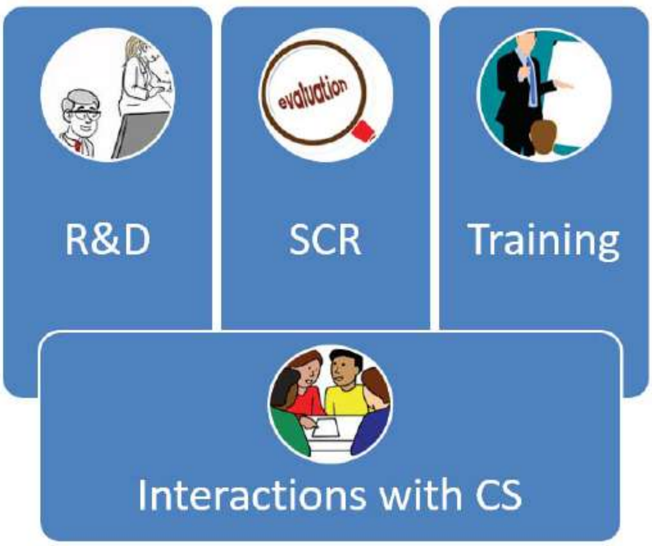
  *« Enhance and foster cooperation at international level in order to achieve a high quality expertise function, independent from organizations responsible for the implementation of waste management programmes, aiming at supporting the Nuclear Regulatory Authorities, as well as the Civil Society, in the field of safety of radioactive waste management. »*

- Achieved through a close cooperation between its members with a plurality of actors and views: NRAs, TSOs, REs with an expertise function and Civil Society Organizations.

- This plurality of actors and views is seen as an added value of the network, compared to other existing networks.



# SITEX.Network: types of activities




*SCR: activities related to Safety Case Review*

# R&D activities

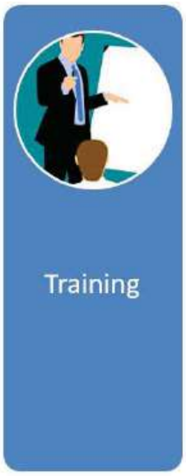

- Coordination of the EURAD Joint Programme TSO College.
  - « Counterpart » of IGD-TP and EURAD Sciences
  - Connection between the College and the Bureau (EURAD 2nd wave, SRA Update and preparation of EURAD 2 proposal…)
- Exchanges about EURAD results with all network members.
- Management of the SITEX.Network Strategic Research Agenda.
- Integration of « hybrid » Social Sciences & Technical topics in the SRA.
- Development of common modelling activities within the Network.



# Safety Case Review (SCR) activities


- Organisation of Topical days:
  - 2019: Governance of radioactive waste management;
  - 2020: Deep Borehole Disposal;
  - 2022 (to be announced soon): Pathway Evaluation Process (PEP).
- Production of a literature survey about Deep Borehole Disposal.
  - Evaluation of pro and cons of DBD compared to the current regulatory framework.
  - Presented at the last EURAD Lunch & Learn and (draft) available at http://sitex.network.
- Organisation of a Safety Case review benchmark:
  - A Fictive SC for a Disposal Facility was reviewed by SITEX.Network members.
  - Exchanges about review outcomes and approaches between the members (CS included).
  - Lessons learned from this exercise will be documented and recommendations shared.

## Training activities



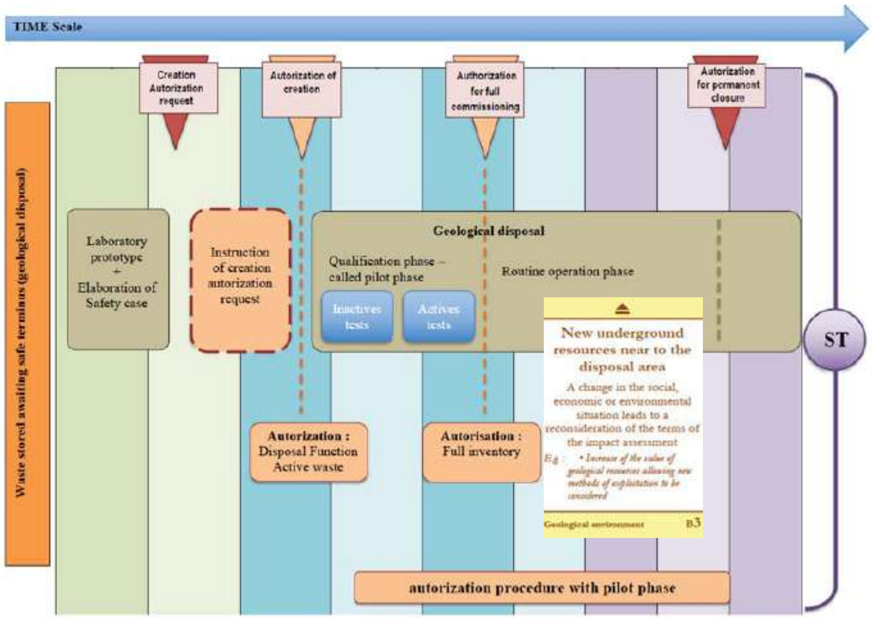

- A training module for generalist experts was developed and given in 2020.
- Participants from various kinds of actors, as well as CS.
- 2021: no training sessions organized (COVID).
- 2022: new training session will be organised as a contribution to an EURAD Course on « Safety Case development and review ».
  - In collaboration with other EURAD Colleges and NEA.
  - To be announced soon.

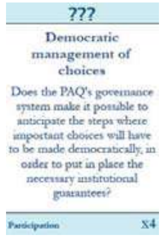


## CS Interaction activities


- Transversal activity: involvement of and interactions with SITEX.Network CS members in all types of activities.
- Development and management of the PEP.
- PEP is a "serious game" allowing:
  - structured discussions,
  - about possible waste management pathways,
  - between actors and persons with various backgrounds (non « experts » from CS included).

## The Pathway Evaluation Process (PEP)




1 game board = 1 pathway towards a Safe Terminus



## The PEP is living !

- France: part of the French Public debate about RWM (PNGMDR).
  - 24, 25 May 2019: “L’atelier de la relève” about 40 students.
- Belgium: in collaboration with the University of Liège (ULg)
  - 24 April 2021: more than 80 students.
  - 18 November 2021: about 30 students.
- Online for SITEX.Network members (2021)
- In the framework of SITEX.Network training sessions
- Other uses of PEP are already planned in 2022.

*We are developing a « Charter » for the use of the PEP by organisations outside of SITEX.Network.*

*→ Will be presented at an upcoming SITEX.Network Topical Day !*

## Some upcoming challenges

- SITEX SRA Update (input to EURAD SRA Update).
- Coordination of TSO & CS views in the development of an EURAD 2 proposal.
- PEP Charter and further development.
- EURAD Safety Case training.



## Conclusions

- Since 2012 the SITEX initiative answers to a need for more coordination of the Expertise Function views in RWM. This need is growing since several years, notably with the development of joint programming in RWM (e.g. EURAD).
- SITEX.Network contributes to build a strong Expertise Function, connected with its stakeholders and providing a high quality support to the Regulatory Function.
- SITEX.Network involves a plurality of actors with an Expertise Function and Civil Society Organizations. This plurality of views is seen as an important added value of the network, compared to existing networks.
- It allows notably the development of joint activities between the Expertise Function and Civil Society Organizations, involving the Public (e.g. PEP). Such activities contribute to maintaining a mutual trust between RWM stakeholders.
- SITEX.Network supports EURAD and its multi actors dimension (CSOs included), and looks forward to contribute to the preparation of an EURAD 2 proposal.

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EPJ Nuclear Sciences & Technologies

**Euratom Research and Training in 2022: challenges, achievements and future perspectives, Roger Garbil, Seif Ben Hadj Hassine, Patrick Blaise and Cécile Ferry (Guest editors)**

Available online at:
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Review Article

Open Access

# UMAN – a pluralistic view of uncertainty management

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**Abstract.** Decisions associated with Radioactive Waste (RW) Management programmes are made in the presence of irreducible and reducible uncertainties. Responsibilities and roles of each actor, the nature of the RW disposal programme and the stage in its implementation influence the preferences of each category of actors in approaching uncertainty management. UMAN (UMAN – Uncertainties Management Multi-Actor Network is a Work Package of the European Radioactive Waste Management Programme – EURAD) carries out a strategic study about the management of uncertainties based on extended exchanges among actors representing Waste Management Organisations, Technical Support Organisations, Research Entities and Civil Society, a review of knowledge generated by past and ongoing R&D projects, and findings of international organisations. UMAN discusses the classification schemes and approaches applied in uncertainty management, and identifies possible actions to be considered in the uncertainty treatment. The relevance for the safety of the uncertainties associated with waste inventory, including spent fuel, near-field, site and geosphere and human aspects, as perceived by each type of actors, and approaches used in their management are explored with the aim to reach either a common understanding on how uncertainties relate to risk and safety and how to deal with them along the programme implementation, or at least arrive at a mutual understanding of each individual view. Finally, uncertainties assessed as highly significant and the associated R&D issues that can be further investigated are being identified.

## 1 Introduction

Decisions associated with radioactive waste management (RWM) programmes are made in the presence of irreducible and reducible uncertainties. In the early phase of a programme, several choices must be made on the basis of limited information and need to be confirmed before or during the construction and operation of the disposal facility. At the end of the process, some uncertainties will inevitably remain and it should be demonstrated that these uncertainties do not undermine safety arguments. Hence, the management of uncertainties is a key issue when developing and reviewing the safety case of waste management facilities and, in particular, of waste disposal facilities due to the long-time scales during which the radiotoxicity of the waste remains significant.

In the European Joint Programme EURAD, it was agreed that a clear strategy and commitment to actors' involvement are essential to the decision-making process at all stages of a waste management programme [1]. Furthermore, scientific activities associated with an RWM programme (on-site characterisation, process modelling, safety assessment, etc.) are evolving over time, sometimes leading to new viewpoints and new uncertainties that may require additional efforts to resolve. Accounting for such uncertainty has thus become a key part of successful programme planning, which can benefit from the continued sharing of methodologies and experience.

Uncertainty is a cross-cutting issue of the different themes and stages identified in the EURAD Roadmap [2], and is associated with several topics of common European interest considered as having a medium or a high priority, such as inventory uncertainty, geological uncertainties, or uncertainty treatment.

R&D activities aim at improving the state of knowledge and thus are expected to reduce uncertainties. Understanding the contribution of these activities to the overall uncertainty management is important for the different actors involved in the decision-making process as well as for the identification of future EURAD priorities and activities.

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An extensive experience in uncertainty management has been already acquired by each category of actors. The Work Package *"Uncertainty Management Multi-Actors Network"* (WP UMAN) is therefore a strategic study intended to provide an opportunity for organisations and different actors of the Member States to share their experiences and views on uncertainty management and to identify emerging needs associated with this topic. Its specific objectives are:

- to develop a common understanding among the different categories of actors in uncertainty management and how it relates to risk & safety. In cases where a common understanding is beyond reach, the objective is to achieve a mutual understanding of why views on uncertainties and their management are different;
- to share knowledge/know-how and discuss common methodological and strategical challenging issues on uncertainty management;
- to identify the contribution of past and ongoing R&D projects to the overall management of uncertainties;
- to identify remaining and emerging issues and needs associated with uncertainty management.

In order to capture a pluralistic view on uncertainty management, WP UMAN brings together the main categories of players involved in the RWM programme, namely Waste Management Organisations (WMOs), Technical Support Organisations (TSOs), Research Entities (REs) and Civil Society (CS).

## 2 General approach

To reach its objectives, WP UMAN dedicates activities, organized into five tasks (Fig. 1):

- compiling, reviewing, comparing and refining uncertainty management strategies, approaches and tools that could be used in a radioactive waste disposal programme to assess and demonstrate repository safety (Task 2);
- identification & characterization of potentially safety-relevant uncertainties that need to be taken into consideration when implementing a disposal programme and in the safety case (Task 3);
- identifying possible options for the management of specific safety-relevant uncertainties in a safety case at different programme phases (Task 4);
- identifying methods to discuss and exchange uncertainties and uncertainty management during the development and review of the safety case (Task 5), therefore contributing to building mutual trust and understanding between various actors.

Besides the interactions between different types of actors, including Civil Society, UMAN collaborates and seeks synergies with other EURAD WPs, and international initiatives and organizations (i.e. IAEA, NEA, NUGENIA).

The UMAN scope covers any waste type for which there are uncertainties requiring adequate management in order to assess or ensure safety. A particular focus is put on uncertainties in direct link with the EURAD R&D WPs and with high (and where relevant medium) priority subdomains of the EURAD Strategic Research Agenda (SRA) [1]: waste inventory and spent nuclear fuel, near field, site and geosphere, and human aspects.

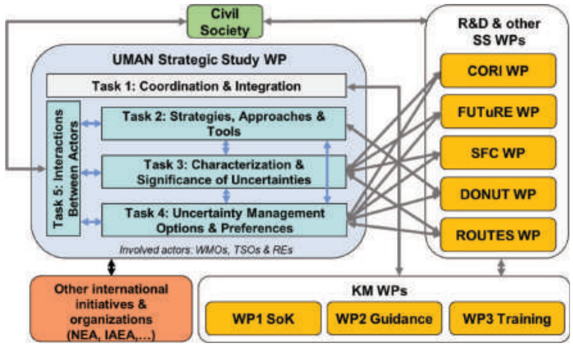


**Fig. 1.** UMAN structure, activities and interactions inside and outside EURAD.

Expert groups consisting of specialists from REs, TSOs and WMOs from Member States with different disposal programmes, at different stages of implementation, have been established to identify the uncertainties with high significance for safety as well as discuss options and strategies to be used for their management. Their findings are discussed with a broader range of participants from the technical actors during dedicated UMAN Workshops, and further on, complemented/validated by a wider range of actors including the Civil Society, during Seminars.

## 3 A mutual understanding of uncertainty management

Radioactive waste management programmes and related safety cases are very complex topics reaching into several fields of science and involving several categories of actors. This leads for instance to multiple understandings and definitions for certain terms associated with uncertainty management. Reaching a mutual understanding of uncertainty management first requires:

- the identification of the categories of actors involved in the different phases of a radioactive waste disposal programme;
- the definition, the classification and the management of uncertainty along the phases of a radioactive waste disposal programme.

As illustrated in Section 4, this mutual understanding was used as a basis to identify and analyze the preferences of the different categories of actors involved in UMAN for the management of uncertainties associated with several topics.

### 3.1 Categories of actors involved in a radioactive waste disposal programme

To succeed in the decision-making process in RWM, the involvement of all actors is particularly important [3].

Identification and characterisation of the actors with respect to their roles/engagement in all phases of an RWM programme were possible on the basis of the answers received to the 1st UMAN questionnaire from 10 *WMOs*, 7 *TSOs*, 6 *REs* and 1 *TCC (Technical Consulting Company)* participating in EURAD strategic studies (WPs UMAN and ROUTES). The survey covered 17 countries in different phases of their disposal programme, including the Member States with Small Inventory [4] and allowed for the classification into 18 actors' categories and definition of their role, mission and responsibility in each phase of the RWM programme with a focus on safety case-related activities [4]. The 18 categories of actors are WMOs, TSOs, REs, Waste Generators, Waste Owners, Regulators, Governments/ Legislators, Ministries, Municipalities, State Authorities, Civil Society, Environmental Actors, NGOs, Geological Surveys, Technical Surveys, Operating Companies, Technical Consulting Companies and Miscellaneous Actors.

The results show the complexity of the actors' system, characterised by very strong interactions and dependencies [4]. This system is multidisciplinary and includes organisations and individuals with different technical, political, scientific and societal backgrounds. The types and number of actors vary among countries, reflecting the diversity of approaches employed in the national RWM programmes, as well as the different national frameworks and thus political, administrative, and regulatory systems. Particularly in the early implementation phases, it is likely that the overall RWM framework, including the system of allocation of competencies and the decision-making process, will evolve, and therefore the functions of all actors are not yet fully clarified.

The categories of the actors identified in UMAN represent an important input in planning the assessment of the preferred options used in uncertainty management by each of them.

### 3.2 Definition: uncertainty vs. risk

A prerequisite in reaching a mutual or even common understanding of uncertainty management is to have a clear and common definition of uncertainty and risk, as these two terms are very often mixed in (not only public) discussions.

Here, *uncertainty* is understood as a total or partial lack of objective information (evidence) or subjective information (knowledge) [5] and is used to express ambiguity about a result. This includes also ambiguities about the validity of concepts, methods, measurements and values.

*Risk* is "a quantity expressing hazard, danger, or chance of harmful or injurious consequences associated with exposures or potential exposures, and relates to quantities such as the probability that specific deleterious consequences may arise, and to the magnitude and character of such consequences" [6]. A risk thus relates to a scenario or sequence of events and can be interpreted as the measure of the significance of uncertainty.

Uncertainties can be epistemic or aleatory. *Epistemic uncertainty* addresses the uncertainty about a used model due to limited knowledge of conditions and processes. In principle, it can be reduced by performing adequate research and acquiring more information about the systems [7]. *Aleatory uncertainty* addresses the uncertainty that is stochastic for the parameter in a model. This type of uncertainty is an intrinsic property of the system and cannot be reduced [5]. Therefore, considering the nature of uncertainties (i.e. aleatory, epistemic or a mixture of both), it is important to address the aspect of uncertainty reducibility if more knowledge is gained.

### 3.3 Classification of uncertainties

Besides the general classification of uncertainties mentioned above, the views of a large number of actors representing WMOs, TSOs and REs on the uncertainties associated with radioactive waste disposal safety, collected via the 1st UMAN questionnaire, led to a three-level classification scheme, illustrated in Figures 2 and 3.

This complex scheme which integrates all points of view and covers all stages of the RWM programme distinguishes five main types of uncertainties:

1. Programme uncertainties, associated with the RWM programme and other prevailing circumstances (societal, resources, etc.);
2. Uncertainties associated with the initial characteristics of the disposal system and its environment;
3. Uncertainties associated with the evolution of the disposal system and its environment, which include effects of events and processes that may affect the initial characteristics (e.g. uncertainties associated with the radiotoxic and chemotoxic elements) as well as human influence or intrusion;
4. Uncertainties related to concepts (models) and parameters (data) used in the safety assessment;
5. Uncertainties associated with the completeness of the safety assessment (uncertainty in overlooking certain aspects relevant to safety).

Each type of uncertainty is grouped in topical groups of uncertainties, which represent the second level of this classification, listed in Figure 2.

The third level of the classification scheme includes the uncertainties potentially significant for the disposal safety of each topical group. Figure 3 illustrates the third level for the uncertainties associated with the site and geosphere, as identified in UMAN.

On another side, from the point of view of the availability of knowledge, uncertainties can belong to one of the three categories illustrated in Figure 4: we know what we don't know (known unknowns), we don't know that knowledge exists or we ignore existing knowledge (unknown/ignored knowns), and we don't know what we don't know (unknown unknowns). The last two circumstances represent the uncertainties associated with the completeness of the safety assessment, which corresponds to the 5th type of uncertainty in Figure 2.

The two approaches can be merged in an Uncertainty matrix (Fig. 4) which has been used by the actors involved in UMAN as a tool to classify uncertainties associated

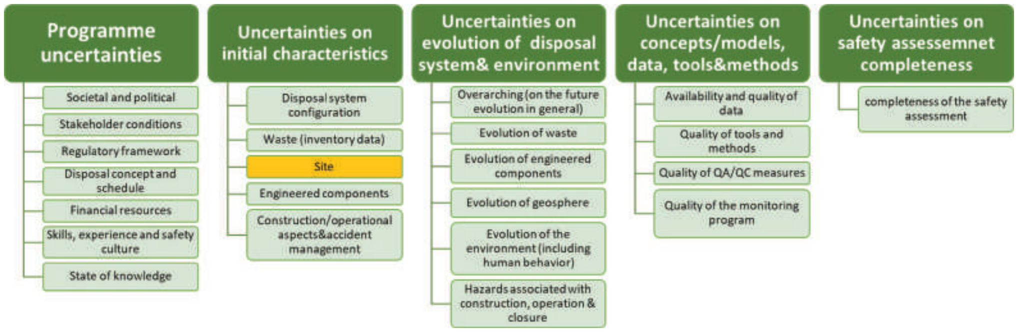


**Fig. 2.** Multi-level classification of uncertainties into different types of uncertainty and each type into different topical groups that various actors consider potentially relevant for the safety case. The third level (see Fig. 3) represents uncertainties specific to each topical group.

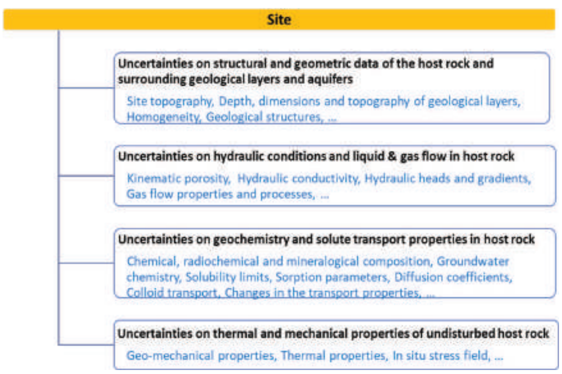


**Fig. 3.** Site specific uncertainties representing the third level of the classification scheme.

with several topics, as further illustrated in Section 4 for site and geosphere. The uncertainty matrix can provide a comprehensive picture of the stage reached in the treatment of uncertainties at a given moment and could guide the actors in the management of uncertainties.

### 3.4 Uncertainty management strategy

Safety strategies are based on: (1) a stepwise, iterative approach, (2) a regular dialogue with actors and (3) a safety-oriented management process. These include approaches for uncertainty management, currently at different stages of development in EU Member States, depending on the phase of the national disposal programme.

Managing uncertainties also requires an iterative approach, correlated with the progress of the disposal programme. This includes an iterative approach to research and data acquisition activities aimed at reducing or avoiding uncertainties or mitigating their impact. At each stage of such a process, safety assessment results can be used to understand the processes to which performance measures are most sensitive and therefore guide subsequent investigation activities to reduce the importance of the associated uncertainties in a meaningful way.

The safety case is typically expected to include a programme for uncertainty management, which generally involves the following steps, discussed in WP UMAN by integrating the views of all actors involved in this work:

- identification of uncertainties and their characterisation,
- analysis of the safety relevance of uncertainties,
- representation of safety-relevant uncertainties in the safety assessment,
- evaluation of uncertainties impact on safety assessment results,
- identification of uncertainties that need to be reduced, avoided or whose impact could be mitigated,
- actions to reduce, avoid or mitigate the uncertainties impact.

All these steps are framed and depend on a number of factors, such as state of knowledge, size of the RWM programme, national policies, regulations, actors, and resources, which altogether represent the prevailing circumstances in the uncertainty management strategy.

Figure 5 represents the common view reached in UMAN about the key elements of the uncertainty management process and strategy.

As illustrated in Figure 5, each step of the uncertainty management strategy is updated progressively and iteratively as the disposal programme and its prevailing circumstances progress. For example, the identification, characterisation and analysis of uncertainties is an ongoing process that needs to consider the newly identified and emerging uncertainties. The assessment of uncertainties' impact on disposal safety is iterated as new information on safety-relevant uncertainties is acquired through appropriate activities for uncertainty avoidance, mitigation and reduction. Such activities may include R&D, further data acquisition (e.g. waste characterisation), site selection and site characterisation, adapting the disposal concept (either at the high level or in the detailed design), adopting particular construction methods, adapting the limits, controls (e.g. reduction of uncertainties on as-built properties by additional Quality Assurance/Quality Control [QA/QC] measures) and conditions for the construction and operation of the repository, as well as interacting with the actors. The choice of particular measures depends, in part, on the stage of the programme and the prevailing circumstances.

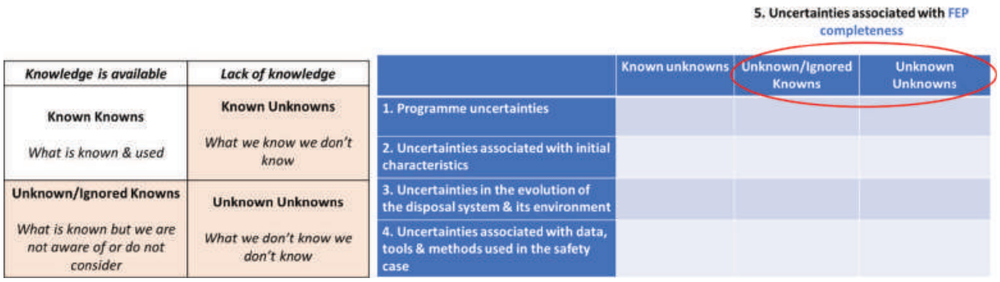


**Fig. 4.** Classification of uncertainties according to the availability and use of associated knowledge (left) and the uncertainty matrix combining specific uncertainties types with availability of knowledge (right).

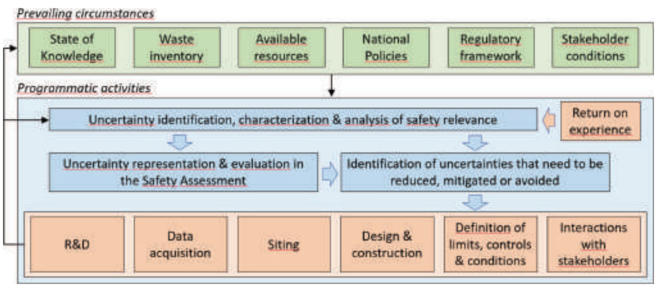


**Fig. 5.** Key elements of an uncertainty management strategy, and its associated stepwise and iterative process.

The possible measures to reduce, mitigate or avoid uncertainties associated with several topics, as well as the preferences of the various actors involved in UMAN for these measures, have been investigated by the multi-actors network and are illustrated in the following section for the case of site and geosphere related uncertainties.

## 4 Application of UMAN strategy to uncertainties associated with site and geosphere

To test and validate the uncertainty management strategy and the actions proposed by UMAN for uncertainties reduction, mitigation or avoidance, the following sequence of activities has been implemented for all five topics approached in UMAN (waste inventory, spent nuclear fuel, near-field, site and geosphere and human aspects):

– uncertainties identification and assessment of their significance for safety;
– identification of appropriate options for uncertainties reduction, avoidance or impact mitigation;
– interaction with actors in order to confirm/amend/complete the uncertainty management strategy via workshops and seminars.

Up to now, this sequence has been fully implemented only for the uncertainties associated with site and geosphere, and human aspects. This paper focuses on the process and results related to site and geosphere; findings for the other topical uncertainties are/will be publicly available on the EURAD website (`https://www.ejp-eurad.eu/`).

### 4.1 Identification and assessment of significance for safety

Based on the expert group experience acquired in the national disposal programmes in France, Switzerland, Czech Republic and Romania as WMO, TSO or RE, on the IAEA guidance [8] and the review of other safety assessments reports publicly available [9–11] a comprehensive list of uncertainties associated to site and geosphere, potentially significant for safety, has been developed. Sixty four uncertainties associated with 15 thematic groups were structured in three broad uncertainty categories, as shown in Figures 6 and 7.

The significance for safety of each uncertainty has been assessed based on the evaluation provided by actors representing WMOs, TSOs and REs collected via the 2nd UMAN questionnaire addressed to all EURAD participants, thus covering the diversity of national disposal programmes in terms of repository types and implementation phase, as well as the diversity of actors.

The 22 answers (received from 7 WMOs, 4 TSOs and 11 REs) on the significance of safety as perceived by each actor *at the current phase* of his geological disposal programmes generally show comparable levels of the potential impacts of uncertainty on safety, for of each group of uncertainties (Fig. 7). In particular, there is a consensus among the three categories of actors on the low significance for the safety of the uncertainties associated with volcanism. The low number of answers from TSOs explains the large, dominated groups of uncertainties by *not known/ not considered yet* answers, *which* is the reason for large discrepancies in the level of significance for safety.

In justifying the impact on disposal safety and the level of impact (high, medium or low) the arguments provided by the actors complement each other, providing a more comprehensive picture.

The site and geosphere uncertainties of the greatest significance for the geological disposal safety, scored as medium or high *by all actors*, are those associated with:

– conditions and hydraulic properties of the host rock;
– geochemistry and transport properties, with particular emphasis on groundwater chemistry and host rock-specific sorption properties;
– thermal and mechanical properties of the host rock in its natural state.

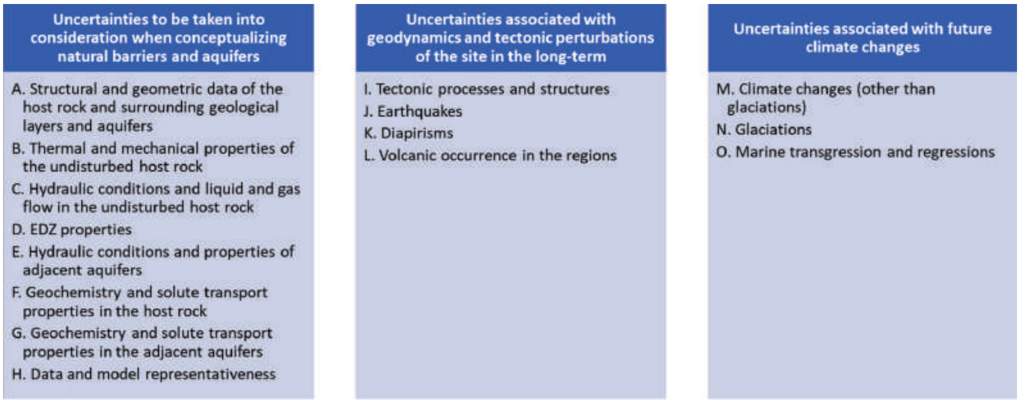


**Fig. 6.** The thematic groups of site and geosphere uncertainties addressed for safety relevance assessment.

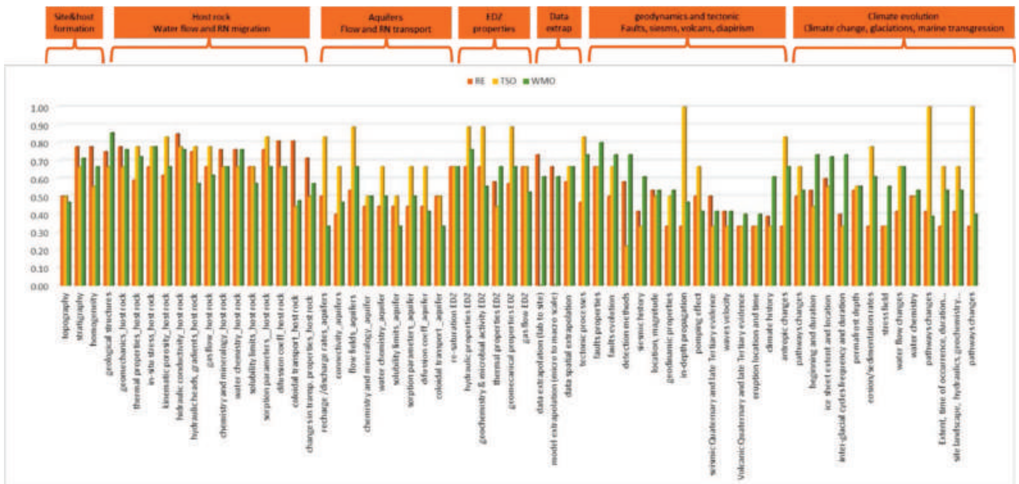

**Fig. 7.** Distribution of "significance for safety" level for geological disposal (low: <0.33; medium: 0.33-0.66; high: >0.66).

As illustrated in Figure 7, *REs* are mainly concerned with the uncertainties related to natural barriers characterisation (in particular host rock homogeneity, flow and transport parameters) and data extrapolation, while *TSOs and WMOs* tend to give a higher significance to uncertainties related to the long term evolution of the geosphere (future climate changes and glaciations effects, and geodynamics and tectonic perturbations of site).

### 4.2 Consolidation of available information on uncertainty management options

The different available approaches and options for uncertainty management were identified for a few uncertainties selected with respect to their relevance for the safety case. In order to cover as wide as possible range of uncertainty management options, these uncertainties were selected to cover all types of uncertainty in the uncertainty matrix, except for programme uncertainties, which address mainly human aspects.

These are (Fig. 8):

- *Hydraulic conductivity* of the host rock (and other geological units) – as an example of uncertainty related to the *initial state* of a disposal system. The uncertainty on hydraulic conductivity is primarily linked with the measurement errors on the very low permeable rocks and with the upscaling of permeability (or conductivity) value at the disposal site. Even more uncertain is the resaturation process of the host rock in the presence of the hydrogen build-up pressure generated in the repository. Over-pressure measured in the clay rocks adds new uncertainty related to its potential impact on the radionuclide transport in this host environment.
- *Sorption capacity* of the host rock (and other geological units) – as an example of uncertainty related to the *initial state* of a disposal system as well as to *conceptual models, data, tools and methods.* A particular concern is raised by the anionic species, which could have a large range of distribution coefficient values ($K_d$) depending on the chemical conditions in the host rock, the presence of organic matter, etc. Sorption reversibility introduces additional uncertainties on the migration kinetics with a direct impact on long-term safety.
- *Heterogeneities* of the host rock (and other geological units) – as an example of uncertainty related to the *initial state* of a disposal system as well as to *data, tools and methods.* This uncertainty is mainly linked to the degree of variability of site parameters up to which a geologic unit/layer can be considered homogenous.

| | | Known unknowns | Unknown/Ignored Knowns | Unknown Unknowns |
|---|---|---|---|---|
| 1. Programme uncertainties | | | | |
| 2. Uncertainties associated with initial characteristics | Hydraulic conductivity | Upscaling errors, saturation recovering | | |
| | Sorption | Speciation, anionic species, reversibility, Organic Matter | | Other processes speeding up migration |
| | Faults | Locations, detection Undetected faults | | |
| | Heterogeneities of host rock | Discontinuities; anisotropy, gradients | | |
| 3. Uncertainties in the evolution of the disposal system & its environment | Faults | Reactivation | new faults formation | |
| | Climatic evolution (glaciations) | Start &duration Isostatic adjustment Ice thickness Erosion Permafrost layer and temperatures | Depth and location of glacial erosion (mapping quaternary sediments) | Unexpected evolution of the next glaciations |
| 4. Uncertainties associated with data, tools & methods used in the safety case | Sorption | Kd - measurement and models accuracy | Changes in geochemistry | |
| | Heterogeneities of host rock | Transport properties | | |

**Fig. 8.** Uncertainty matrix filled in for safety-relevant site and geosphere uncertainties.

- *Fault location, detection and reactivation* – as an example that addresses the uncertainties related to the *initial state* and the *evolution* of a disposal system. Uncertainties on the tectonic and seismic activity of the site are in particular linked to the detection accuracy of active and passive faults location considered in the safety assessment. An additional concern is raised by the uncertainty on the reactivation of passive faults (which ones, when), or in the creation of new ones in the future (where, when, in what direction and what properties).
- *Climate evolution* with a focus on glaciations and *permafrost* – as an example of *evolution*-related uncertainty and allowing to address *completeness* (FEP's, scenarios) arguments. The high concern about the uncertainty of glaciations and permafrost is justified by the long-term period considered for safety assessment. This uncertainty sums up the uncertainties on a series of factors such as the beginning of the next glaciations, duration of intra- and inter-glacial cycles, ice sheet extent/thickness, erosion depth, and permafrost depth, all these parameters being important in defining changes in the radionuclide transport pathways and preservation of safety functions of the disposal system.

The identification of the different management options was done primarily through compilation, review and synthesis of existing documentation such as regulations, guidelines, handbooks, national reports, lists of options, cross-mappings and analysis of pitfalls.

Figure 9 synthesizes the options appropriate for the uncertainties considered, and applicable at different stages of the disposal programme implementation. In this paper, however, uncertainty management options are discussed only for an example of the climatic evolution with a focus on glaciations and permafrost.

The uncertainty related to climate evolution (specifically to glaciations and permafrost) includes further uncertainties such as (i) occurrence and duration of the next glaciations, (ii) magnitude of the isostatic adjustment associated with glaciation/de-glaciation, (iii) extent and thickness of the ice sheet, (iv) depth and location of glacial erosion, (v) depth of the permafrost layer or temperatures at repository depth, (vi) induced loading/unloading and related changes in hydraulic conductivity or seismicity, (vii) induced changes in groundwater flow regimes and chemistry, (viii) induced changes in the biosphere. Relevance of these uncertainties for safety is however dependent on several aspects such as assessment period, waste inventory, considered site, developed safety concept and repository system design.

The uncertainty associated with climate evolution can be identified through a FEPs list analysis, being part of an overall FEPs management process. The assessment period, within which the evolution of a disposal system shall be evaluated, may be defined by national guidelines (e.g. [12]), law and ordinances (e.g. [13–16]) or regulatory requirements (e.g. in [17]).

Framework for handling climate events in safety assessment is specified by safety-related principles with respect to siting and repository design (e.g. as defined by NAGRA [18]), requiring predictability, avoidance of and insensitivity to detrimental phenomena, as well as stability and longevity of a barrier system (e.g. as in [14–16]). Possible options to manage the uncertainties associated with climatic evolution can be identified in compliance with the abovementioned framework:

- Definition of specific site selection criteria and/or minimum requirements with respect to the depth of a repository (i.e. the depth of the repository ensures that all or a sufficient portion of the host rock is below the maximum anticipated erosion thickness or permafrost depth [13,19]). It is also possible to include safety margins in these criteria/requirements.
- Definition of specific design requirements or "design-basis glacier scenarios" [20] in order to account for those significant, glaciation-induced perturbations that cannot be excluded. The induced conditions and

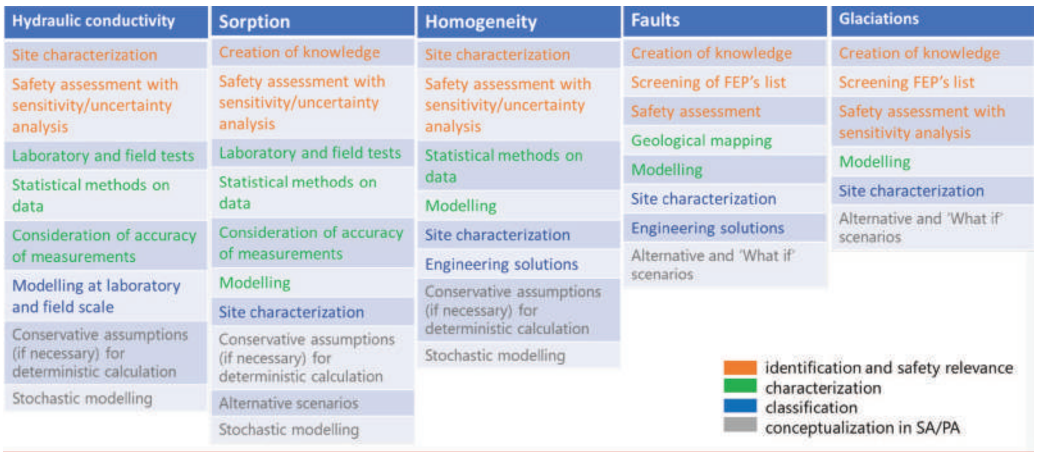


**Fig. 9.** Steps and options for uncertainties management at different stages of disposal programme implementation.

the corresponding uncertainties can be considered in numerical modelling by using conservative or bounding assumptions. Optionally, safety margins can be included in the repository design to address these uncertainties.

– Performing R&D to reduce the uncertainties related to climate evolution/climatic events (e.g. improving climate evolution models to predict future glaciations, dating of quaternary sediments, analysis of erodability of the overburden, investigation of the influence of decompaction on host rock properties (e.g. as in [21]).

## 4.3 Exchange in a workshop

Workshops organized in the framework of WP UMAN contribute to the development of a common understanding among "technical" actors representing WMOs, TSOs, and REs with a focus on (i) discussing views and preferences of these actors on different options for uncertainty management and (ii) identification and understanding the differences among these views/preferences (if any). Further, the workshops allow for the identification of remaining and emerging future R&D, Knowledge Management or strategic study activities in EURAD.

The exchange and discussion during the workshops dedicated to site and geosphere uncertainties indicated rather homogeneous views of the different actors in their management [7]. Generally, the uncertainty management strategy was perceived by all actors as an iterative approach, accompanied by a communication/regular dialogue with all involved actors, particularly with the public it was underlined that the preferred uncertainty management strategy might differ among EU member states, depending on the considered host rock and the associated safety concept. Some other minor discrepancies result from the different roles the actors play in the RWM programme. While WMOs and TSOs are sinterested in developing management strategies for safety-relevant uncertainties in compliance with current regulatory requirements/international guidelines, REs are interested in performing much broader investigations towards the provision of a sound scientific basis for assessing the significance for safety, including also processes that are not safety-relevant but contribute to a deeper and more confident understanding.

## 4.4 A seminar for a larger exchange

Several results emerged from the UMAN seminar dedicated to site and geosphere uncertainties, notably the fact that a stepwise, transparent and flexible decision-making "process" is important to manage the site and geosphere-related uncertainties. This process involves decisions regarding the selection and use of complementary measures at different programme phases to avoid/reduce safety-significant uncertainties and mitigate the impact of residual uncertainties and manage "surprises" that could occur, for instance, during construction and through monitoring (even if very unlikely). Civil Society should have the possibility and the means (i.e. access to independent expertise, legal provisions, etc.) to be involved early in this process and to monitor the situation now and in the future (several generations involved). In order to do so, could the concept of rolling stewardship be addressed?

As a typical example, regarding climate evolution, the exchanges underlined that the management of this type of uncertainty would strongly benefit from a very transparent process with a detailed protocol to make clear how the decisions were made, modified by new knowledge, and even changed. The citizens should be informed about the refinement of climate models and related uncertainties. The climate scenarios should be regularly and pluralistically assessed to ensure it remains in the safety envelope. Climate is evolving and deviation from the previous assumptions should be a trigger for a dialogue.

The governance to manage such uncertainties could be applied during different stages of the programme on two levels: the first level of discussion between technical experts exchanging scientific and technical knowledge in order to establish a rational programme and relevant roadmaps for the uncertainty management activities. This should also include non-institutional experts (coming from civil society). The second level of discussion should consist of interactions between technical and non-technical actors such as NGOs, representatives from society, mayors, local public, and should address the programme and the roadmaps, but also decisions. Discussion on climate models rises societal challenges and should stay open for dialogue between actors along the programme phases but should also foresee a longer-term interaction between government, experts, and society.

## 5 Outlook

The same methodology was applied for the uncertainties on human aspects. Preferred options applied in the management of waste inventory and spent nuclear fuel were investigated as well, while those related to the near-field uncertainties will follow in 2023. These exchanges allowed the identification of the needs for future activities to be addressed by EURAD partnership as R&D or strategic studies on site and geosphere topical area.

Therefore, there may be benefits from *theoretical studies* addressing the uncertainties associated with the long-term effects, in particular future climate changes and their effects on host rock and biosphere, as well as the structural geology in combination with geochemistry and geostatistics. *Experimental studies on hydraulic conductivity* are still found useful for the investigation of clay re-saturation kinetics taking into account diffusion/advection in host rock, plugs & seals, hydraulic conductivity of host rock and EDZ, hydrogen production and transport, and counter-pressure build-up. *Large-scale and laboratory experiments on sorption of anionic species*, targeting large-scale diffusion in clay for low but non-zero $K_d$, and identification of relevant sorption processes/ mechanisms for the development of mechanistic sorption models based on a bottom-up approach for improved sorption models. Upscaling from batch systems on pure phases to the real host rock in confined conditions could bring an in-depth understanding and supplementary knowledge of the radionuclide transport mechanisms.

Further work should be done to *develop geochemical codes* allowing to combine of uncertainty components in a non-additive model (additive ones leading to unrealistic results due to the propagation of uncertainty), *improve glaciations codes* coupling the climate evolution, permafrost and groundwater flow models, *validate* permafrost depth models and decompaction influence on host rock properties.

A *strategic study on climate change* could provide additional insight into how to deal with glacial periods in safety cases and safety assessment, while a *strategic study of on-site homogeneity* could clarify the conditions under which a host rock volume can be considered homogeneous.

## 6 Conclusions

The approaches to uncertainty management developed in WP UMAN capitalize on the experience of a wide variety of disposal programs, the results of past and ongoing research, as well as the exchanges of views both at the scientific-technical level and with Civil Society, that have allowed to develop a mutual understanding of uncertainty management issues.

The uncertainty management strategy, its classification scheme and the management options proposed by WP UMAN represent the result of the integration of the points of view of all the actors involved in unitary and comprehensive concepts, which can be used in the planning and implementation of uncertainty management in any geological disposal programme and at any stage of its realization.

Uncertainties associated with the site and the geosphere with a potentially significant impact on the safety of geological disposal for all categories of actors are related to hydraulic conductivity in low permeable rocks and resaturation process, sorption of anionic radionuclides, homogeneity of host geological units, and long-term climate evolution, with focus on glaciations and permafrost.

## Conflict of interests

The authors declare that they have no competing interests to report.

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## Data availability statement

This article has no associated data generated to be disclosed.

## Author contribution statement

All authors contributed equally to this publication. Daniela Diaconu prepared the introductory sections and the section on the uncertainty significance for disposal safety, Valéry Detilleux prepared the sections on mutual understanding of uncertainty management, Dirk-Alexander Becker prepared the section on identification and classification of uncertainty, Agnieszka Strusińska-Correia and Astrid Göbel prepared the sections about the options of the uncertainty management and actors' preferences, while Julien Dewoghelaere provided the aspects of civil society views on uncertainty management.

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# EURAD EC project – overview of the routes work package: identified key issues and open questions about waste management routes in Europe, from cradle to grave

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**Abstract.** The ROUTES Work Package (WP) is one of the two strategic studies being conducted as part of the European Joint Programme on Radioactive Waste Management (EURAD). ROUTES' objectives are (i) to provide a framework for European Union's member states (MS) to share methodologies, experiences, and knowledge in situations in which a waste management strategy is difficult to define as well as to (ii) to compare national approaches and strategies of waste management. The work considers national programmes at different stages of their development and deals with different amounts and types of radioactive waste. The expected output is identifying Research & Development (R&D) needs and opportunities for collaboration between MS, which need not be confined to ROUTES or EURAD frameworks. This work has enabled ROUTES partners to identify key issues such as retrieving poorly characterised legacy waste from a predisposal or disposal facility, implementing specific waste management solutions in the absence of well-defined WAC or developing innovative or shared solutions for MS that have only limited amounts of waste to manage. Discussion of these questions is illustrated through some of the case studies identified and analysed under the ROUTES WP.

## 1 Introduction

The ROUTES WP has been implemented in response to the Strategic Research Agenda (SRA) of the European Joint Programme on Radioactive Waste Management (EURAD), a five-year initiative which aims to coordinate activities on agreed priorities of common interest between European Waste Management Organisations (WMOs), Technical Support Organisations (TSOs) and Research Entities (REs), based on the conclusions of EC JOPRAD project [1].

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The ROUTES WP is a strategic study whose objectives are to:

- provide an opportunity to share experience and knowledge on waste management routes between interested organisations from different countries, with programmes at different stages of development and with different amounts and types of radioactive waste to manage.
- Identify safety-relevant issues, and their R&D needs associated with the waste management routes from the cradle to the grave, including the management routes for legacy waste, considering interdependencies between the routes.

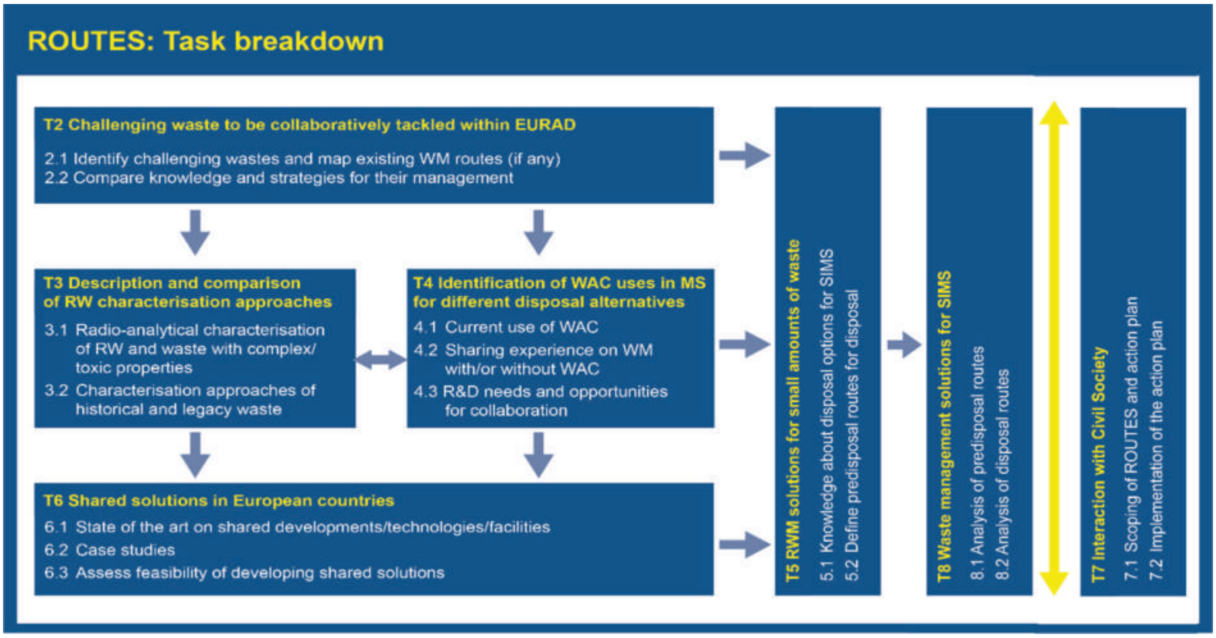


**Fig. 1.** ROUTES task breakdown.

- Describe and compare the different approaches to characterisation, treatment and conditioning, and long-term waste management routes, and identify opportunities for collaboration between European Union (EU) Member-States (MS).

The scope of the ROUTES WP is limited to so-called "challenging waste". This encompasses those waste streams considered challenging or problematic, for which MS are encountering difficulties in defining appropriate management routes due to intrinsic properties of the waste (e.g. specific hazard), an unknown or uncertain inventory (e.g. legacy waste) or uncertainties related to their behaviour in different waste management life-cycle steps (e.g. treatment and conditioning issues, long-term behaviour in disposal situations).

Activities within the ROUTES WP have been organised under seven tasks in order to explore the different challenges and potential solutions (Fig. 1):

- task 1: coordination, state-of-the-art and training materials.
- Task 2: identification of challenging wastes to be collaboratively tackled within EURAD.
- Task 3: description and comparison of radioactive waste characterisation approach.
- Task 4: identification of Waste Acceptance Criteria (WAC) used in EU Member-States for different disposal alternatives in order to inform the development of WAC in countries without WAC disposal facilities.
- Task 5: radioactive waste management solutions for small amounts of waste (focusing on disposal strategies for small-inventory Member-States).
- Task 6: description of the state-of-the-art shared solutions in European countries for characterisation, treatment, storage and disposal and planned sharing of facilities between Member-States, as well as identification of gaps and R&D requirements.
- Task 7: interactions with Civil Society.

In addition, an eighth task has been included in the ROUTES' work within EURAD second wave WPs selection process in Year 2 with the objective to strengthen collaboration between Small Inventory Member States (SIMS) and Large Inventory Member States (LIMS) and to ensure knowledge transfer with respect to the SIMS needs. The resulting Task 8 evaluates the possible waste management solutions for member states without WAC and with small inventories (SIMS).

The task breakdown covers the technical and non-technical key factors that must be considered when choosing a radioactive waste management route. Broad factors influencing technology selection notably include the availability of a final disposal site and well-established WAC, regulatory considerations and, finally, public involvement. Waste-related aspects mainly include the type of waste, volume, radioactivity level, intrinsic physicochemical properties, chemical and physical interaction between waste and the conditioning matrix and availability of suitable waste treatment technology.

Differences in the management route can also arise from the overall volume of radioactive waste a country has to manage. One of the major differences between SIMS and LIMS is that the latter may have access to existing facilities, infrastructures and knowledge and can also distribute fixed costs over a broader range of waste. For SIMS, moving forward with programmes for treatment and conditioning wastes in the absence of a disposal strategy and facilities is risky. The small volume to be managed makes the development of specific treatment capabilities disproportionately expensive. For this reason, specific attention is paid within ROUTES to knowledge transfer between SIMS and LIMS and to the conditions for developing shared solutions which could be a valuable alternative for SIMS to move forward.

## 2 Methodology

The ROUTES' work is primarily based on inputs from partners. The initial work (in year 1, i.e. 2019–2020) was devoted to gathering the data necessary for all tasks. A significant amount of data and information was gathered via a questionnaire disseminated to all ROUTES participants, covering all important aspects of managing challenging waste. One reply per country was requested to receive consistent information and strengthen the exchange between the main actors involved in the national RWM programme (WMO, TSO, RE).

The respondents to this questionnaire were asked about general information on the RWM programme in their country, such as national waste classification, waste inventory, disposal facilities and stakeholders' involvement. The questionnaire also addressed more specific issues concerning WAC, data relating to inventories of challenging waste and management routes, including uncertainties associated with the waste streams. With respect to this, the respondents also provided information concerning characterisation methods for each challenging waste they identified. To acquire knowledge about waste-related and broader issues for the management of challenging waste streams, the respondents were also asked whether a management strategy for each challenging waste stream had already been identified in their respective country and, if not, how the waste is managed safely in the meantime. Finally, to assess the feasibility of developing further shared solutions at a European level, respondents were asked to provide information on technologies, facilities and possible structures for such shared solutions and to present relevant case studies. Following the subsequent analyses of the answers, findings and results were published in already developed ROUTES deliverables.

Year 2 (2020–2021) activities focused on comparing approaches and strategies adopted by MS to cope with issues related to waste management. This was mainly achieved through analysis of case studies, including both successful and unsuccessful experiences. This methodology has been chosen based on the belief that lessons learnt by experience are often more relevant and representative than information gained by looking at collated inventories or a too high-level approach.

Based on the data acquired and the analysis resulting from case studies, upcoming work to be carried out for each task in years 3 to 5 (2021 to 2024) will be focused on the definition of R&D needs related to the management of challenging wastes. These needs will be identified and prioritised, and potential collaboration between the Member States and recommendations for future R&D projects will be proposed. Finally, the knowledge generated in ROUTES through knowledge/know-how sharing and discussions of common challenging issues will be consolidated and integrated as input to EURAD KM activities.

In addition to the work performed within the framework of the ROUTES WP, interactions are also organised with other EURAD work packages (e.g. joint session during the first EURAD Annual Meeting on "Influence of organics and other wastes on redox and RN transport processes in geological disposal facilities in different programmes" in cooperation with CORI, FUTURE and KM work packages, dissemination of outcomes related to organic waste to CORI WP) and with other EU-projects, such as PREDIS (organization of joint webinars, participation of PREDIS and SHARE representatives to ROUTES workshops and vice versa). These interactions will be reinforced in years 3 to 5 (Fig. 2).

## 3 Outcomes

This section presents the main outcomes of the ROUTES WP at this stage. In the following, the identified challenging waste is presented, and some overarching topics will be illustrated by means of case studies collected.

### 3.1 Challenging waste

In order to compare strategies and experiences in the management of challenging waste streams, preliminary work to compare the classification and categorisation schemes in each participating country was deemed necessary to constitute a baseline. Indeed, even if the IAEA approach to classification is applied in most participating countries, the terminology used does not always correspond strictly to the classes of "low-level waste" and "intermediate-level waste" as defined in the IAEA General Safety Guide for the Classification of Radioactive Waste (GSG-1) [2], that corresponds to waste suitable or not suitable for near-surface disposal respectively. Indeed, some countries (e.g. Bulgaria, Lithuania, Netherlands) combine low and intermediate-level waste into one class (LILW), which, in turn, can be subdivided into short-lived and long-lived RW. Generally, short-lived LILW could be associated with LLW within the meaning of GSG-1, whereas long-lived LILW could be associated with ILW within the meaning of GSG-1. This has proved crucial in analysing the inventory of challenging waste to compare the management route and strategy for waste streams of similar composition but different activities. A comprehensive description of this work, which also offered the opportunity to identify a preliminary list of challenging waste and the difficulties related to its management, has been published in [3].

Challenging wastes are defined as those for which no complete solution for their safe management is available, mainly because one of the predisposal steps (including characterisation, treatment and conditioning) is missing, or the disposal strategy is not yet defined. The reasons for this can be either technical or organisational. As a first analysis, the main difficulties faced by the member states that participated in the ROUTES questionnaire are the lack of disposal route (31%), characterisation (22%), and conditioning or treatment issues (20%). Regarding disposal route aspects, it turns out that the end state of

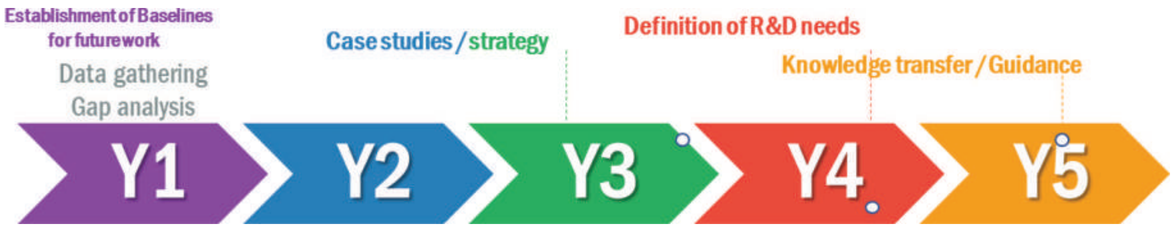


**Fig. 2.** ROUTES yearly priorities.

the waste management strategy is not clearly defined in many countries, which leads to difficulties in developing treatment and conditioning techniques, as the packages produced may not be suitable for the Waste Acceptance Criteria (WAC) of future facilities. For characterisation issues, a vicious circle has been pointed out, consisting of saying that not having a management route prevents prioritising the characterisation of waste, and the lack of characterisation prevents the identification of management routes.

Eleven types of challenging waste have been identified by the ROUTES' partners: sludges, spent ion exchange resins (SIER), organic waste, bituminised waste, graphite waste, decommissioning waste, disused sealed radioactive sources, Ra/Th/U bearing wastes, spent fuel, wastes containing reactive metals and wastes containing chemotoxic substances. Experiences and difficulties encountered by the member states to define management routes and strategies to manage these waste streams have been compared and analysed in the framework of task 2.

For some, precise technical or technological challenges related to the absence of or immature technical solutions have been identified. This is the case with, for example, the management of graphite waste, reactive metals (Be, Mg, Na etc.), liquid organic waste, and sludges for which dedicated conditioning matrices are not available yet, or specific characterisation issues are at stake (i.e. determination of 14C content in graphite waste). The challenges identified for each waste stream at the different steps of the waste management life-cycle and the preliminary R&D needs are summarised in [4]. Although some questions are still open, these challenges are usually quite well identified and efficiently addressed in the framework of national and international (EC-funded) R&D Projects [5–7]. For example, new matrices for the conditioning of some of the mentioned challenging waste are being studied and tested in the framework of the PREDIS Project (WP 4, 5, 6). Although extensive work is still needed in terms of R&D (durability, compatibility with the different waste streams), development work is also necessary to implement them at the industrial level and ensure that this innovation will finally be implemented.

### 3.2 Issues related to characterisation of legacy waste

Several member states are facing difficulties in managing legacy waste, including both unconditioned and conditioned wastes. Difficulties are mainly related to characterisation uncertainties, as most countries need to manage legacy radioactive waste without adequate information about their origin and radionuclide content, and in some cases, waste streams have been mixed.

Such uncertainties may be related to the quantification of some specific radionuclides estimated with indirect methods (i.e. 14C in graphite waste) or to techniques for detecting particular species such as activation products or complexing substances, but one of the major overarching topics concerns the strategy to put in place for the retrieval of unconditioned waste when their characterisation is uncertain. Two experiences managing legacy sludge in the UK and France highlighted difficulties that might be encountered due to characterisation uncertainties.

In the UK, storage of Magnox spent fuel in ponds for several decades has given rise to a large inventory of sludge streams (around 90 sludge waste streams). This case study notably highlights that implementation of sampling allowing a better knowledge of radiological and chemical inventories is very complicated, as sludge stored in tanks and ponds tends to settle. This results in different stratifications that make it challenging to obtain representative samples. Concerning sludge that has already been conditioned, some drums have corroded, which implies reconditioning and transfer to new containers may be required. Therefore, further sampling and establishing a new analysis regime would be possible at this stage of the waste life cycle.

In France, the same difficulties as those mentioned by the UK have been reported concerning 9000 $m^3$ of LL-ILW (according to French classification) sludges generated in La Hague by spent fuel reprocessing and liquid effluent treatment, placed into seven adjoining tanks and considered as legacy waste. This sludge presents high variability due notably to different production processes implemented over time. The lack of characterisation has led to the current difficulties in identifying a safe management route for this sludge. Extensive work was needed to determine their radiological and chemical composition (see Focus 1 on the French case study provided in [4]), which has been conducted on the basis of both historical records and 6 characterisation campaigns with sampling at different depths.

The UK and French experiences illustrate two "vicious circles" related to characterisation of legacy waste: (i) on the one hand, not having a management route prevents prioritising the characterisation of waste, and the lack of characterisation prevents the identification of management routes and, (ii) on the other hand, waste needs to be retrieved to be characterised, but in order to be retrieved, a detailed inventory is required that needs to be characterised first. To address this situation, France has chosen to conduct extensive characterisation campaigns based on samples in order to be able to retrieve and condition certain wastes. Examples of similar situations were also shared by SIMS, and this presents an opportunity to learn from LIMS's experience. This is the case for cemented sludge in Greece, which characterisation has been presented in the ROUTES workshop about Sharing Experience on Waste Management with or without WAC [8]. The Greek case notably highlighted that characterisation of cemented sludge was hindered because of a lack of financial resources. This lack of characterisation has led to current difficulties in identifying a safe management route for this sludge. This highlights a crucial point: sampling and characterisation require consequent means implying financial and human resources, which are not always available for SIMS. For this reason, an EC-wide approach and EC support in terms of technology and safety doctrine from LIMS to SIMS are highly beneficial.

More generally, future progress in terms of non-destructive characterisation may provide significant improvements to solve the challenge of characterising legacy waste. However, the implementation of any solution should be analysed regarding a strategic question: which level of uncertainty should be considered acceptable in order to implement operations on legacy waste? The Chance Project [9], specifically devoted to characterisation methods and approaches to conditioned waste, analysed the impact of these uncertainties and how to deal with them. While the importance of uncertainties was considered critical, suggestions for dealing with them are too general and not clear enough to be easily implemented (creation of new standards and regulations, need to upgrade the system of characterisation, need to improve skills and techniques applied in characterisation). In view of the elements presented above, an outcome of ROUTES WP is that a specific project dedicated to the characterisation issues and techniques related to legacy waste management might be considered a priority for future EC-funded projects.

### 3.3 Issues due to early or delayed conditioning

Several member states have had to deal with wastes conditioned decades ago which are since then undergoing a degradation process. Early conditioning offers the advantage of a final solution and encourages standardisation contributing to cost minimisation, but it requires a close dialogue between all the stakeholders, especially the waste producers, the waste management organisation and the regulatory body, as well as stability in waste acceptance criteria. In turn, delayed conditioning has the advantage of leaving options open and reducing the initial investments when no disposal solution is under development, but it inevitably requires future retrieval and re-packaging with potential degradation of the initial waste form and the potential risk of producing additional secondary waste. In the absence of an established disposal route, all member states face the dilemma of when to implement the final conditioning of radioactive waste while requirements for safe disposal and associated WAC are still being determined. This theme has been extensively analysed in the framework of the ROUTES workshop about Sharing Experience on Waste Management with or without WAC [8], notably through the Belgian, Dutch and UK cases cited thereafter.

Again, the lack of disposal WAC and/or available disposal routes prevents member states from developing or using the appropriate treatment and conditioning techniques since the packages produced may not be in line with future WAC. An obstacle to early conditioning is that conditioning waste into a matrix significantly reduces flexibility for further management (without reconditioning). It also strongly influences the behaviour and performance of the waste over the long term, potentially giving rise to properties that may be undesirable in a disposal facility if a matrix is selected without adequate knowledge of the disposal environment and properties of the wider multi-barrier system underlying safe disposal. Finally, early conditioning might reduce flexibility and then limit the implementation of innovative techniques. This observation is apparent from the Belgian case. In this case, a yellow gel-like material was found on drums conditioned in a cementitious matrix containing evaporator concentrates or ion exchange resins from waste packages produced by NPPs until 20 years before. A research programme found that the gel most likely results from alkali-silica reactions between the highly alkaline pore solution and the reactive siliceous aggregates of the matrix, which might have consequences in terms of the long-term safety of future near-surface disposal. This finding led to a suspension of the cementation processes of concentrates and ion exchange resins produced by the NPPs.

However, early conditioning might be seen as preferable in order to reduce early hazard and consolidate the safety of storage facilities, even if the uncertainties over the disposal route persists. This point is illustrated by the Dutch case study of waste processing and consolidated storage of LILW at COVRA's facilities for as long as 100 years. Indeed, geological disposal is planned for both LILW and HLW in the Netherlands, but the final decision for disposal is to be made around 2100. Currently, waste treatment and conditioning depend mostly on the safety of the storage facility in which the waste will be stored and the corresponding WAC. This strategy relies on the assumption that requirements for waste to be accepted for storage are similar or higher to those still to be defined for future geological disposal, as key considerations include degradation of the waste forms and packaged waste during these long timespans and the resulting impacts on the safety of the storage facility. This would enable the direct transfer of waste packages to the DGR, once available, without further processing (such that all stored waste is ready for final disposal). It is worth noting that some resin waste streams are stored for short periods ($\sim$5 years) in packages that do not meet the dose rate WAC for the storage facility. This allows time for COVRA to identify and deploy suitable conditioning solutions. In the meantime, "smart packaging and stacking" is employed to ensure safe storage, such as adding an extra concrete shielding package placed around some waste packages for a period of time, thereby enabling dose rate criteria to be met.

A "middle ground" approach has also been presented by the UK [4], consisting of packaging waste in new containers without matrix conditioning. This can provide a flexible and, crucially, reversible solution whereby a limited amount of waste processing facilitates the emptying and decommissioning of ageing facilities while retaining the waste in a form that can still be further treated or conditioned in many different ways before its eventual disposal. This point is particularly well illustrated by the case of non-reprocessed spent fuel currently stored in cooling ponds on the Sellafield site in the UK. This spent fuel will be transferred to a geological disposal facility in the future, but the process of identifying a suitable site is still at an early stage. During decades of storage, corrosion of the fuel and surrounding Magnox cladding has occurred. In the meantime, legacy storage facilities for non-reprocessed Magnox spent fuel are ageing, and there is a pressing need to empty them so that they can be decommissioned. With this in mind, work is underway to transfer Magnox spent fuel into high-integrity containers called Self-Shielded Boxes (SSBs). These thick-walled, vented, ductile cast-iron containers will be used for ongoing storage of the spent fuel at Sellafield in a new waste and spent fuel store so as to enable decommissioning of the ageing storage facilities to proceed. Work is currently being undertaken to assess whether the filled SSBs would be suitable for direct disposal to the geological disposal facility; if this is not feasible, then further conditioning or re-packaging would be required.

### 3.4 Conditions and main issues for development of shared solutions or facilities

Some programmes across Europe are considering or have considered the feasibility of shared solutions or facilities, including multinational repositories, which can provide infrastructure for all, or part, of the waste management route for a specific waste type.

Shared solutions have been researched over the last 20 years, and much of the knowledge base lies within the ERDO Association [10]. The founding feasibility studies for sharing disposal solutions in Europe were carried out by ERDO members in the European Commission SAPIERR projects [11,12]. This led to the establishment of the ERDO Working Group in 2009. Over the following decade, the fundamental concepts and practical aspects of multinational waste management solutions were researched and promoted by the IAEA, with the central involvement of ERDO members [13]. The ERDO Association (Association for Multinational Radioactive Waste Solutions) was founded in 2021 by some ERDO WG members, it is an association of national organisations with a mission to work together to address the common challenges of safely managing the long-lived radioactive wastes in their countries. A multinational disposal facility is of particular interest to countries with relatively small inventories of radioactive waste. The development of shared solutions for disposal is still in its feasibility phase, though, as only one agreement for the disposal of small amounts of institutional waste (from Luxemburg to Belgium) has been notified.

To our knowledge, no shared facilities have been implemented in Europe up to now. For this reason, the ROUTES WP enlarged the frame of situations considered as a shared solution in its work, including some hybrid situations which cannot be considered, strictly speaking, as shared solutions but which present some analogies or mechanisms of interest for their implementation. For these reasons, some commercial solutions treating or having treated foreign waste have been included in the analysis. This choice is driven by the observation that hundreds of transboundary shipments of spent fuel and nuclear waste are authorised each year in member states with available capacities for processing or reprocessing in Europe, notably in Sweden and Germany. The development of shared solutions or facilities, notably mobile treatment or conditioning facilities, would represent an alternative option for transboundary shipments.

The development of shared treatment and conditioning facilities could be of interest in at least two situations: for countries with small or medium-sized inventories or some categories of problematic radioactive waste of quite small amounts. In these two situations, most waste producers have a fairly small volume of waste to manage (e.g. batteries, solvents or pyrochemical waste), which would make the development of treatment capability at each site disproportionately expensive per volume unit. Individual member states may not be able to afford a solution, but an EC-wide approach could potentially be utilised to develop effective processes. This would avoid having to construct a treatment or conditioning facility for only a very small amount of radioactive waste. Shared solutions for RW management could provide the best-added value, especially for small inventory countries which do not have the infrastructure and know-how to deal with the waste, financial and other resources required for the exercise. This specific theme was identified as a high priority in the SRA.

Nevertheless, planning such facilities encompasses important and innovative developments (including the legal framework), which have been considered in work under the auspices of the EC or IAEA. The mechanisms to implement shared solutions depend both on the type of multilateral options and on the type of chosen technical solution, as a shared mobile facility jointly developed would probably be implemented more easily and raise fewer concerns about acceptability than a facility thermally treating nuclear waste. The establishment of the legal framework for shared solutions was broadly analysed under task 7 [14], which proposed the following definition of a shared solution behind the mere technical definition: "*Shared solutions encompass all the elements, be they tangible or intangible, that are developed and used in concert between entities in different countries, or between the countries themselves at various levels in any phase of the nuclear fuel cycle. In the frame of RWM, it includes the research carried out, the knowledge used, the technology developed, and transferred and the facilities constructed* *and operated through all the phases of the RWM, the legal and institutional arrangements established to run things smoothly and safely, and the process of interaction among the stakeholders, including safety culture and governance issues*". The work performed within ROUTES task 7 also identifies the public concerns related to shared solutions and notably stresses the necessity of a common safety culture and a level playing field as prerequisites to develop such solutions. In particular, if such a playing field is not in place, the development and localisation of shared facilities might gravitate towards countries with the lowest environmental and social standards, causing environmental and social dumping. Finally, three cases of different shared situations have been analysed with the contribution of the ICS larger group and some general findings derived:

- shared solutions for RW management would provide best-added value for small inventory countries that do not have the infrastructure, but their implementation raises critical issues.
- Good transparency (public access to information, evidence-based decision-making, effective public participation and access to justice) must be established.
- A specific deliberative process should be developed, with proper representation from local, national and multinational actors besides officials.

## 4 Conclusion

The initial work carried out in the framework of the ROUTES WP has been devoted to gathering data on radioactive waste management, especially related to waste identified as challenging, as well as to comparing approaches and strategies adopted by member states to cope with issues related to these challenging wastes through the comparison of case studies. This has enabled ROUTES partners to identify issues which will be further analysed, notably related to the retrieval of poorly characterised legacy waste from a predisposal or disposal facility, the implementation of specific waste management solutions in the absence of well-defined WAC or the development of innovative or shared solutions for member states that have only limited amounts of waste to manage. Future work will be focused on the identification and prioritisation of (i) common R&D needs related to the management of challenging wastes and (ii) opportunities for collaboration between member states. A particular focus will be made on the harmonisation of WAC or treatment and conditioning processes as potential precursors to more extensive shared waste management and disposal activities in future.

## Conflict of interests

The authors declare that they have no competing interests to report.

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This article has no associated data generated and/or analysed.

## Author contribution statement

Conceptualisation, E.L, F.M; methodology, all authors; validation, all authors; investigation, all authors; resources, all authors; writing – original draft preparation, E.L; writing – review and editing, F.M; visualization, all authors. All authors have read and agreed to the published version of the manuscript.

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# SESSION 3: KNOWLEDGE MANAGEMENT IN RADIOACTIVE WASTE MANAGEMENT

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# Session 3 summary

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## Scope

Research and development in radioactive waste management (RWM) and deep geological repositories (DGRs) has been progressing since 40 years now, leading up to the construction and operation licensing of the first deep repositories for spent nuclear fuel in countries like Finland and Sweden. An important lesson learned includes the statement that knowledge management (KM) is critical to ensure safe and efficient RWM over the entire life cycle, up until the final closure of deep geological repositories. According to IAEA, knowledge management is defined as "an integrated, systematic approach to identifying, acquiring, transforming, developing, disseminating, using, sharing and preserving knowledge, relevant to achieving specified objectives". Because of its importance, KM is encouraged by the European Commission, through the waste directive Euratom/2011/70, to improve the progress towards implementation of national radioactive waste disposal programmes. The presentations in this Session focused on how KM is being incorporated in current Euratom projects, and more specifically in the EURAD programme and PREDIS projects. Also outside perspectives from international organisations (IAEA and NEA/OECD) were presented.

## Knowledge management within EURAD and PREDIS

Knowledge management (KM) has been more central then ever within the recent EURAD programme and PREDIS projects. The start of EURAD marked an important step change as how "traditional" KM has been handled in past Euratom projects. Indeed, EURAD was faced with both opportunities (a more holistic view on KM, covering both general broad aspects as well as specific; possibility to access a wide pool of experts, …) and challenges (starting from zero with new vision that needed to developed; avoid duplication with other initiatives; making it sustainable for longer term, …).

Within EURAD and PREDIS, the knowledge gathered in 40 years of RD&D projects in RWM will be accessed through several initiatives. This will also help Member States oblige to requirements present in Euratom 2011/70 directive. The main KM objectives within EURAD/PREDIS are to enhance KM and transfer between organisations, member states and generations: 1) preservation/capitalization of generated knowledge; 2) transfer of knowledge between Programmes; 3) transfer of knowledge between generations; 4) dissemination of knowledge.

KM structures in EURAD and PREDIS are largely overlapping: they are using the same strategy and methodology, and are implementing the same type of activities. The common understanding also resulted in a joint statement on KM. This is thanks to the coordination of these activities in both projects through the Joint Research Center (JRC). KM activities include the development of the

Roadmap, State of Knowledge, Guidance, Training&Mobility, Networking and Tools. The Roadmap and GBS (goal breakdown structure) function as the central entry point to the KM system, and were produced within EURAD. The Roadmap provides a systemic view and common framework of RWM where all radioactive waste management domains are incorporated. The Roadmap is comprised of 7 Themes, of which PREDIS focusses on Theme 2 (Pre-disposal). Training and mobility activities have been centralized in the newly created School of Radioactive Waste Management, and is mainly dedicated to the student activities (~100 students present within EURAD and PREDIS).

Several issues still require additional efforts and attention to become fully effective: 1) how can KM exchange help to improve the cross-WP collaborations in EURAD to prove that EURAD is making a step-change; 2) how to integrate and contextualize critical information from knowledge providers on key issues; 3) how do we improve and speed-up transfer of knowledge between advanced programmes and early-stage programmes and between generations also considering knowledge generated in previous EC programmes?; 4) how can we ensure KM sustainability beyond EURAD and PREDIS: there is a need for a strong end-user engagement and for a long-term commitment. The initiation of Communities of Practices (CoP) in RWM KM is seen as a very important activity, which still needs some time to fully come into force.

**Concluding**, after a necessary start-up phase which was needed to align different actors on the goals, objectives, structures and tools that would be developed with respect to Knowledge Management within EURAD, the activities have now been ramped up in both the EURAD programme and the PREDIS projects. The structure that has been set up is judged to be suitable, appropriate and sufficiently robust to ensure the development of these important activities for years to come. The ambition set out in the programme is to create a lively KM culture within the community. There are, however, some issues which still need to be addressed: 1) within KM, information management is distinguished from know-how management. Know-how management is not only limited to researchers, but it is also vital for WMOs and regulators. There is a high likelihood that know-how management is more challenging for research when funding is declining. How can EURAD deal with this? 2) Integration of knowledge is very much done in safety assessment, but it has not really been handled within EURAD. It should be considered how it can be taken up also within the Programme, perhaps through the NEA IGSC. 3) EURAD should try also to fully exploit lessons learned from KM practices in other countries, to implement those which have proven the highest effectivity. 4) KM should also be more integrated into the other WPs (with perhaps additional budget assigned).

### Knowledge Management Work Packages in EURAD

Within EURAD, three different work packages are explicitly devoted to KM activities. These are 1) WP11 State of Knowledge (SoK), focused on the capturing of the state of knowledge, defined as the science and technology underpinning RWM in a given topic; 2) WP12 Guidance, on issuing Guidance documents targeting (specifically) starting and/or changing radioactive waste management Programmes; 3) WP13 Training&Mobility, supporting competence (skills and attitudes) building.

The main goal of the SoK WP is to preserve, capitalize and provide open-access to the available knowledge. The approach assumed is to collect experts' view on the most relevant knowledge and associated uncertainties in a specific domain associated to KM. The main challenges of this work are: 1) transfer from advanced to early-stage programmes; 2) assessment of work that has been performed within advanced programmes; 3) generational change; 4) transfer of knowledge to new entrants in the field; and 5) identify knowledge gaps for developing new RD&D or for initiating initiatives in Guidance or Training.

The SoK WP is centered around the Roadmap and GBS in which activities on radioactive waste management are expressed as a goal. The KM document structure is comprised of 4 tiers: theme overview documents at quite generic level (all documents almost available); 79 domain insights (user-friendly, context documents, entry points into the field); SoK reports (more in-depth documents including experts' view of most relevant knowledge and associated uncertainties); SOTA reports with very detailed knowledge. A learning-by-doing approach was adopted allowing to steer and adapt processes based on lessons learned.

Some of the key lessons learnt so far include: 1) a central, but challenging pillar to this WP concerns the identification and engagement of experts. These experts, which are typically integrators of knowledge, need to be timely identified and requires; 2) the EURAD community, although very broad, does not cover (necessarily) the required expertise in all Domains; 3) because authors come from different organisations and countries, this might end up in slightly different views on the scope and content of the documents..

In order to make knowledge available, a survey of KM systems (KMS) and tools was done in 11 organisations (6 of whom were waste management organisations). Existing tools appeared very diverse and tailored to the organisations' needs. A portal-KMS should allow storing different types of information and should allow commenting. Using a wiki-tool (easy-to-use, end-user friendly, simple and affordable IT) to make documents available is therefore a preferred option. It must be made clear that there is no competition or redundancy between the EURAD wiki and the KM systems of other international organisations like IAEA. The goal of EURAD is indeed not to bring all knowledge together, but to point to existing knowledge. Efforts were to collect information, not to create fancy tool.

Challenges of KM capturing include the useful structuring of knowledge into topics and providing knowledge on the needed level of detail. Also, some knowledge may be protected by Intellectual Property (IP) rights, making it difficult for commercial parties to cooperate since results should become public as public money is being spent. Similarly, for scientific results, several partners do not want to share data before they are published. It could be envisaged to install KM ambassadors in the more technical work packages to help streamline visions and processes.

Within the Guidance WP, topics were selected in close relation to the Strategic Research Agenda, using both top-down (combination of identification of gaps using the Roadmap and experts) and bottom-up (specific needs raised directly by wider community of potential end-users and stakeholders) approaches.

In parallel, an analysis of available guidance and guide-like technical documents was performed, by scouting several sources like ICRP, WENRA, IAEA and NEA. This resulted in an updated list of topics for guides. From the review it was found that a description how to manage requirements and implement them into the disposal programme has low coverage, while all the other topics were sufficiently covered already. By applying another selection filter, 5 topics were found to be potentially developed.

On this basis a topic was selected, which led to the development, review and publication of a pilot guide on "Cost assessment and financing schemes of radioactive waste management programmes".The lessons learned from this pilot provided input to adapt the production process in order to involve from the beginning much more the final end-user. This way, it is also avoided that guidance is being developed in an ivory tower, but instead thrives on maximum interaction with the intended users.

Within the Training&Mobility Work Package, the newly-established School of Radioactive Waste Management acts to coordinate all training activities, paying attention to the best-fitted training format, and guaranteeing scientific state-of-the-art by enlisting subject matter experts as lecturers and by following IAEA's Systematic Approach to Training quality criteria.. A varied portfolio of activities are undertaken linked to the EURAD roadmap, including  training courses, webinars, PhD community support, and a mobility programme. The identified end-users include professionals, students, and the "next generation of experts". There are no registration fees for training, making these very accessible for everyone.

In order to ensure that new training courses are needs-driven, a survey was conducted with end users from EURAD and PREDIS (80 and 33 respondents, respectively). In parallel, over 150 existing courses were identified. This resulted in a gap analysis in order to identify which trainings were missing, responding to urgent needs within end-user communities. Webinars, on the other hand, were organized on broad and specific topics by subject-matter experts (also from outside EURAD) with the aim to share knowledge with the entire RWM community and beyond. Webinars are recorded to preserve knowledge and facilitate dissemination afterwards.

The EURAD and PREDIS mobility programmes support internships and technical visits, or serve to attend training courses and conferences. In contrast to training courses, they are focussed mostly on implicit and tacit knowledge transfer, based on learner needs. An on-line application system has been set up for this objective. Learners may also find appropriate research infrastructures through the School's website. Alternatively, project partners can also offer internships. Specific dissemination is also targeting the PhD students within EURAD and PREDIS in order to foster a community between the students and professionals.

The following achievements have been recorded so far: 1) there were 4 training courses organized (low number due to covid) and 24 webinars. The latter attracted on average 115 persons who attended a webinar live. 2) Mobility programmes are also picking up after covid with30 applications approved. More than 120 students are involved in the PhD program (90 in EURAD, 34 in PREDIS). Six student events were organized and students could present themselves through project newsletters.

**Concluding**, the different work packages supporting KM within the respective EURAD programme and PREDIS project have now started to pick up speed, after a period of "trial-by-doing" and pilot projects which brought important lessons learned. EURAD and PREDIS are working towards completing the Roadmap GBS by actively developing Theme overviews and Domain insights, brought by recognized experts in the field. An important outreach has been reached using webinar formats (necessary in covid times). Also, an impressive body of PhD students is present within both programmes, which receive appropriate training and might constitute the next generation of experts. Attention points consist in being able to attract the right (or "top") experts, given that integrators of knowledge are relatively scarce and that, sometimes, knowledge is protected because of commercial reasons. For guidance, already a lot of documentation is out there, and the WP should focus on those topics where end-users have a real need. Also, it must be strived for that live training courses as well as the mobility programme picks up now that covid is hopefully behind us. Another attention point concerns the dissemination to the wider community (outside EURAD), and bringing to the attention that an impressive body of knowledge and know-how is already present in the field, and gathered through the EURAD and PREDIS projects.

### Outside perspectives from NEA and IAEA

The Nuclear Energy Agency (NEA) comprised of 34 countries and additional strategic partners seek to cooperate on different aspects of nuclear safety, technology and policy, through the establishment of 8 standing committees and 80 working parties. Two standing committees relate to radioactive waste management, namely the RWMD (Radioactive Waste Management Committee) and the CDLM (Committee on Decommissioning of Nuclear Installations and Legacy Management). Radioactive waste management is approached using a holistic view combining regulatory/legal, environmental&operational safety, societal and economic aspects. As one of the highlights in the functioning of the NEA in this field, the Integration Group for the Safety Case (IGSC) just celebrated its 20 year existence, and published a brochure containing the evolution of the safety case structure over the last 20 years.

On KM, a new Working Party on Information, Data and Knowledge Management (WP-IDKM) has been established. The reason for the interest in this is that 1) an increasing number, type and quality of data is produced as national programmes proceed through the successive stages of repository commissioning; 2) these data and the associated information need to be reliable, accessible and understandable for the long-term; 3) both implicit and explicit knowledge needs to be transmitted from generation to generation to reduce the risk of loss. Prior to WP-IDKM, 3 expert groups existed: RK&M (toolbox for preservation of records, knowledge and memory), RepMet (repository metadata management) and EGIRM (inventorying and reporting methodology), which have now been combined and centered on the implementation of the results obtained through the pre-existing expert groups by means of process of value realisation. The WP-IDKM will deal with issues both on the short (from decades to a few hundres of years) and long term (millennia scale). To this end, 4 new expert groups were created: EGSSC (digital safety case activities), EGKM (KM strategy, benchmark survey, general KM strategy guidelines), EGAP (long-term awareness preservation, capacity building for future literacy perspective), and EGAR (archiving – libraries, digital info, … how to access information).

The NEA also frequently holds workshops which might be of interest for the community, like the COMAREG workshop on competency management for regulators (taking place May 18-20, 2021). The NEA's NEST (Nuclear Education, Skills and Technology) initiative also supports knowledge management by providing a multinational framework to maintain and build skills and to nurture the next generation of nuclear subject matter experts through transfer of practical experience and knowledge through a long-term investment of associated countries, requiring strategic vision and involvement.

The International Atomic Energy Agency (IAEA), established in 1957 and comprising 174 Member States, has different tools to capture and transfer information and knowledge (publications, practitioner networks, peer review, training workshops and courses, E-tools, expert missions), promoting good practice. Publications remain central for capturing information and knowledge (in the form of Principles, Objective, Guides and Technical Reports). The IAEA clearly expressed the positive voluntarism regarding continuous engagement with EURAD and PREDIS, exhibited since their inception. This has led to mutual awareness & understanding, the development of similar structures for information & knowledge (broad themes, domains within the Roadmap), and on an alignment of scope and objectives.

Several topical examples were brought forward which identified opportunities for future cooperation, such as: 1) Technology optioneering during predisposal: developing a catalogue of tried &proven technologies; 2) developing a technical document on approaches for the management of bituminized radioactive waste; 3) Guidance on a Roadmap for implementing a Deep Geological Repository; 4) Managing site investigations; and 5) Current understanding of disposal options for graphite bearing waste.

However, cooperation could also include the tools that were already developed by IAEA and could be utilized by EURAD and PREDIS, including e-learning platforms, joint webinars, the nuclear wiki (easy to use, accessible platform allowing exchange, creation, and review of knowledge and technical/scientific information), the INIS database (on-line library containing the largest public record of nuclear information on the planet with over 7 million publications). Finally, the IAEA promoted their extensive Technical Cooperation Programme as a major pillar of capacity building supported by a suite of training courses, following systematic approach to training.

**Concluding**, now that the KM strategy and processes within the EURAD programme and PREDIS project have taken shape, we are at the right moment to think about concrete actions to move forward in the cooperation with IAEA and NEA, after several years of very constructive interaction. Several opportunities for synergies with EURAD and PREDIS can be identified, avoiding duplication of efforts.

**Roundtable discussion and conclusions**

The session on Knowledge Management proved to be very constructive, and raised a lot of interest from EURAD and PREDIS participants and external stakeholders. Everyone agreed that the structure of KM set up in EURAD and PREDIS is good and robust. The beacons for KM being set and aligned, all KM work packages are now progressing with the implementation. At the same time, given the richness of initiatives that are present and/or in development within EURAD, PREDIS, the IAEA and NEA, one cannot wander how to optimize this huge task of KM. It could be wise to adopt a step-by-step approach, with as a first step of optimizing, doing it together. Secondly, the strategic structuring of topics could be aligned even further, with the work done within EURAD providing already good start, going from bird's eye perspective to the very detailed level. At the same time, it will remain important to continuously capture (end-)user feedback. These end-users are the customers of the KM system, and may vary also dependent on the country's programme (e.g., large or small). The initiative already ongoing in PREDIS for PhD students is a good start. Similarly, it is important to learn and build from work that has been done previously, by different organisations.

One of the most difficult aspects in KM, and a major issue to be tackled, is how to capture and make accessible tacit knowledge. Here, it is very important to have the young generation part of the planning and to look at the tools they are using for accessing information in this day and age (e.g., simple videos will probably not work anymore). The overall feeling with the session participants is that actually going to organisations where the expertise is present, and getting hands-on experience, seeming somebody do the work, is a cornerstone for learning. The attraction of young researchers, on the other hand, comes from two aspects: 1) the research has to have meaning, and a feeling of responsibility; 2) the research has to be innovative and using attractive technologies (like artificial intelligence). Another aspect of keeping tacit knowledge accessible, is to keep communities of practice active, meaning to continue RD&D in these areas.

Knowledge Management is also broader than people, it also involves infrastructures and capabilities. Here, synergies with other platforms, such as the newly started OFFERR project, could help in creating a long-term perspective for supporting important (nuclear) infrastructures, to the benefit of the whole community. This long-term perspective presents also one of the key issues where more dialogue and involvement is needed, especially with waste management organisations (WMOs) that have such long time-scales in their planning. However, also important international organisations like the IAEA could provide the sustainability and stability needed to set up the necessary systems and tools.

A last reflection comes from the fact that managing information and knowledge is not only about data and tools, but it also depends on cultures, both within organisations and within countries. It should therefore be considered if the system that is set up is sufficiently flexible to allow optimal use by all considered end-users.

Finally, one aspect of KM that did not come to the foreground in this session, concerns the outreach to the wider community outside EURAD and PREDIS, both other scientific/technical communities (within nuclear, like FISA, but also outside nuclear), and the wider societal stakeholder groups. The wealth of information, know-how and expertise that is gathered through EURAD and PREDIS should be more widely known and more actively communicated in order to increase the impact of the joint programming initiative. It is encouraged that the community also reflects on how this can be achieved in the future.

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EPJ Nuclear Sciences & Technologies

**Euratom Research and Training in 2022: challenges, achievements and future perspectives, Roger Garbil, Seif Ben Hadj Hassine, Patrick Blaise and Cécile Ferry (Guest editors)**

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Review Article

Open Access

# Overview of knowledge management in EURAD

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**Abstract.** Knowledge management is a core activity for the European Member States (MSs) implementing the Council Directive EC 2011/70/EURATOM. Twenty-one MSs and two associated countries have mandated their respective radioactive waste management, safety and research organisations to contribute to the European Joint Programme on Radioactive Waste Management (EURAD). EURAD has established a Knowledge Management and Networking Programme which supports the capturing of knowledge and its transfer among organisations, Member States and generations. EURAD as a Joint Programming has an utmost advantage, compared to individual projects, as it provides:

- processes for knowledge sharing, for example interaction between the different radioactive waste management (RWM) actors to find out what is already known and what is most useful to investigate further.
- Resources and people to develop new knowledge and/or to support preservation of existing knowledge at risk, for example access to experts, networks and communities of practice.
- Tools and technology capable of handling different forms of knowledge, with a focus on socialising, signposting and aggregating existing knowledge sources.

This paper intends to describe the role of knowledge management and networking in EURAD, how knowledge generated by EURAD Workpackages and RWM organisations is captured and how we provide added value to MSs. Furthermore, it explains how we cooperate and work together towards common knowledge preservation goals with the EC PREDIS project, IAEA and OECD/NEA, to avoid duplication of work and maximise impact.

## 1 Introduction

Considerable scientific and technical knowledge has been acquired in Europe in the field of radioactive waste management (RWM) and deep geological disposal for over 40 years, fostering what is today a strong cooperation between implementers, laboratories and institutions. The first spent fuel and high-level waste disposal facilities are now close to realization in a number of European Member States (e.g., Finland [1], Sweden [2] and France [3]), while other disposal projects are at a rather early stage of implementation in a number of other EU countries [4].

In line with the European waste directive 2011/70/EURATOM [5], EURAD (the European Joint programme on radioactive waste management) launched in 2019, intends to make a step-change (from individual projects to an integrated programme) in European collaboration between advanced and early-stage programmes allowing for access to expertise, skills and technology on radioactive waste management and disposal

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[6]. Collectively EURAD pursues a more effective and efficient long-term-oriented use of public research and development (R&D) funding in Europe [7], building on the basis of activities and priorities of common interest of the three Colleges: European waste management organisations (WMO, represented by the Implementing Geological Disposal-Technology Platform (IGD-TP)), technical support organisations (TSO, represented by SITEX.Network), and research entities (RE, represented by EURADSCIENCE). EURAD aims to generate new and manage existing knowledge and to support Member States at various stages of disposal implementation. It is focussed on scientific and technological R&D, closely aligned to implementation needs, safety considerations and an ambitious knowledge management programme.

Working together, the EURAD Colleges have jointly developed a strategic research agenda [8] which in 2022–2023 will undergo a periodic update to take account of recent developments and integrate knowledge management (KM) issues identified by EURAD and the European project on Predisposal Management of Radioactive Waste (PREDIS) [9,10]. This foundational work in KM, completed in the first half of EURAD, has established a basis to understand what exists already, what complementary pipeline activities are planned by international radioactive waste management (RWM) organisations (IAEA, OECD/NEA and EURAD Colleges) and to gather the specific needs of the EURAD community. The Joint Programme has established the EURAD Roadmap [11,12] as a central tool for organising and coordinating its Knowledge Management and Networking Programme 2020–2024 [13]. Four dedicated KM Work Packages have been established to learn and test what works well, to hear feedback from contributors and users, to adapt approaches, and ensure that we maximise impact. The programme will remain reactive and responsive to the knowledge management and networking needs of the EURAD community, the pre-disposal community within the PREDIS project (associated to EURAD), and other interested organisations, including IAEA and OECD/NEA.

This paper focuses on how the EURAD KM is structured, operated and extended to PREDIS, on the goals, views and accomplishments (lessons learned) and provides an outlook on the perspectives beyond HORIZON 2020 (EU's research and innovation funding programme from 2014–2020).

## 2 Role of KM in EURAD

The European Joint Programming in Radioactive Waste Management is founded on the step-change as described in the EURAD vision [14], i.e., moving from individual projects to an integrated programme promoting collaboration and networking between different actors (WMO, TSO and RE). The Joint Programme provides an opportunity for national programmes to collect, share knowledge and experiences, organise (in a common way) a preservation and transfer knowledge between organisations/programmes and for future generations [15].

This requires acknowledgement of existing RWM knowledge structures and networks, developed over 30 years, and how this is codified and accessible in the various documents, procedures and processes, organisations, and people of the broad RWM community.

The role of KM in EURAD is therefore to better harvest this existing knowledge and integrate with it newly created knowledge, giving weight to:

- improved orientation of knowledge – how knowledge contributes to specific implementation goals and activities in radioactive waste management;
- improved definition of needed competences – what level of proficiency is needed and available to support programmes;
- improving accessibility to knowledge by signposting to people and documents – promote networking;
- use of a common structure, digitisation, or other codification activities – how knowledge is documented, stored and easily reused;
- improving socialisation, training, and networking – how knowledge is transferred and spread.

Where there are risks of knowledge loss or opportunities for improved knowledge preservation and transfer, the Joint Programme can support addressing such issues (partly using a small internal budget, or through future SRA, channelling information to EC or by other means) and by leveraging the access to the broad RWM network. It cannot be enough stressed that the Joint Programming for the first time collects a large part of European expertise, covering WMO, TSO and RE aspects, in one collective RD&D, Strategic Studies and KM and Networking programme, thus creating a platform for collaboration, networking and communication. Currently EURAD has four dedicated workpackages (WPs) to deliver the specific KM actions:

- WP1 EURAD Roadmap – activities to orientate people to existing knowledge via a generic roadmap for implementing radioactive waste management, leading to disposal. This provides an integrated and systemic framework for organising, structuring and sharing available RWM knowledge.
- WP11 State of Knowledge – documents with experts' view of the most relevant knowledge and associated uncertainties in a specific domain applied in the context of a radioactive waste management programme.
- WP12 Guidance – activities consisting of developing a comprehensive suite of instructional guidance documents that can be used by Member States with RWM programmes.
- WP13 Training and Mobility – activities consisting of developing a diverse portfolio of tailored basic and specialised training courses taking stock of and building upon already existing initiatives and creating new initiatives to bridge the identified gaps.

## 3 EURAD KM positioning in the European RWM landscape

Reformulating a definition given by IAEA [16] EURAD knowledge management is:

> *An integrated, systematic approach to identifying, managing and sharing an organisation's knowledge and enabling groups of people to create new knowledge collectively to help in achieving the objectives of radioactive waste management including geological disposal of radioactive waste.*

A survey [17] among European RWM organisations within EURAD (WMO, TSO, RE and Waste Generators) has shown that knowledge management is gaining a wider interest and support in view of the generation change and necessity to transfer tacit knowledge between generations. The survey reviewed existing and available knowledge management approaches and tools in use (or being developed) and has established a basis for what KM challenges exist. The survey is further complemented by ongoing exchange and cooperation activities with IAEA, OECD/NEA and PREDIS to identify those KM and networking activities that are of most value to conduct within the EURAD. A key output of this work has been the recognition that IAEA KM activities are positioned at a policy level, whereas EURAD is able to pursue KM activities hands on and at a more practical level.

The EURAD KM survey identified that most organisations in EURAD are in varying degrees of advancement towards the establishment of internal KM systems (i.e., a system is in place or planning has started to prepare for implementing a KM system). It can be remarked that only few large European organisation provide "pure" knowledge management on RWM; generally, KM is integrated in the knowledge production activities such as Research and Development (R&D), of which KM is a small part. Among "pure" KM activities supported by EC, one could mention the on-going ENS [18], ENEN [19] programmes and, from the past 10-year period, ENEN+ [20], ANNETTE [21], PETRUS III [22] and A-CINCH [23].

In addition to nuclear KM activities supported by the EC, there are a number of national initiatives and RWM schools [24–26]. These are complemented by the large cooperation efforts coordinated by international nuclear organisations, such as SNE-TP [27], the IAEA [28–33] and OECD/NEA [34–36]. Even though there are a large number of KM initiatives, few programmes, schools and training organisations provide the full "cradle to grave" and systematic, comprehensive and contextualised structure that covers all activities and needed competence for all phases of a radioactive waste management programme.

It is this KM niche that EURAD can support by aggregating the components that exist already, i.e., signposting to existing knowledge bases and available guidance, identify important lessons learned, connecting people and organisations to experts and communities of practice (CoP) and providing a platform to share knowledge and network across Europe.

To organise and structure this effort, the EURAD roadmap has been established [11,12], which is now being populated with latest state-of-knowledge documents written by experts in the area and complemented with latest references to needed capabilities (competences and infrastructures), training courses and guidance documents. Many of these components are provided individually by some of the knowledge providers; however, it is the completeness of the EURAD roadmap structure and hierarchy of information organised at different levels of detail, which provide an entry point for different actors (RWM managers, waste producers, regulators, scientists, students and public).

This allows all actors to access and contribute to the EURAD roadmap and find relevant information for them [37,38]. For the moment, EURAD uses a Wiki platform to structure the roadmap and its population with State-of-Knowledge documents making the content easily accessible to experts and students, and provides easy navigation across 80+ RWM domains. The roadmap currently involves signposting to relevant content (as rated by experts) so that we capture first the knowledge which has already been gained worldwide in RWM. Second, through assessment of the population of the roadmap, we can identify gaps and identify new needs. It is not only explicit knowledge that is provided on the Wiki platform and connected to the EURAD School of RWM, but also the possibility for all actors to interact via a chat function and form networks, including Communities of Practice, in many disciplines.

An important contribution to acquiring and making use of the knowledge is provided by the EURAD Guidance work package that feeds the State-of-Knowledge (SoK) documents with existing, but also newly produced guidance (on topics where guidance is missing and asked for by MSs). These guidance documents support the MSs with tacit knowledge on how to implement a RW disposal, also providing examples [37,39].

Complementing the explicit knowledge, the EURAD School of Radioactive Waste Management (School of RWM) is creating a hub where information on past and present training courses exists, latest information on RWM conferences and a chat function for students to meet senior researchers, thus supporting networking [40,41].

It is also worth to mention some limitation/opportunities/challenges of EURAD in comparison to KM performed in large non-nuclear companies, such as:

*Opportunities*

- As a Joint Programme, there is opportunity to change, adapt and re-shape tasks.
- Maximise the KM, R&D and strategy output while profiting from access to EU's expertise in RWM field.
- Covering general broad aspects (roadmap, strategy) as well as specific ones (R&D, guidance).
- Very diversified and specialised work groups (scientists, technologists, engineers, experimentalists, modellers, programmers, and many more), having different roles as implementers, technical support organisations (supporting regulators) and researchers.
- Access to a wide pool of external experts and mechanisms for technical governance and strategic oversight

(EURAD External Advisory Board and Chief Scientific Officer).
- Involving end-users, stakeholders and civil society to steer the programme and review our advancement.

*Challenges*

- As an organisation or entity, EURAD is newly created, and continuously evolving.
- Adaptation of resources and working parties, since the programme changes every 5 years.
- Requires a broad scope to support the advancement and implementation of national disposal programmes.
- A significant fraction of contributors consists of short-term participants (MSc, Ph.D., PostDoc and young scientists).
- EURAD knows what to develop, but needs to avoid competition and respect complementarity with national RWM companies and international organisations (e.g., IAEA, OECD/NEA).
- Establishment of a business case for a broad commitment to a joint activity on KM (SoK, guidance and training) based on and taking into account continuous end-user feedback.

## 4 KM in EURAD

EURAD KM activities are an integrated part of the EURAD vision [14], shared also by the PREDIS project:

> *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.*

To underline the importance of knowledge management in EURAD, this vision is complemented with a specific vision on knowledge management [14]:

> *It is essential to implement an efficient and integrated Knowledge Management programme at the EU level in order to establish, capitalize and transfer the state of scientific and technical knowledge in the field of RWM.*

EURAD's KM vision emphasises the principle that KM is part of every EURAD component: the Project Management Office (PMO, WP1), ten R&D WPs, two Strategic studies WPs and three KM WPs, Figure 1. Each work package contributes to knowledge production, knowledge management, networking or dissemination of results.

Within this overall structure, the three colleges (WMO, TSO and RE) contribute through position papers sharing their view on KM with the Bureau and PMO that are brought forward together with opinions of the External Advisory Board and Chief Scientific Officer to guide the update of the EURAD roadmap and connect knowledge production, management, networking and/or dissemination of results.

The EURAD roadmap gives a structure for all collected knowledge and functions as mainly explicit knowledge hub, incorporating knowledge from all EURADs WPs and by external experts. The ten R&D WPs and the two strategic studies WP support the knowledge management as knowledge providers. This is done through writing of State-of-the-Art (SotA) documents, which on a fine granular scale address end-user need-defined research topic. The ten R&D and the two strategic studies WPs are;

- WP2 – Assessment of Chemical Evolution of ILW and HLW Disposal Cells (ACED), involving a multiscale approach and process integration to improve long-term modelling and assessments;
- WP3 – Cement-Organic-Radionuclide interactions (CORI), oriented to improved understanding of the role off 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), focussed on improved understanding of the upscaling THMC modelling for coupled hydro-mechanical-chemical processes in time and space;
- WP5 – Fundamental understanding of radionuclide retention (FUTURE), addressing 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), concentrating on to increase understanding and predictability of gas migration in different host rocks;
- WP7 – Influence of temperature on clay-based material behaviour (HITEC), tackling improved THM description of clay based materials at elevated temperatures;
- WP8 – Spent Fuel characterisation and evolution until disposal (SFC) aiming at reduce uncertainties in spent fuel properties in predisposal phase;
- WP9 – Waste Management routes in Europe from cradle to grave (ROUTES) is dedicated to share experience and knowledge on RWM routes between WMOs, TSOs and REs from different countries, with programmes at different stages of development, with different amounts and types of radioactive waste to manage;
- WP10 – Understanding of uncertainty, risk and safety (UMAN), intends to further refine methods to make sensitivity and uncertainty analyses and the development of multi-actor network for uncertainty management;
- WP15 – Container corrosion under disposal conditions (CONCORD) addresses to optimise and evaluate the behaviour of materials for disposal containers in view of their long-term barrier performance;
- WP16 – Chemo-Mechanical aging of cementitious materials (MAGIC) focussed on increasing the confidence in Chemo-Mechanical simulations by reducing uncertainties in input data and understanding of key coupled processes, and

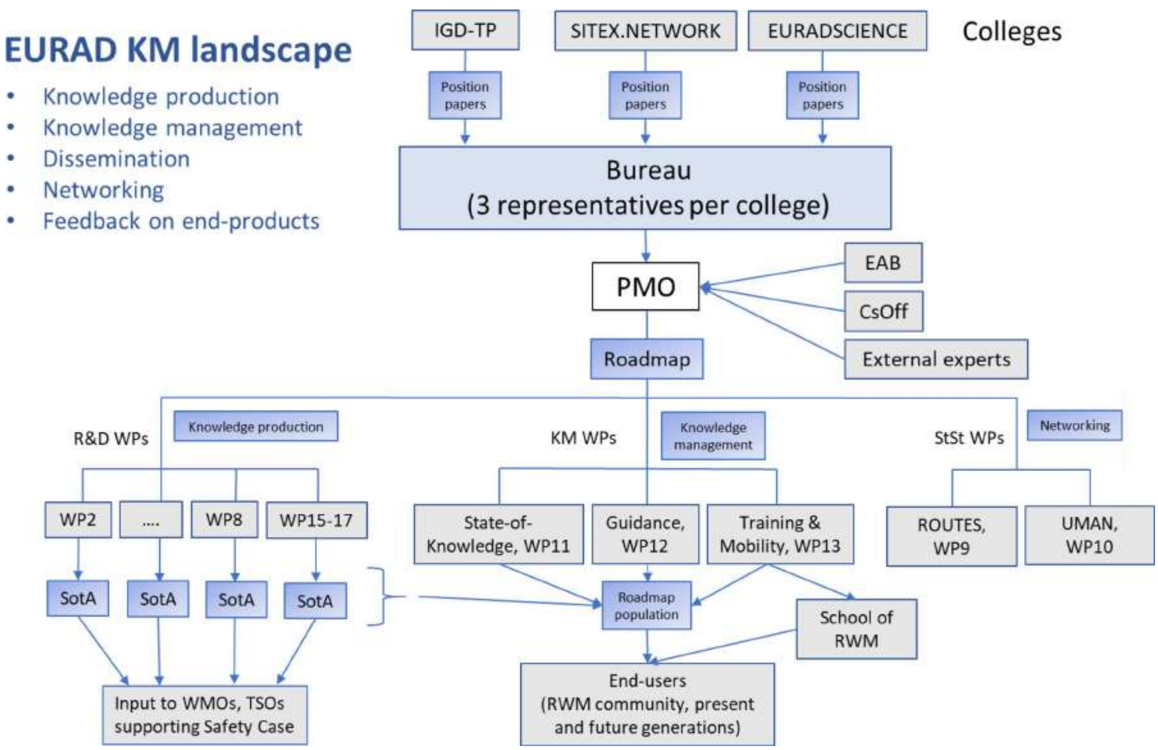


**Fig. 1.** EURAD knowledge management structure.

- WP17 – Monitoring equipment and data treatment for safe repository operation and staged closure (MODATS), aims to evaluate, develop and describe methods and technologies, and to provide the means to measure, treat, analyse and manage data in a consistent manner.

The R&D WPs are contributing also through creation of courses to disseminate their achievements. It needs to be pointed out that that the current R&D WPs and strategic studies WPs cover only a small part of the overall KM of relevance for implementing disposal solutions.

The three KM WPs (State-of-Knowledge, Guidance and Training & Mobility) manage the core of knowledge management in EURAD. Their tasks are all need-driven and the work prioritised by the three colleges (through General Assembly decisions). The State-of-Knowledge WP, with the help of external experts, is populating the roadmap with State-of-Knowledge documents in all relevant RWM thematic. The SoK documents are arranged in a hierarchical order with increased amount of details including (from the top-level) Theme Overview, Domain Insights, State-of-Knowledge and State-of-the-Art (SotA) documents [37]. The top-level documents are 10–15 pages long and sign-post to existing knowledge blocks. They are produced through engagement of external experts and include also input from the Guidance and Training & Mobility WPs.

The Guidance WP identifies "missing" guidance through a top-down (input from experts with overview of the disposal implementation process) and bottom-up (scanning the EC CORDIS, EU RWM organisations and international organisations) approach. The WP team writes the guidance document when competences exist within the WP or uses EURAD internal/external experts. The training and mobility WP is likewise focussed on identifying/defining previous, existing and planned, "missing" or requested courses by the EURAD partners or MS RWM organisations. The newly produced courses are mainly provided by organisations such as IGD-TP, the SITEX.Network and EURADSCIENCE, or by EURAD partners. A common EURAD School of Radioactive Waste Management [40] has been created by the Training & Mobility WP, gathering and collating all information relevant to young scientists and EURAD students (as of July 2022: >100 MSc, Ph.D. and Postdocs) as well as giving access to networking (within EURAD, but also with external RWM organisations). The School of RWM functions as a hub where students and partners can receive information on RWM issues through, for example, EURAD Lunch & Learn lectures, webinars, workshops, conferences, access large EU infra-structures (e.g., underground laboratories, hot-cells and large computer centres), learn about job-positions, and requests for EURAD mobility actions. The School of RWM performance is continuously improving its performance based on feedback from students and supervisors that participated in, for example, student meetings and trainings and performed mobility actions.

## 5 Interactions, integration and exchange

This section aims to describe the KM interactions in EURAD among partners and WPs, integration with other

EC-funded projects (e.g., PREDIS) and exchange with external organisations (IAEA, OECD/NEA).

### 5.1 Interactions within EURAD

The KM WPs jointly defined and wrote the EURAD Knowledge Management and Networking programme (KM+NW programme) [13] that was sent for consultation to PMO, the colleges (IGD- TP, SITEX.Network and EURADSCIENCE) as well as PREDIS coordinator. The programme was adopted at the EURAD General Assembly N° 4. The main attributes of the integrated KM and Networking programme are that:

- it is centred around the Roadmap with its individual cornerstones: contextual insight (theme descriptions, Domain insight, SoK), competences, guidance, training and access to infrastructures (mobility) oriented to the needs of future users;
- it describes the dependence and interactions between EURAD RD&D, Strategic Studies and KM WPs;
- it foresees more intensive interactions/feedback with RWM end-users to guide the knowledge production;
- it outlines the importance of EURAD collaboration and networking with national RWM communities, ongoing projects (in particular PREDIS) as well as with international organisations, such as IAEA and OECD/NEA;
- it addresses future challenges and risks, as well as defines the success criteria, and
- helps to structure the future KM work in terms of what can be realistically achieved by 2024.

The transfer of knowledge between generations is a central theme in EURAD and is carried out by supporting the different national organisations in this task. The School of RWM forms a hub around training and mobility. The activities are focused on cohesions between EURAD-PREDIS students (to promote networking), as well as interactions between students and experts in EURAD R&D WPs and with RWM end-users through the School of RWM chat function and a physical or virtual coffee corner at EURAD's annual events to promote students' future career. Furthermore, the School of RWM provides Lunch & Learn sessions that are 1 h lectures on actual and requested topics in the RWM field and are open to the public. The total number of students in EURAD and PREDIS is close to 140; this is a significant number of potential future RWM actors carrying forward EURAD's accomplishments.

### 5.2 Integration with other EC-projects

The strong link between EURAD and PREDIS is based on the joint interest of radioactive waste management from "cradle to grave". So far, after almost three years of EURAD and one and a half years of PREDIS, the two programmes are running largely integrated with each other, with a strong interaction in the KM area.

In order to further strengthen project interactions, a number of KM-related initiatives have been started, such as:

- publishing a joint PREDIS-EURAD statement on knowledge management, defining the complementarity and interactions between the programmes;
- common webinars (3–4 h workshops, with a mixture of oral presentations and break-out rooms discussion to reach consensus on specific questions or topics);
- exchange of student participation to student sessions in the two programmes;
- defining Theme 2 (Pre-disposal activities) in the EURAD roadmap and populating it with State-of-knowledge documents, such as the Theme Overviews and Domain Insight, which is part of PREDIS KM WP's responsibility;
- joint initiatives, such as common posters, scientific publications, papers and presentations.

Integration with presently running or recently ended EC-projects such as MICADO, SHARE, CHANCE and DISCO provides additional input through the corresponding projects' KM activities, such as R&D outcomes (input to SoK document) and trainings and mobility that are registered among the training offers and announced on the School of RWM website. These projects are integrated with the EURAD knowledge management work and used to identify shortcomings or knowledge gaps stemming from these projects that could lead to future post-EURAD activities.

### 5.3 Exchange with external organisations

EURAD strongly interacts with international knowledge providers such as IAEA and OECD/NEA, to avoid KM overlaps and duplication. A rough differentiation of the KM activities among the three organisations is that IAEA works more on the policy level, OECD/NEA is identifying and work on different KM aspects/methodologies (Information, Data and Knowledge Management, IDKM) related to RWM while EURAD is closer to the "hands-on" work, supporting integration of KM for the R&D disposal implementation.

EURAD, having reached its mid-term is now profiting from the vast and complementary KM activities ongoing at IAEA [42] and can benefit by signposting relevant IAEA documents; in other areas, EURAD KM can benefit from the large supply of KM trainings and RWM guidance documents.

A certain degree of interactions with OECD/NEA (IDKM) was there from the beginning of EURAD and EURAD's Chief Scientific Officer has a delegate mandate to join OECD/NEA regular bodies as an observer. Furthermore, there is an ongoing collaboration with OECD/NEA on safety case training, where OECD/NEA will provide training input.

Interactions with external organisations is intensive, especially between the R&D and Strategic studies WPs with their end-users giving input to both R&D, strategy and indirectly to KM. Furthermore, a large number of experts from external organisations and companies, such as roadmap advisory board, guidance WP editorial board, External Advisory Board and EURADs programme end-users, are engaged to give advice on EURAD's KM programme.

## 6 Lessons learned

It is time to appraise our KM efforts and draw conclusions on what we still can improve during the second half of EURAD, until 2024, and also give some hints on what could be proposed for a possible follow-up of EURAD. EURAD KM has so far progressed very well and is on a good way; a conclusion shared with the EC mid-term assessment committee. The collaboration among the three KM WPs is very well developed and looks promising for the future.

Five basic challenges defining EURAD's goals remain in focus for the future:

- how can KM help to improve the cross-WP collaborations in EURAD to prove that EURAD is making the step-change, from past individual projects to an integrated programme?
- How to integrate and contextualise critical information from knowledge providers on key issues?
- How do we improve and speed-up transfer of knowledge between advanced programmes and early-stage programmes, also considering knowledge generated in previous EC programmes?
- How do we promote transfer of knowledge between generations?
- On a long-term perspective, how do we keep alive EURAD building blocks, roadmap, Strategic Research Agenda, continuation of R&D initiatives and KM structures in near-future and for future generations?

In the following sections of this paper, we discuss the aspects outlined above on two time scales: until the end of EURAD (2024) and after the end of EURAD.

### 6.1 Until 2024 (end of EURAD)

The initial period of the EURAD programme was mainly focused on getting the programme to function and to fulfil the requirements from EC; from the governance point of view, this included the update of the EURAD roadmap, the production of initial SotA in the R&D WPs and the setup of procedures and methodologies in the KM WPs. The second year was concentrated on the selection of the second wave R&D WPs and the re-direction of the KM programme. Approaching the end of third year, we are reflecting on what we would like to accomplish until the end of EURAD.

*How can KM help to improve the cross-WP collaborations in EURAD?*

The KM WPs of EURAD have identified a lack of experts within their WPs to cover the themes of relevance for KM. This was also observed in the PREDIS project. The two programmes identified that the mobilisation of EURAD and PREDIS communities towards KM activities may not be sufficient and therefore involvement of external experts is needed. Thus, a significant effort is necessary before being able to fulfil end-user needs and expectations. Attempts are ongoing to improve the situation by involving external experts.

A deficit identified within the KM WPs, but that is valid for the whole consortium, is that, despite efforts for strong and lasting interaction, there is still a too weak inter-WP interactions. These interactions are the cornerstone of a joint programme, and the full potential of the programme is not utilised until all partners have knowledge of and insight into all WP activities and exercise cross-WP collaboration with mutual integration. This is a part of the step-change that EURAD is targeting.

In this process, the KM WPs can bridge the R&D WPs via their input to the roadmap structure and SoK production (e.g., identifying capabilities, guidance, teaching in training courses, offering mobility places, reviewing SoK documents, holding webinars, writing State-of-the-Art papers and giving Lunch & Learn sessions), to make more visible the inter-dependence between different R&D roadmap topics. Nevertheless, there are still missing competences within EURAD to cover all the RWM issues and external support is therefore a key issue.

To reinforce the interaction between the KM WPs and the other EURAD WPs, KM representatives are present at the meetings to bring the science into the KM and the KM activities into the R&D and Strategic studies WPs, so that KM becomes a natural part of these WPs. The benefit identified goes in both directions: all R&D WP members are aware of the possibilities for trainings and mobility and get support for their internal WP KM work, while the KM WPs can tap in on the huge expertise that exists within the R&D WPs for authoring State-of-Knowledge documents, reviews, producing training materials and giving trainings, as well as arranging for students' mobilities both inter- and intra-WPs and possibly to external RWM organisations.

*How do we improve and speed-up transfer of knowledge from advanced programmes to early-stage programmes?*

One of the central tasks within EURAD, involving KM, R&D and Strategic Studies (with inclusion of external experts), is to stimulate collaboration and networking between early-stage programmes and advanced programmes, to transfer knowledge to the early-stage programmes for their implementation of their radioactive waste management and disposal solutions. This is a challenge as the advanced programmes often have their associated business companies that are selling services related to their experience. Furthermore, there are less and less experts available with a broad overview "from cradle to grave", due to a generation change. EURAD needs to use these scarce expert resources where they are urgently needed. EURAD KM will therefore target crucial areas where only partial support from advanced programmes is needed. The support given is through identifying the needs and giving the main direction on how to proceed, while the early-stage programmes are "learning by doing". At the end of his process, the advanced programme will review the outcome. It is in this iterative process that tacit knowledge is transferred. The outcome of this process might take time and be noticeable in future EC national reports [43] on the implementation of the radioactive waste and spent fuel management directive and IAEA's ARTEMIS review programme [44] describing progress of MSs' RWM programmes.

Additionally, EURAD KM intends to stimulate the creation of Communities of Practice (CoP) where practitioners regularly meet over specific subjects and share their knowledge and advancements. A first step in this direction is that EURAD KM WP leaders will initiate a pilot KM CoP consisting of EURAD KM participants, but with the intention to extend it and invite experts that have been involved in EURAD KM activities and/or interested to use their knowledge management competences. The intention is not only to gather first insights into how CoP might work, but also to learn from existing CoP, such as the IAEA networks on International Network on Spent Fuel Management – SFM Net [30], Underground Research Facilities Network for Geological Disposal – URF Network [33], International Predisposal Network – IPN [29], where some EURAD partners are already participating.

*How do we promote transfer of knowledge between generations?*

With world's first deep underground repository for spent nuclear fuel being licenced for both construction and operation in Finland and Sweden (in January 2022) a milestone has been reached [1,2]. It marks a 40-year long era of not only research and development but also public involvement to support a safe disposal in Scandinavian granitic bedrock. The huge amount of knowledge, created and managed by a presently partly retiring workforce needs now to be transferred to the next generation of RW managers. While this is a principal mission of the national WMO and TSO, EURAD may help to support this knowledge transfer between generations. In that respect, it is important for the new managers to not only obtain new knowledge, but also acquire the "old" knowledge, such as why were things done as they were, what were the pitfalls that were never published, under which assumptions were decisions taken and many such historical questions will turn up in the future and need to have an answer for the upcoming regular licences. Even though EURAD will not be able to capture all this tacit knowledge, it needs to find methods and processes to capture tacit knowledge and turn it into explicit knowledge to be passed on to the RWM organisations. In this respect, also research entities (active in the RWM domains) play an important role as much of the research and development was performed in close cooperation between RE and WMO.

With that insight, one perceives that today's RWM students will play an important and difficult role in the future, needing to know about the past, present as well as the future of the waste management routes. In that respect, it is important to build networks, sharing all that knowledge and maintaining it active to consult an expert when needed. EURAD KM provides all types of networking opportunities. Networking requires visibility and contact surfaces, which EURAD KM is promoting through students' presentations at EURAD's scientific workshops and events.

Activities are undertaken (student days, student personal and scientific presentations) to create cohesion between students in the Ph.D. group and to get students to speak with one voice, so that the EURAD knowledge management activities can more effectively respond to students' needs.

*On a long-term perspective (15–20 years), how can we contribute to ensure that knowledge created in EURAD, PREDIS and other initiatives remains useful to future generations?*

We are convinced that the need-driven path via the structuring of the existing knowledge in the form of SoK, SotA and its links (signposts…) and contexts to other knowledge providers and communities of practice in the roadmap is a path that has the potential to survive generation changes. There is an increasing awareness to assure that the EC, REs, TSO and RWM organisations' investments in EURAD, PREDIS and other projects/programmes, in the form of manpower, knowledge accumulation (all reports and scientific publications), R&D output (SotA), knowledge structuring and contextualising (populated roadmap), will be used regularly, retained and conveyed into close future (15–20 years) and for future generations. The condition is that the KM platform of EURAD is regularly used by the national programmes and feedback is integrated. Links to other initiatives should be transparent, making clear that no duplication of work is foreseen, while maintaining the need of access to critical knowledge by the national waste management programmes of all Member States.

Before the end of EURAD, we need to have a solution for the hosting of the platform (possibly Wiki) containing the roadmap, theme descriptions, the Domain insights and the SoK documents. Furthermore, a solution needs to be found for hosting the School of RWM. These tasks need to be with an organisation that ensures the longevity of the system, making the platforms accessible to all Europeans (possibly to the world in a similar manner as IAEA), investing competent resources to keep the software programme up-to-date, maintaining the IT-hardware, control the content accessibility and working with future generations to update the content. However, only if the next generation uses the EURAD KM platform, it will survive.

### 6.2 A follow-up of KM beyond EURAD

In view of the long implementation times for RW disposals and considering that MSs are at different phases of their disposal programme, there is increasing awareness on the need for a long-term vision for knowledge management in Europe.

Based on the lessons learned, we can already identify some elements of what could be useful to consider while establishing a long-term KM programme. Building on the strong support of the EC to promote the KM in EURAD for a long-term vision, a strong support by the national programmes and the colleges is also essential. In that process, the national KM programmes (WMO, TSO and RE) need to be engaged in shaping and designing the future orientation of a long-term European KM programme driven by the largely varying and evolving national needs from programme initiation to implementation.

A future KM programme might become even more than today a central part in continued European Joint Programming, providing a visible platform for interaction to ensure active and effective knowledge transfer, including training and mobility, networking, and creating or contributing to Communities of Practice.

The School of RWM could function as a market place, or an active platform, where end-users with identified needs, using the EURAD roadmap, meet the knowledge providers/producers to optimise the European

R&D efforts and exchange knowledge between MS organisations and across generations.

## 7 Summary

EURAD has materialised from ideas to a real and functioning Joint Programme, through a step-wise integration of the three components; R&D, Strategic studies and Knowledge Management and the commitment of the three colleges.

The first half of the 5-year long joint programme has taught us how important it is to communicate and engage all actors: researchers, technical support organisations, disposal implementers, end-users, stakeholders (such as EC, external experts, waste generators, regulators and international bodies e.g., IAEA and OECD/NEA) and the civil society, to become a successful programme.

Throughout this time, the knowledge management activities have been focused on the design of the EURAD roadmap and to populate it with components, such as needed capabilities, state-of-knowledge documents, guidance and training. In this way, the EURAD roadmap has become the central structure in the programme that unites the partners in striving to complement and integrate understanding of the coupled processes that are necessary for implementation of a radioactive waste disposal. Entering the second half of the programme necessitates the reflections of what we have achieved so far, what remains to be done and how the "lessons learned" can be used to improve the present programme and possibly shape a follow-up programme beyond EURAD. One of the stronger recommendations is that KM should be an integral component in all R&D and strategic studies work packages. It is the actual usage of the EURAD KM platform, by the existing and coming generations, that decides if it will survive. With that statement comes a requirement on how to assess, in an objective and measurable way, the usefulness of the EURAD KM platform.

It cannot be stressed enough that a successful future programme and useful knowledge management for the coming generations depend on a strong end-user engagement and a long-term commitment.

## Conflict of interests

The authors declare that they have no competing interests to report.

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## Author contribution statement

All authors equally contributed to this work.

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REVIEW ARTICLE

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# Capturing the state-of-knowledge in EURAD knowledge management

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**Abstract.** Knowledge about a wide variety of aspects is fundamental for the safe management and disposal of radioactive waste. This importance of Knowledge Management (KM) is also recognised by EURAD, the European Joint Programme on Radioactive Waste Management (RWM), which brings together over 100 organisations from different countries and backgrounds (Waste Management Organisations, Technical Support Organisations, and Research Entities). This vast resource of expertise and experience feeds into several dedicated EURAD KM programme activities. One of these activities, led by Work Package 11 State-of-Knowledge (WP11 SoK), is capturing experts' views on the current State-of-Knowledge on topics relevant to RWM and making this knowledge accessible through dedicated documents. For this, EURAD has developed the "Goals Breakdown Structure" (GBS), which provides a framework in which topics are structured thematically, as well as a hierarchy of documents that allows accessing knowledge on different levels of detail (see `EURAD Roadmap`). To make this knowledge available, EURAD is currently developing a Wiki (i.e., a web-based resource that allows access to knowledge and collaborative interactions) and is drafting a sustainable Knowledge Management System and other supportive KM-IT tools while already feeding the tools with content. This article gives an insight into the general EURAD KM concept, the approaches used, and the results obtained until EURAD's mid-term, after 2.5 years.

## 1 Introduction

The safe management and disposal of radioactive waste are urgent issues many nations face worldwide. It has been a matter of concern for many decades and will remain one for many decades or centuries. In addition to its long runtime, the safe management and disposal of radioactive waste is also a complex task, meaning that various aspects from different fields need to be considered for its successful implementation. Hence, a thorough understanding, i.e., knowledge, of many different aspects is crucial. This need for knowledge has been addressed through decades of R&D and also benefits from decades of practical experience, which has led to a vast resource of generated knowledge. The necessity to manage the already existing knowledge so that availability and usefulness can be ensured becomes increasingly pressing. As mentioned, this is even more evident considering the long lifetime of radioactive waste management (RWM) programmes, where knowledge needs to be managed over many generations. All in all, Knowledge Management (KM) is crucial and will keep getting more important to achieve safe and feasible RWM.

The topic of knowledge management has been studied in various fields for more than 30 years, and its importance and acceptance are growing [1]. In nuclear sciences and specifically in the field of geological disposal of radioactive waste, KM is an extremely dynamic and fast-moving field that synthesises information from a wide range of disciplines. Several international organisations involved in the RWM are working to develop KM systems, e.g., the Japanese Atomic Energy Agency [2,3], the International Atomic Energy Agency [4,5], BGE [6], the EURAD programme (e.g., [7–9]), OECD-NEA [10], etc.

### 1.1 Knowledge Management in EURAD

The importance of KM is also recognised by EURAD, the "European Joint Programme on Radioactive Waste Management", which aims to support the Member States with implementing the Waste Directive (EC 2011/70/EURATOM) [11]. It brings together 116 organisations from different backgrounds and countries that

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work jointly to advance safe and feasible RWM and disposal through (i) dedicated Research and Development (R&D) projects; (ii) Strategic Studies (StS), and, importantly, (iii) Knowledge Management activities. To achieve this, the ministries of 23 European countries (20 member-states + 3 associated countries) mandated 51 organisations to act as beneficiaries in EURAD. Furthermore, 62 organisations are associated as Linked Third Parties of beneficiaries, and also, there are three non-european international partners. The involved organisations are not only from different countries, but they also belong to three different organisation types, meaning that they have different backgrounds in their intrinsic tasks and responsibilities in the field of RWM. These three different categories are called the three colleges and are: (i) Waste Management Organisations (WMOs) (e.g., ANDRA, BGE, NAGRA, SKB etc.), (ii) Technical Support Organisations (TSOs) (e.g., BelV, GRS, SSTC-NRS, etc.) and (iii) Research Entities (REs) (e.g., HZDR, PSI or universities). The diversity of the ideas generated by the different colleges and their interactions are indispensable for the successful implementation of RWM. Hence, a sound mutual understanding and collaboration are highly beneficial. Having so many organisations from different countries and categories brings an enormous wealth of expertise and experiences to EURAD, a unique resource and opportunity. This combination of forces is considered as:

> "*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.*" (Quote from EURAD Vision document [12])

The EURAD programme started in June 2019 with a runtime of 5 years (until May 2024) in its first funding period. It is a european joint co-funding programme, where a part of the funding is provided by the beneficiaries themselves, and the other part comes from the European Union's Horizon 2020 research and innovation programme 2014–2018 (grant agreement N$^o$ 847593). These resources are put to work in a number of dedicated R&D projects, Strategic Studies (StS), and with a high priority, Knowledge Management activities [13,14]. Activities regarding Knowledge Management are organised in three dedicated Work Packages (WP). These Work Packages are:

- WP11 State-of-Knowledge – the work in this WP focuses on capturing and making available the experts' views on the most relevant knowledge and associated uncertainties on topics that are important for safe RWM.
- WP12 Guidance – this WP works on developing guidance documents that are useful for national RWM programmes [15].
- WP13 Training & Mobility – WP13 deals with the development of a portfolio of training courses. For this, already available courses are taken into account and new courses initialised where gaps are identified. Another part of the work is the realisation of a mobility programme that fosters exchange between different organisations [16].

Importantly, all three KM WPs work closely together, profiting from each other's experiences, working in joint activities and benefiting from synergies where possible. Thereby, these KM WPs comprise the core of EURAD KM, which in turn is complemented by vital input and support by other WPs and actors, such as the Programme Management Office (PMO/WP1), the EURAD Bureau, the Chief Scientific Officer and the Civil Society Organisations in EURAD. Last but not least, the R&D and StS WPs provide an invaluable source of knowledge and experience, which is the crucial resource at the core of EURAD KM. Tapping into this resource and making it available in a useful and end-user-friendly way is the ultimate objective for EURAD KM and networking (and arguably for all KM activities). Should relevant knowledge on specific topics not be available within EURAD to a sufficient degree, this knowledge will be collected from other sources. For this, the EURAD community is again instrumental in identifying these gaps and signposting to the appropriate external sources.

The targeted end-users for EURAD KM are, in general, all persons that are involved in RWM, including generalists and non-specialists. This implies that the end-users will be from diverse backgrounds, which include, but are not limited to:

- people newly entering or transitioning to the field of RWM and/or a specific domain, such as employees of a Waste Management Organisation (WMO) or Technical Support Organisation (TSO). This can be from outside the RWM sector or moving within the RWM sector.
- The scientific community will be aided by EURAD KM in the identification of future research needs, as well as the training of new employees (see above).
- National programmes that are at an early stage and want to benefit from experiences made by advanced programmes.
- Advanced national programmes that face the challenges of generational change and need to capture the knowledge of the retiring experts.

First and foremost, EURAD KM shall serve the overarching goal of EURAD to support the safe and feasible implementation of RWM and disposal. If other end-users than the ones stated above are identified as relevant for this, they shall be considered in all EURAD KM activities. An overview of the knowledge management and networking in the EURAD programme is given in [13].

Importantly, KM in EURAD is not an isolated activity but accompanies and supports the rest of the programme. It is about creating a KM mindset within the whole EURAD community and beyond. Only by bringing in all EURAD members as contributors, not just as end-users, can the EURAD KM programme be successful. Then it has the potential to be a great success story for KM in RWM far beyond the runtime of EURAD-1 and, together with other KM initiatives, provide real tangible support for the national programmes and the implementation of safe management and disposal of radioactive

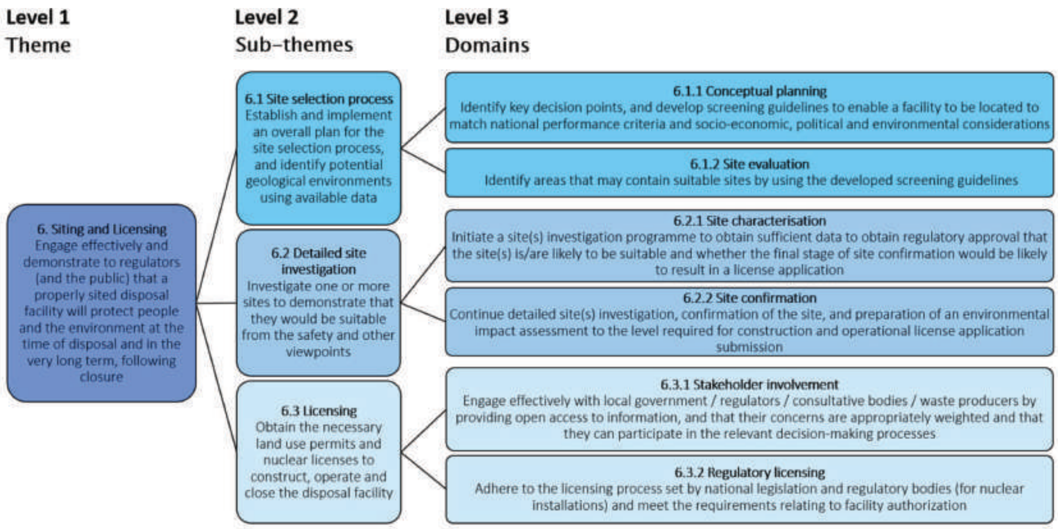


**Fig. 1.** Example for the breakdown of one theme (Theme 6 – Siting and Licensing) of the EURAD Goals Breakdown Structure (GBS) into the three levels (theme, sub-theme, domain) and the formulated "goals".

waste. The contribution of the EURAD community to the EURAD KM programme can happen in a number of different ways. One important way is by participating in the production of specific documents, which capture the relevant knowledge on a certain topic and make it accessible. Participation in the production of these documents can happen, for example, as authors, reviewers, or editors and is coordinated by EURAD Work Package 11 – State-of Knowledge (WP11 SoK). This article will give an insight into the work performed by WP11 SoK and describe the approaches, goals and first results after the half-time point of EURAD-1.

## 2 Capturing the State-of-Knowledge

As mentioned, many different topics need to be considered for safe RWM and disposal, such as geoscience, programme management, (radio-) chemistry, material science, civil engineering, and many more. For the work in EURAD WP11 SoK, documents for many different topics need to be produced. To do that, it is necessary to clearly define which topics need to be addressed. Furthermore, one needs to consider the scope of a topic because too broad topics cannot be handled appropriately in a single document while keeping the documents somewhat concise. This means that topics should also be broken down into suitable sub-topics. For this, EURAD has developed the so-called "Goals Breakdown Structure" (GBS). It serves as a thematic roadmap and fulfils the goal of organising and breaking down the topics relevant to safe RWM and disposal [17].

### 2.1 Structuring the Knowledge – the "Goals Breakdown Structure" (GBS)

The EURAD Goals Breakdown Structure is a valuable tool to structure and organise topics relevant to RWM and disposal. It is especially important in the context of KM and other activities, such as RD&D or Strategic Studies. The development of the GBS was done in the first two years of EURAD-1 under the auspices of the EURAD Programme Management Office (PMO/WP1), with the strong involvement of EURAD internal and external experts. Topics in the GBS are formulated as "goals" rather than simple "buzzwords", hence the name "Goals Breakdown Structure". For example, the goal formulation for a topic, e.g., Domain 6.1.2, would be "Identify areas that may contain suitable sites by using the developed screening guidelines" instead of just calling the topic "Site evaluation" (see Fig. 1).

It should be emphasised that by design, the EURAD GBS is generic, it does not claim to be complete, and it is understood that topics and knowledge can be organised differently. Hence, the numbering and order of the topics are not a representation of their importance or temporal order. There are also inter-dependencies between topics, which need to be considered. National Programmes and individual organisations might find other ways of organising better suited for them, depending on their specific situations. This does not contradict the idea of the EURAD GBS since it is intended to serve as a useful tool in EURAD and beyond the programme, which can be used to spark discussions and encourage thoughts about how to organise and structure topics and knowledge relevant to RWM and disposal.

To achieve the breakdown of broader topics into smaller, more manageable "packages", the GBS is hierarchically subdivided into three different levels. On the highest level, there are seven themes, namely: Theme 1 – National Programme Management; Theme 2 – Predisposal; Theme 3 – Engineered Barrier System; Theme 4 – Geoscience; Theme 5 – Design and Optimisation; Theme 6 – Siting and Licensing; Theme 7 – Safety Case.

On the next lower level, the 7 themes are subdivided into sub-themes, i.e., 27 sub-themes in total, and below

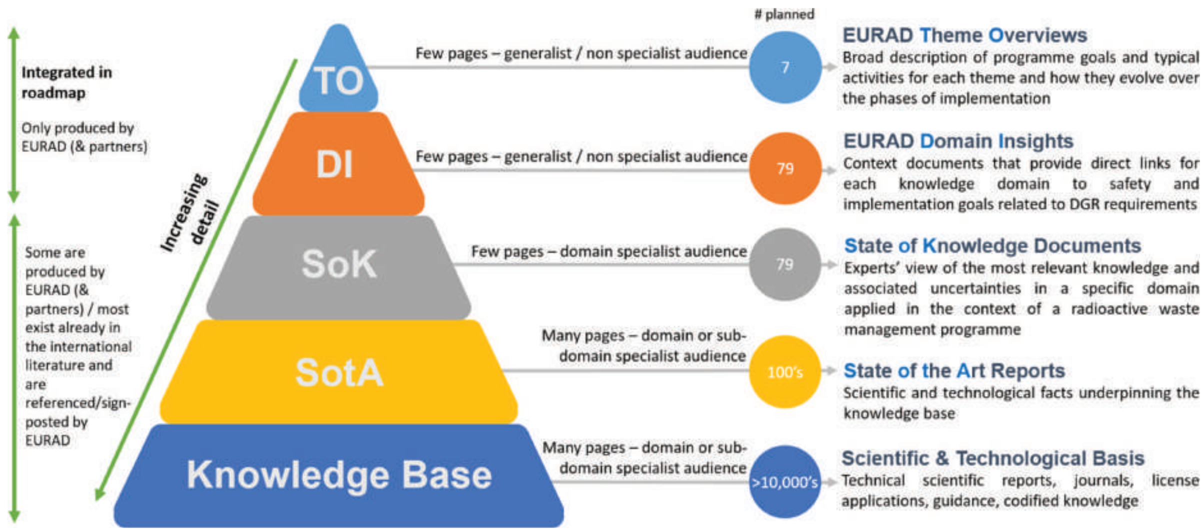


**Fig. 2.** Hierachy of documents that are relevant for the work of WP11 SoK in the EURAD KM programme.

that, there are 79 domains. Hence, the domains are at the lowest level of the GBS. Should the need arise in the future, the GBS has the flexibility to add more levels or add further elements to the different levels.

The complete overview of all themes, sub-themes and domains can be found in EURAD Deliverable "D1.7 – EURAD Roadmap extended with Competence Matrix" [17]. With this GBS at hand, EURAD has a valuable tool that provides a common language and useful framework for KM. This framework now waits to be filled with content, such as the KM documents of WP11 SoK.

## 2.2 The types of KM documents

The EURAD KM programme can only be considered a success if it has a high level of end-user friendliness and provides a tangible benefit to the end-users. Hence, this guiding principle of end-user friendliness and benefit also applies to the documents produced within WP11 SoK. To provide the level of detail needed by different end-users, and thereby the best possible benefit, different types of documents will be produced within EURAD KM. These documents cover various aspects of one topic on different levels of detail while keeping the respective document concise. Therefore, end-users can tap into a topic on the appropriate level of detail. Beginners can start on the lowest level of detail and read their way through increasing levels, while advanced readers can start with the higher level of detail. As described in Section 2.1, the scope of the documents (i.e., the topics) is defined by the GBS.

For WP11 SoK, three different types of documents are relevant. These three types of documents are called: (i) Theme Overview documents, (ii) Domain Insight documents, and (iii) State-of-Knowledge documents. Although the documents vary in detail (with the level of detail increasing from theme Overviews over Domain Insight to State-of-Knowledge documents), scope and style, all of them have in common signposting to other existing resources and literature is fundamental. It should be noted that other types of documents are produced in the framework of EURAD KM, such as Guidance documents, under the coordination of WP12 Guidance, Mobility Reports, under the coordination of WP13 Training & Mobility, and State-of-the-Art Reports by the R&D WPs, which all are an integral part of the EURAD KM programme.

The basic principle of the document hierarchy can be seen in Figure 2. The existing knowledge base (e.g., reports, scientific publications) is and remains crucial for thoroughly understanding RWM-relevant subjects. These EURAD KM documents can only aim at giving an overview, context and orientation to this knowledge base resulting from decades of hard work. The documents produced within WP11 SoK will also reference each other where useful, e.g., one Theme Overview will reference another Theme Overview or Domain Insight document to allow easier navigation and orientation for the end-user.

### 2.2.1 Theme Overview documents (TO)

The Theme Overview documents are located at the highest level of the GBS, the themes (level 1, see Fig. 1). They are designed to be concise documents (~20 pages) that give a very broad overview of the themes (see Sect. 2.1), focusing on typical programme goals and activities and their change over the different phases of a programme.

### 2.2.2 Domain Insight documents (DI)

The Domain Insight documents are located at the lowest level of the GBS, the domains (level 3, see Fig. 1). These short documents (10–20 pages) give information about the safety and implementation goals of the domain relevant to RWM and disposal. It further provides context and orientation to safety and implementation goals related to DGR requirements. This also includes providing links to other domains and knowledge documents. The main aim of the DI documents is to give a general overview of the domain.

#### 2.2.3 State-of-Knowledge documents (SoK)

The State-of-Knowledge documents are located at the lowest level of the GBS, the same as the DI documents, the domains (level 3, see Fig. 1). This means they cover the same topics as Domain Insight documents but with a different scope and level of detail. Compared to DI documents, the SoK documents go into more detail about the scientific and technical aspects. They reflect the most relevant knowledge as well as uncertainties about the domain at hand, according to the expert's judgement. It should be noted that SoK documents are different from SotA documents. SoK documents are much shorter (a few dozen pages) and typically cover a broader topic, whereas SotA documents are much longer (possibly hundreds of pages) and go into more detail. Usually, a SotA will also cover a narrower topic, i.e., a specific aspect of a domain. SotA documents are an important part of the further knowledge base and are therefore signposted in SoK or DI documents.

### 2.3 KM document implementation procedures

All the documents discussed here have in common that they are written by recognised experts, who are asked to share their expert views on the knowledge relevant to implementing RWM. This allows us to benefit from the expertise of those who have worked hands-on in their respective fields for a long time and to capture scientifically sound content. The experts are also best qualified to judge what is most relevant, what needs to be included in the documents and to which level of detail. Defining the scope and level of detail is challenging, even with the help of the GBS. This is even more true when considering that the documents should be end-user friendly, i.e., despite their scientific excellence, they should be easy to read and concise. Hence, the availability and involvement of experts are crucial for the success of the work. This is where EURAD represents a unique opportunity due to the vast number of involved organisations and, by extension, of involved experts associated with these organisations. Identifying, involving, and supporting the appropriate experts are some of the core tasks performed by WP11 SoK, with the support of the PMO, Bureau, and the whole EURAD community. The documents undergo review by experts and the WP11 SoK team to assure factual quality and that the right level of detail and scope was found to provide end-user benefits. Furthermore, the WP11 SoK team conducts editorial work to ensure consistency between documents and end-user friendliness. The review process, editorial work, and publication (for the time being via EURAD channels like the homepage) are coordinated by WP11 together with the EURAD coordinator. For all these steps and particularly the content scope of the documents, defined quality assurance procedures and requirements are applied (EURAD, in prep.). As knowledge evolves, it is crucial to keep the documents up to date. For this, monitoring the progress in the individual topics is essential. Due to the high number of different themes and domains, the involvement of the whole community is needed to identify outdated knowledge.

## 3 Status of KM document production

The production of the EURAD KM documents is set up as an agile learning-by-doing approach. This means creating useful content and developing the necessary procedures in parallel. This approach offers the advantage that the results of work can be disseminated quicker than with an approach where processes and procedures are developed first and only put to work after that. By doing this, end-users should benefit as quickly as possible from work performed, increasing positive reception and participation. Furthermore, the approaches developed are put to work immediately, and therefore, problems and weaknesses can be identified immediately and rectified. This agile approach, of course, also has some downsides. Estimating schedules and resources becomes more challenging when downstream processes are not or only partially worked out.

Work on the EURAD KM documents started with producing SoK documents during year 1 of EURAD. First, a "pilot case" was conducted, followed by two "demonstration cases" (see Sect. 3.3). During the first two years of EURAD, it was realised that additional types of documents with a different level of detail than the SoK documents would be beneficial for the end-users. Hence, the concept of the Theme Overview and Domain Insight documents was developed by the PMO/WP1, considering input from experts and the EURAD community (see Sects. 2.2.1 and 2.2.2). The production of the Theme Overview documents was coordinated by the EURAD PMO/WP1. As with the other types of documents, experts were identified and involved as authors and reviewers to provide a high level of quality and relevance. The production of the Domain Insight documents was handed over to WP11 SoK in mid-year 2 (early 2021). Subsequently, efforts in WP11 SoK were to prioritise DI production over SoK production.

### 3.1 Theme Overview documents status

As of August 2022, six of the seven planned Theme Overview documents (one for each theme of the Roadmap GBS) were finalised and published on the EURAD homepage (https://www.ejp-eurad.eu/roadmap). These documents are Theme 1 – National Programme Management; Theme 2 – Pre-disposal; Theme 4 – Geoscience; Theme 5 – Disposal Facility Design and Optimisation; Theme 6 – Siting and Licensing; Theme 7 – Safety Case. The remaining seventh Theme Overview document, Theme 3 – Engineered Barrier Systems (EBS), is currently in the final phases of production, and it is anticipated that it will be published in 2022.

### 3.2 Domain Insight documents status

The production of Domain Insight documents was the last of the KM document types to go into production. Similar to the other types of documents, these will be written by experts. Therefore, the identification and engagement of experts were and are at the core of the activities in the first steps. As of August 2022, experts for the production of 34 Domain Insight documents could be secured. For the domains in Theme 2 – Pre-disposal, a cooperation with the PREDIS (https://predis-h2020.eu) project was established, meaning that all DI documents in this theme will be authored by the PREDIS project and its associated experts. The first Domain Insight documents are planned to be available by mid-2022. However, five draft versions are already available in the EURAD internal Wiki, where they are open for comments and feedback from the EURAD community that will be invaluable input for their finalisation (see Sect. 4.2).

### 3.3 State-of-Knowledge documents status

For the State-of-Knowledge documents, it was decided at the start of EURAD to conduct a brief "pilot case" on Domain 3.1.1 – Spent Nuclear Fuel with EURAD internal experts available at the PMO. This pilot case was designed as a EURAD internal study and provided relevant insight into the concept and approaches to producing SoK documents. As the first fully-fledged documents, two so-called demonstration cases were planned to be conducted before the start of a broader implementation of SoK production. The two domains selected for the demonstration cases were: (1) Domain 3.1.1 – Spent Nuclear Fuel; and (2) Domain 3.2.1 – HLW and SF Containers. The rationale and the selection process of these domains were laid out in the EURAD Deliverable "D11.2 List of selected demonstration cases, criteria for final selection, proposal and estimation of effort and resources", published in March 2020 [18]. In short, although the demonstration cases produce high-quality and highly-relevant SoK documents, it was also important that the production of the documents was feasible and relatively uncomplicated. For example, domains were to be selected where a sound scientific base exists, where multiple experts were anticipated to be available, and which were expected to be of high interest to EURAD members. As of November 2021, the SoK document demonstration case on Domain 3.1.1 – Spent Nuclear Fuel was finalised and published on the EURAD homepage [19]. The second demonstration case on Domain 3.2.1 – HLW and SF Containers is currently under production and is planned to be published by mid-2022.

### 3.4 Lessons learnt from KM document production

In line with the concept of agile learning-by-doing applied for KM document production, a number of insights have been gained during the production of the document types described above. These insights are not necessarily unexpected but come as a confirmation of anticipated challenges. The key lessons learnt are summarised below and are later discussed in the text:

- identification and engagement of experts for specific RWM topics are challenging.
- Integration of critical information from knowledge providers on key issues needs to display different views.
- KM implementation using the agile learning-by-doing approach requires adaptation.

**Expert identification and engagement:** one central pillar on which the successful production of high-quality KM documents relies, and by extension, the success of the whole EURAD KM programme, is the participation of experts as knowledge contributors, for example, as authors and reviewers. Securing the involvement of experts has proven to be challenging. The first step of this process is the *identification of experts*, which has been done mainly in two different ways (i) utilisation of networks and expertise of the WP11 members and the broader EURAD community (PMO, Bureau) to identify suitable experts (inside and outside of EURAD), and (ii) dedicated activities, such as presentations at events and a "Call-to-action" within the EURAD community, to motivate EURAD internal experts to actively volunteer as contributors.

At this step, it was realised that neither the personal networks nor the EURAD community covers the totality of topics displayed in the EURAD GBS. To overcome this, collaboration and exchange with organisations outside of EURAD needs to be extended.

Writing the KM documents requires not only in-depth scientific expertise in a given topic but also a broader view of putting things into the perspective of implementing RWM. Therefore, some researchers may not feel comfortable enough to cover the whole topic of a KM document. For these cases, it can be helpful to create expert teams that can cover different aspects of the topic, such as the scientific basis as well as the implementation perspective.

After identifying experts, the *engagement of these experts* and securing their participation follows. This step has also proved challenging, one reason being that top experts are highly sought-after persons by nature. Therefore, experts are, on the one hand, very busy, which can make it difficult for them to allocate the needed resources for this kind of work, especially if other work is prioritised for one reason or another. On the other hand, experts might choose or at least have a say in which kind of work they want to conduct. If the importance and benefit of the EURAD KM documents cannot be conveyed, this work will not be prioritised and is, therefore, unlikely to happen at all due to the tight schedules and high demand for other activities. These issues show once again what an invaluable resource and opportunity the EURAD community and its experts are. It offers the much-needed framework in which these issues of available resources and prioritisation of work can be addressed. Furthermore, having several documents ready and published is expected to trigger participation. The efforts of the experts involved as authors or reviewers need to be recognised.

To address this challenge, it is helpful to allocate resources (time and money) within EURAD Work Packages for internal experts and a sufficient budget for contracting external experts for full reimbursement of their work for the KM programme. If experts need to be contracted, as is the case of EURAD external experts, contractual challenges are not to be underestimated. Setting up a contract that satisfies the requirements of all parties involved can require a significant amount of time that needs to be factored into the scheduling of activities. Furthermore, experts need to be provided with clear instructions on what is expected from them (e.g., what is the purpose, how does the structure of the Roadmap GBS look like, what is the benefit for RWM organisations and experts, and why should they contribute to the KM documents, what are the document contents, delivery dates and reimbursement rates, etc.) and be burdened with as few administrative tasks as possible to facilitate their willingness to contribute. The purpose of their work should be clear and well established. For this, active communication and promotion of the EURAD KM programme within the RWM community and beyond is necessary. It should also be realised that using personal networks can facilitate the involvement of experts and should be taken advantage of wherever possible. After all, it does make a difference if one is being approached by a familiar colleague or some completely unfamiliar person. Additionally, clear authorship and assignment of digital object identifiers (DOIs) would be beneficial, especially for experts from academia. If despite these efforts, an expert is not willing or able to contribute, it has proven to be a good secondary option to at least ask for suggestions for alternative experts. Usually, the experts will be able and willing to name other experts and maybe even act as the first contact to the other experts. Yet, overcoming all these issues still requires considerable effort and is not done easily. In this context, the enduring Covid-19 pandemic has not helped established networks and personal relationships across EURAD due to the cancellation of all physical meetings. Despite the size of the joint program, the EURAD community does not cover the required expertise in all domains. The domains in Theme 2 – pre-disposal are covered by experts from the PREDIS community. Further involvement of external experts is required in some other domains.

**Integration of critical information from knowledge providers on key issues:** other insights that were brought up during the KM document production are that there can and most likely will always be slightly different views on the scope and content of the documents. This is understandable and to be expected due to the vast number of different organisations and their different backgrounds. What might be relevant for one reader might be irrelevant to another. Consequently, it is important to collect broad feedback so all voices can be heard and a representative overview of opinions is formed when discussing specific issues and future work. At the same time, one should not assume that in all cases, a consensus can be found that satisfies everyone to a hundred per cent. Diverging or contradicting opinions are a reality in all big organisations and collaborations, which is also the case in EURAD. To mitigate this situation, it is essential to moderate the discussions and to remember to keep content on a somewhat generic level and/or cover all points of view. In this context, diverging and contradicting views should also be actively acknowledged. In fact, they can become a valuable resource of information since they might indicate a matter that needs to be addressed through R & D activities or an improved understanding of the diverging positions. Furthermore, the produced documents can be followed by lectures from the same experts who wrote them. This would offer a discussion platform between the knowledge providers and end-users and enhance the quality of the feedback.

**Agile learning-by-doing approach:** it was also realised that the implemented agile learning-by-doing approach leads to its own challenges. This realisation is neither specific to EURAD KM nor surprising but should be considered for future work. Agility implies frequent and extensive exchange of concepts and progress and can make scheduling and planning of resources challenging due to the less defined nature of future activities and the higher degree of uncertainty. Undoubtedly, an agile approach brings many benefits with regard to flexibility and the time needed for first results. However, it also requires the appropriate mindset and tools, such as frequent exchange and flexibility in scheduling and budgetary questions.

Further lessons learnt will be assessed continuously, and the approach improved accordingly during the second half of EURAD until 2024. A more detailed analysis of findings will be reported in upcoming dedicated EURAD deliverables produced by WP11-SoK.

## 4 Making the State-of-Knowledge available

In addition to capturing knowledge through dedicated documents (see Sect. 2), these documents, i.e., knowledge, also need to be made available to the end-user easily and efficiently. To this end, one important, novel, and ambitious goal of WP11 SoK is the development of a Knowledge Management System (KMS), i.e., a systematic approach to transfer the captured knowledge to the end-users in the field of RWM. The aim of the envisaged KM system is to be not only a digital tool but also a lively instrument with which the participating actors can actively share and exchange their knowledge. To reach this target, a survey was carried out in which different organisations, all active in the field of RWM, participated and were asked about their current situation regarding knowledge management in their organisation [20]. The following 11 organisations participated in the survey: ANDRA (Agence nationale pour la gestion des déchets radioactifs, WMO, France); BelV (Belgian Agency for Radioactive Waste and Enriched Fissile materials, TSO, Belgium); CIEMAT (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, TSO, Spain); GRS (Gesellschaft für Anlagen- und Reaktorsicherheit gGmbH, TSO, Germany); JRC (EC Joint Research Centre, RE, EU); Nagra (Nationale Genossenschaft für die Lagerung radioaktiver Abfälle, WMO, Switzerland); PURAM (Public Limited Company for Radioactive Waste Management, WMO, Hungary); RWM (Radioactive Waste Management, WMO, Great Britain); SKB (Svensk Kärnbränslehantering AB, WMO, Sweden); SSTC-NRS (State Scientific and Technical Center for Nuclear and Radiation Safety, TSO, Ukraine); SÚRAO (Správa úložišť radioaktivních odpadů, WMO, Czech Republic).

### 4.1 Review of existing Knowledge Management Systems and tools

The above-mentioned survey [20] showed that many organisations already have a KMS in use. Based on already existing tools and available basic experience, these organisations are now in the process of combining these tools with new ideas to set up a suitable KMS. In this process, KMSs are based on a systemic approach involving interactions between people, processes, and technologies. However, there is a need to design such KMSs together with the respective target users and integrate them into existing systems of organisations. The KMS aim to provide assistance on how to manage distinct knowledge and information types for implementation and to ensure the sustenance and preservation of critical nuclear knowledge for safe and efficient management of radioactive waste.

All screened systems utilise methods to identify the holders of critical knowledge. Among the techniques enumerated for capturing critical knowledge can be found (D11.1 [20] Q14): On job training dialogue, Elicitation interviews, Mentoring/Coaching, Communities of Practice, Explicit capture (narrative documentation), Experience feedback, Decision tracking, Audio or video recording of "storytelling", Annotation of existing documents, calculations, procedures, database capture, (see IAEA NG-T-6.10 [21] and references therein for a more detailed description of the methods). The document management system of those organisations contains relevant documentation (guidelines, standards, regulatory documents, project reports, publications etc.). Besides the documents, end-users try to get tacit and implicit knowledge from case studies, feedback, and other formats from internal and external sources. For this, organisations regularly implement pre-input screening and review processes, issues of updating the content, a quality check of content relevance and actuality, lessons learnt and surveys.

There is no clear tendency of how the surveyed organisations set up their KMS. Some are organised in a centralised way, others in a decentralised way, and some even describe it as a hybrid one. The contacts from outside are controlled by user access systems, and security here plays an important role. Already available modules of other organisations will be checked for suitability to become a useful component of such a EURAD KMS. In such a way, it is possible to act cost-efficient and rapidly adopt or adjust finished solutions into the prototype development. All interviewed organisations considered a written policy essential for implementing the KM strategy in their organisation. A clear policy and strategy in KMS development and implementation will avoid many traps and pitfalls and thus will increase the chances for high usage and sustainability.

The existing KM tools are diverse and adjusted to the respective organisational needs. The same has to be done within the EURAD programme. However, existing modules of KM tools could turn out to be useful. They could be adjusted to the EURAD needs and implemented into the EURAD KM programme. Since the EURAD KMS is planned to be generalised and web-based, the selected KM tools – which will support knowledge capture, storage, sharing and transferring – are portal-KMS, Community of Practices (CoP) and Trainings (Lunch and Learn sessions series). Some further important findings of our surveyare also in good agreement with the results of the anonymous benchmarking exercise conducted by the National Nuclear Laboratory (NNL) [22] to explore the KM activities and approaches of organisations from across the UK and internationally, are summarised below:

- the importance of KM is proven and shown by the continued interest and investment of organisations in KM.
- Knowledge management is implemented more effectively when it follows a top-down approach.
- The organisational culture is important to facilitate the knowledge exchange between people. KM is not only about transferring knowledge through documents (explicit knowledge) but through direct interaction between people, asking questions, and carrying out dialogues (tacit and explicit knowledge).
- Identifying critical knowledge and measures to preserve this knowledge is extremely important for organisations.

Key knowledge holders should be visible and active parts of the KM programme (e.g., debriefing, mentoring, coaching), and their efforts should be acknowledged.

In conclusion, organisational culture is extremely important for KM implementation. This addresses not only the access modalities but also the potential of interactive usage. The essential part of a successful KMS is knowledge sharing. The stronger the trust factor in an organisation, the more easily knowledge will be shared. Eventually, this strongly promotes the active usage of the KMS and, therefore, leads to the creation of a sustainable KMS.

### 4.2 The EURAD Wiki

One commonly used and, therefore, rather a familiar way for most people to retrieve knowledge is via a so-called Wiki, with Wikipedia undoubtedly the best-known example. In the field of RWM, the IAEA Nuclear Wiki is a good example of the usefulness of Wikis. The popularity of Wikis can be attributed to many attractive features, which have also led to the decision to set up a EURAD Wiki under the auspices of WP11 SoK. This Wiki is used to make the KM documents accessible to the EURAD community and provides some functionalities that are essential for successfully implementing the KM documents and the EURAD KM programme as a whole. Among these positive features is the relative ease with which a Wiki can be set up based on free software solutions. This allowed to quickly implement a useable EURAD Wiki without an overly long time for detailed specification of requirements and options or programming. The intention of the EURAD Wiki is in no way to duplicate or compete with the IAEA Nuclear Wiki but rather to complement it and possibly profit from synergies.

The Wiki was developed in 2021, and access was provided to all EURAD members in December 2021 to allow end-user feedback and real-life testing. For the future, it is intended to have an area with restricted access, which would allow to discuss draft versions of documents that are still undergoing changes and have not yet been reviewed. Therefore, these documents do not fulfil the necessary quality standards for dissemination. Once reviewed and approved, these documents would then be made available in the openly accessible part of the Wiki. The Wiki will be developed further, taking into account the feedback gained from end-users and experts. As a further upside, Wikis have a built-in discussion function that allows users to comment on individual documents and the overall KM approach. The editing function allows users to participate easily as content creators or editors. As stated earlier, end-user feedback and engaging the EURAD community as active participants to KM via various functions is crucial (e.g., as authors, reviewers or by pointing out the necessity for updates for a document). For this, the exchange via the discussion functions can be highly useful. This high level of interactivity comes with the risk of "cyber-vandalism", e.g., through deleting parts of documents or writing false statements. Therefore, it is highly beneficial that the Wiki provides control through adjustable access rights. This means there is a level of control regarding who can access the Wiki and with which rights, e.g., just to read without editing rights. These restrictions also have the advantage that documents can be shared internally in a defined user group in their draft status and can be scrutinised via the Wiki before broader publication.

## 5 Conclusions and outlook

Knowledge Management is crucial for the safe implementation of RWM. However, Knowledge Management also has specific challenges, e.g., useful structuring of knowledge into topics, providing knowledge on the needed level of detail, etc. The EURAD programme is an excellent opportunity to tackle these challenges by bringing together many organisations and highly qualified experts from different fields. With the support of this community, the EURAD KM programme can provide a real step change and tangible benefit for the implementation of RWM. As one integral part of the EURAD KM programme, WP11 SoK has taken important steps in the endeavour to capture relevant knowledge and make it accessible to end-users. With the Goals Breakdown Structure, developed by EURAD [17], we have a powerful tool to organise and structure knowledge. Based on this structure, the clear hierarchy and concept of dedicated documents (the Theme Overview, Domain Insight, and State-of-Knowledge documents) allow us to fill this structure with content that enables end-users to orient themselves in the topic at hand and access further Knowledge Base (reports, scientific papers, etc.) through signposting. Filling these documents with content, i.e., capturing relevant knowledge, is a task that relies on the participation of the whole RWM community. Of course, mere capturing of knowledge is not enough. This knowledge also needs to be made available. For this, WP11 SoK has developed a Wiki that already allows sharing and discussing documents and the approach as a whole. In parallel, the crucial groundwork for the development of a broader Knowledge Management System (KMS)/IT Platform was laid through the survey of existing tools and approaches in different organisations. This work will be continued in the following years of EURAD and possibly beyond. Importantly, all of these activities need to and will consider end-user feedback. The EURAD KM programme, and KM in general, depend on end-user acceptance, so listening to the needs and wishes of the community has to be a central part of all efforts. This will also allow engaging the community not only as users but also as contributors, which is the prerequisite to a sustainable and useful KM programme extending beyond EURAD. Such a KM programme can overcome remaining challenges, such as keeping content up to date and adapting the overall approach to changing needs. The work described in this article is an important step toward achieving this goal and supports national programmes in implementing safe and feasible RWM and disposal.

## Conflict of interests

The authors declare that they have no competing interests to report.

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## Data availability statement

This article has no associated data generated and/or analysed.

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T.K. and A.T. were responsible for the conceptualisation of the paper. T.K., A.T. and D.A. wrote the first draft. All authors have contributed to conducting the work, writing and reviewing the manuscript.

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Review Article

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# Development of guidance documents in the EURAD and PREDIS projects

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**Abstract.** Particular emphasis is dedicated to Knowledge Management activities within the EURAD (European Joint Programme on Radioactive Waste Management) and PREDIS (Pre-disposal management of radioactive waste) projects to ensure the capture of existing knowledge, transfer of knowledge between Members States and management of the knowledge for future generations. The EURAD project has three work packages dedicated to knowledge management. One of them, the EURAD Guidance work package (WP12) is developing a comprehensive suite of specific guidance documents that can be used by Members States with radioactive waste management (RWM) programmes that are at an early stage of development but can be beneficial also to more advanced programmes. The PREDIS project does not have a specifically allocated work package for guidance development. Rather, such activities are integrated within deliverables produced as part of the Strategic Implementation and State of Knowledge actions of the Roadmap contributions on predisposal waste management. The EURAD guidance work is based on the existing PLANDIS guide on RD&D planning, developed by the Implementing Geological Disposal of Radioactive Waste Technology Platform (IGD-TP). The guidance documents complement other documents prepared in parallel knowledge management activities inside EURAD project: the State of Knowledge documents. The differentiation is that guidance documents explain in more detail how the process can be established and performed, including illustrative examples. The guides are self-standing documents and integrated with the EURAD Roadmap. The target end users of the guidance are primarily programme owners and managers (i.e., governments/administrations, Waste Management Organisations, Research Entities and Technical Support Organisations) responsible for planning and implementing the RWM programme and the supporting RD&D activities at a national level, even though they might also be of use and interest to other interested stakeholders, such as representatives of civil society. To produce a first list of prioritised topics for guidance documents with the aim to select a topic for a pilot guide, the Guidance WP has developed a screening process that includes review by experts and end users. Based on the priority list, the first pilot guide was developed with the title "Cost Assessment and Financing Schemes of Radioactive Waste Management Programmes". Experience gained during the selection of topics for the pilot guide and during its production are being incorporated into the procedure for identification of new topics for which guides will be developed. First, the degree of coverage of the EURAD Roadmap themes by suitable guide documents will be analysed by the WP 12 team. The analysis will be combined with feedback from experts verifying the needs for missing guides. Finally, the potential end user community representatives will be given the opportunity to comment on the prioritisation of selected guidance documents and make additional suggestions. The potential end users stay involved also during the production of the guides. This procedure aims to optimise the scarce expert resources in relation to the identified needs of guidance documents. This article explains the approach for selecting topics for guidance documents and the results obtained both in EURAD and PREDIS.

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## 1 Introduction

Radioactive waste management (RWM) consists of a large multidisciplinary set of different tasks covering all administrative and operational activities involved in the handling, pre-treatment, treatment, conditioning, transport, storage and disposal of radioactive waste. Typically, RWM has a large time span overarching many decades. These characteristics of the RWM promote the importance of a systematic approach to identify, manage, share knowledge, and enable groups of people to create new knowledge collectively to help achieve safe management of radioactive waste. Activities ensuring this systematic approach are known as knowledge management.

Knowledge management (KM) – including knowledge consolidation – is recognized as a key part of the RWM implementation process and has gained increasing interest in the past 10 years.

The main reasons for the importance of KM are the RW disposal implementation time, spanning several decades, and the complexity and variety of disciplines involved. Each individual phase of a RWM programme from waste generation through processing, disposal, and repository closure, requires continuous RD&D development with improved process understanding.

EURAD supports the implementation of the Waste Directive in EU Member-States, considering the various stages of advancement of national programmes. National RWM programmes across Europe cover a broad spectrum of stages of development, inventories, and level of advancement, particularly with respect to their plans and national policy towards implementing geological disposal.

The PREDIS project targets the development and implementation of activities for pre-disposal treatment of radioactive waste streams other than nuclear fuel and high-level radioactive waste. It is possible to identify several roles which the KM could cover, but within the scope of the project they are closest linked to the technical work package development for characterisation and processing waste streams, as well as waste acceptance criteria (WAC) issues. The long-time span addressed by WM programmes is bringing the need for trans-generation knowledge transfer in all phases of implementation, from pre-disposal through disposal. Another role is to manage effective knowledge transfer inside the multi-disciplinary programmes. The KM is applied to knowledge transfer between different actors within a program or transfer between national RWM programmes themselves. Both EURAD and PREDIS are reactive and responsive while developing ideas for the KM and networking needs of their partner and stakeholder communities.

The KM activities are integrated with technical and strategic activities. This allows KM to benefit from the huge pool of expertise existing within the EURAD programme.

An example of an important programme output which is used not only inside the EURAD project is the EURAD Roadmap [1]. The EURAD Roadmap was prepared as a representation of a generic RWM programme that shall enable users and programmes to orient themselves in the whole area of RWM. The content is focused on what knowledge, and competencies (including infrastructure) is considered most critical for implementation of RWM, aligned to the EURAD Vision and to the EURAD Strategic Research Agenda. The EURAD Roadmap provides detailed information about themes, subthemes and domains and is an efficient tool to map different activities inside a RWM programme.

The Roadmap enables different activities to be linked to the overall RWM process. This addressing provides easier orientation for potential users when they are searching for information on how to start or manage particular activities, taking into account the current best practices.

In the PREDIS project all these items are covered by one work package (WP3), whilst inside the EURAD project there are three different work packages. In EURAD, one team collects existing information (WP11), the second one (WP12) prepares information on how to carry out RWM activities and the third one (WP13) deals with training and networking. The detailed description of the organizational arrangement of knowledge management inside EURAD is given in parallel articles [2–4].

The subject of this article is experience of preparation of guidance documents that are useful for national RWM programs.

In that sense, it is important to identify potential end-users' groups:

- the first group consist of end-users who need to start (or substantially change) a disposal programme implementation. This end-user group is characterized by low experience in a particular area. For this group it is important to get basic orientation. The exchange and sharing of knowledge between advanced programmes and newcomers to the topics is typical. Positive and even negative (if available) examples may be effective but should not be used without taking into account national circumstances. Guides targeted to this end-user are more general, usually covering broad subjects.
- End-users who need to manage knowledge in a relatively narrow area, usually within an established framework, are typical for the second group. Guides for this group are more detailed in a narrow topic. The level of detail and variance in national circumstances often make it difficult to provide guidance that is valid for multiple programmes.

With respect to the nature of the Joint European Programme end-users in organizations at an early stage of the RWM programme were approached to facilitate sharing and transfer of knowledge on "how-to do" different activities in RWM.

Needs are identified from a combination of identification of gaps using the Roadmap and Experts (top-down), and specific needs raised directly by the wider community of stakeholders (bottom-up). This has been done either via surveying the KM needs and gaps among organisations or by listing prioritised topics where gaps exist, or information is not sufficient.

## 2 Method

### 2.1 Selection of pilot guide

Within the EURAD Guidance Work Package (WP12), activities aim to develop a comprehensive suite of instructional guidance documents that can be used by various stakeholders in any country with RWM programmes, regardless of their status in geological disposal implementation.

The goals of the guidance documents are (a) to share existing experience and lessons learned and to assist transfer of knowledge towards Member States with early-stage RWM programmes, as well as (b) transfer of knowledge between generations. Both goals are objectives of EURAD's Vision [5].

Guidance documents can facilitate orientation in the field itself (existing knowledge resources and existing international cooperation and networking) as well as to foster understanding different solutions in different cases and countries.

The main priority of the Guidance WP has been to identify a list of the most needed and prioritised topics of guidance documents from which a topic for a pilot guide could be selected. This included considering topics where there is access (within EURAD) to suitable experts from Member States with an Advanced Programme (AP) who could contribute to the Guidance development.

A pilot guide was compiled to test the guidance development process (and the quality management procedure). The EURAD Roadmap Advisory Committee consisting of experts from AP, proposed areas where expert knowledge of programme history would provide useful strategic guidance to new or early stages programmes. The short list consisted of the following topics:

- funding and financing aspects of radioactive waste disposal.
- Optimization of disposal of radioactive waste.
- Derivation of requirements for the disposal system.
- Waste Acceptance Criteria (reserve).

The Guidance WP team finally proposed the topic of 'Funding and Financing Aspects of Radioactive Waste Disposal' (Domain 1.3.1 [1]) to be developed as a pilot guide as the time and the readiness of resources for its timely development was assessed as reasonable.

### 2.2 Developing further guidance

For future guides to be developed in EURAD the simplified approach – implemented for selecting the topic of the pilot guide – will be complemented by following two strategies, the top-down and bottom-up approach. The bottom-up approach at EURAD level means that the selection process is carried out based on the EURAD Roadmap and the needs for further guidance are identified by the systematic evaluation of the themes, sub-themes and domains. This is implemented using input from the available literature, from experts who have experience from the implementation process and feedback from the potential end-users.

The top-down approach means that experts (selected based on their experience and knowledge accumulated in their respective fields of activities) identify where guidance is needed but not available.

Based on the result of this activity and the ongoing evaluation of end user needs and feedback, the approved list of prioritised topics will be regularly updated as a 'living document'.

#### Analysis of existing guidance literature

The mapping started by establishing a starting reference point related to the mapping of the available guidance and guide-like technical documents, through a detailed literature search of:

- international regulation documents (ICRP and WENRA);
- international guides (IAEA);
- international guide-like technical documents (IAEA, OECD NEA, EC Projects);
- national guides;
- national guide-like technical documents.

Other main sources for the mapping have been EURAD partners' courses and international nuclear entities.

Open web was searched to complete the "big picture" of geological disposal materials.

Based on the survey it was concluded that although the available technical documents and guidance are numerous, early-stage programmes or small inventory programmes often face a challenge of information overload and deciphering which sources of information are most accurate and most recent, thus the guidelines aim at providing concise references to orient the reader.

#### Selection criteria

For selecting guidance topics some basic criteria were defined, clearly linked to and coherent with the EURAD founding documents (Vision document [5], EURAD Roadmap [1] and Strategic Research Agenda [6]):

- interaction with EURAD WPs: are there any outputs from EURAD already available to be used for guidance development? How and to what extent are they used?
- clearly demonstrate European-added value (improved information and knowledge transfer between national programmes and across generations);
- be meaningful, focused and manageable;
- is that any identified guidance gap;
- each contribution should bring complementarity (avoid duplication, keep clear of disconnected, spread or repeated contributions);
- responsive to the end-users needs and expectations (effectively assists the targeted end-users in their programme implementation, i.e. be need-driven);
- importance (it should be evaluated how big an area of the Roadmap is covered by the topic, which more or less correlates with the aspect of how significant a role the given topic has in RWM programme implementation);

- urgency in terms of programme implementation stage (in what stage of RWM programme development should the guidance be implemented, when should the guidance on the given topic be ready for the target end-users);
- expertise (how much expertise is necessary for the development of the given topic outside from Guidance WP, or outside from EURAD);
- length of development (based on the preliminary assumptions how lengthy could the process of development of the guide be).

There are multiple options of materials available for selection that potentially meet the selection criteria and the guidance will be used to identify the strengths and weaknesses of the options. One may want to create early buy-in amongst a wider range of end-users by engaging them in the selection and development process. There is a longer time frame for the decision-making process that allows for a more thorough selection process.

### Topic selection

On the basis of this long list the Guidance WP team members prepared some topic proposals. The short list consists of the following topics:

1. using the safety assessment as a tool to derive requirements for the disposal system elements;
2. role of implementer in planning and managing repository development programme;
3. developing strategy for data management and preservation of records and knowledge in the context of radioactive disposal programme;
4. using the safety case (and safety functions) to prioritize geological disposal RD&D plans;
5. developer/implementer and regulator interactions during the planning, siting, engineering design, RD&D and construction of disposal facilities;
6. managing interactions in multidisciplinary teams (engineers, geoscientists, sociologists; physicists; modellers, lawyers etc.);
7. establishing and managing programme requirements and how these need to be is linked to the findings of the RD&D programme;
8. developing the design basis for a geological repository;
9. assessing the acceptability of site conditions for the location of a geological repository;
10. characterization of high-level waste at different management stages.

The list was evaluated against predefined selection criteria based on the expert judgement of the Guidance team members in a qualitative and semi-quantitative way.

Each team member could score the topic proposals and the results were discussed at the WP web-meeting. It was emphasised that for any guidance document it shall be ensured that it provides an added value to the target end-users (needs driven) in an area, which is not covered by existing guidance (avoid duplication). Feedback from the potential end-users will also be sought for prioritization suggested topics. Final list of selected topics will be approved by EURAD General Assembly.

After having the topic for the guides approved, experts with relevant experience in the given area will be selected to assist the Guidance WP team in the elaboration of the guidance.

Further guides will be elaborated in current EURAD project in collaboration with experts with experience on the given topic (who 'have done it before'). Experts from countries with different status of geological disposal implementation are going to work together, which will create a network of experts (effectively contributing to knowledge transfer at EURAD level).

In the case of the PREDIS project, guidance development so far has been especially focussed in one specific topical area for Waste Acceptance Criteria (WAC). This has been dealt with using the goal of developing a suite of guidance documents for (i) the selection of optimal methods for the determination of WAC parameters, (ii) principles and procedures regarding the qualification of waste forms for storage/disposal, and (iii) formulation of generic WAC whenever a disposal system has been missing. Information about national experience collected from a number of countries worldwide [7] is being converted into a set of practical advice on establishing the mentioned aspects of a national waste acceptance system. There are also additional guidance documentations that will be part of other technical deliverables within the work packages addressing treatment and processing of waste. However, these are not stand-alone documents within the Knowledge Management part of the PREDIS structure. The format of guidance for PREDIS is more incorporated into the overall knowledge management that is provided through training tools, such as Domain Insights, case studies of best practices and lecture materials that target specific issues in predisposal waste management that are not already covered by other sources, such as the IAEA e-learning modules and Wiki.

## 3 EURAD guideline production

The EURAD Guidance team adopted the Quality Management Procedure for Guidance Development [8] where the quality principles and procedures to be taken into consideration while producing and updating guidance documents for RD&D activities in RWM are outlined. The aim of such a procedure is to set the requirements for a quality management system targeted at production of any guide document to ensure quality, inclusiveness and transparency during its elaboration, further improvement, and implementation. Among others this includes:

- quality assurance (QA) criteria for elaboration of RD&D Guides to be developed in the framework of WP 12,
- quality requirements how RD&D Guides should be developed, maintained and used according to the QA criteria,
- consultation and review process during the development of the RD&D Guides.

## 3.1 QA criteria for production/update of guidance documents

Few norms specify how quality, inclusiveness and transparency is assured in a guidance document. Especially, the criteria for selection of authors and guidance production are considered to be relevant for the development of any RD&D guide within EURAD.

### 3.1.1 The competencies of authors

The authors should have experience and competence for the development of particular guidance document, in line with the scientific area the given guide covers. It is an important quality criterion that the authors of any RD&D guides should have wide experiences and highly qualified competencies to the covered topic.

The authors can be experts having wide experience in RD&D planning, individuals, representing WMO responsible for the development of RD&D plans and Technical Support Organisations (TSO), involved in the reviewing process of these plans and Research Entities (RE), involved in the execution of RD&D activities. End-users of RD&D Guides from early-stage programmes and small inventory programmes participating in disposal should be involved in the drafting process of the RD&D Guides as well.

### 3.1.2 Procedure for selection of authors

The procedure of selection of authors for a given RD&D guide should be compatible with the general EURAD rules and it would apply within the Guidance work package.

### 3.1.3 Guidance production criteria

The guidance production criteria have been developed from a list of the scope of criteria for evaluating the overall EURAD Programme and are given in EURAD Quality Management Plan (QMP) [8]. Most important are:

- to support the overall EURAD Roadmap [1], EURAD Vision document [5] (and also Strategic Research Agenda [6]),
- to be ambitious, creative, innovative, and address key needs of End Users with Programmes in Early Stage and with Small Inventories,
- to reach a major impact of the RD&D area of the procedures at relevant phases,
- to systematically outline the set of activities to be implemented,
- to demonstrate procedures intended to be used to attain the stated objectives,
- to describe clearly how appropriate they are for the planned activity and their feasibility,
- to identify the most significant steps to achieving the stated objectives and explain how these will be addressed,
- to show clearly how meaningful and independent peer review can be integrated within the overall implementation plan on a timely basis.

### 3.1.4 Lessons learned on QA from pilot guide development

As there is an expectation of the highest quality of guidance, the process of its development shall comply with all quality assurance requested in the “EURAD Quality Management Plan” [8] and the “Quality Management Procedure for Guidance Development” [4]. The guidance selection process also must comply with the “Approved list of prioritized topics for further guidance documents and selection process of one topic for the development of a pilot guide” [9].

The quality management procedure consists of the requirements for a quality management system on guides production with special emphasis on the quality assurance criteria, quality requirements on guides development and utilisation. The high importance is given to the reviewing process during the guide production.

The whole process must be performed in a close cooperation with the EURAD Chief Scientific Officer, Bureau/PMO and the Editorial Board, ensuring a thorough review process, transparency in guides topics selection and a requested quality of guidance content. All selected topics must be approved by these EURAD governance bodies and EURAD General Assembly members.

## 3.2 Guidance production procedure

Development and approval of a guide is performed in several steps. These steps include initiation, drafting, peer review, finalization, approval and “socialization”.

At the “Initiation” step the Terms of Reference (ToR) is developed by WP12 team and approved by Bureau/PMO. The ToR defines the whole process of development of the guide, including topic justification and selection based on the performed gap analyses and the interest from the target end users. In the ToR there is clear definition of the scope of the guide, the timeline, responsibilities (and their distribution between authors, reviewers, other experts and end-users), requirements in volume and contents, etc. In this step special attention is devoted to the clarification of tasks for the individual authors, confirmation of the guide development schedule and organization of a kick-off meeting(s) between the authors.

At the “Drafting” step, detailed development of structure and contents of the guide is completed with identification of reliable and trusted sources of information (e.g. IAEA, EC and international projects, IGD-TP, SITEX Network, EURADSCIENCE). The writing of the guide is performed based on the collection of information from the identified sources according to the established structure and contents of the guide. In the ToR the supporting experts’ team and end-users are identified and consulted to incorporate their feedback. Finally, draft guide is submitted to Bureau/PMO for peer review.

The “Peer review” step includes independent review of the draft guide organized by Bureau/PMO (including selection of reviewers) and submission of Bureau/PMO feedback to the development team.

The “Finalization” step comprises of revision of the guide according to comments and recommendations received from the peer review, agreement of finalized guide by Guidance WP and submission of finalized guide to Bureau/PMO for approval. At the "Approval" step the final checking the management of reviewer comments or statements by Bureau/PMO and approval of the guide by Bureau/PMO is done. During the "Socialization" step distribution of the guide among Communities of Practice (CoP) is performed including the collection of feedback to be used for future revision.

### 3.3 Consultation, incorporation of feedbacks and final reviews

Consultation with experts and target end-users during the development of a guidance document can bring significant inputs to the deliverable and as a result, can increase its quality. Consultations with PMO representatives/coordinators on the objectives and scope of the given Guide is important to be in line with the general expectations of EURAD. Consultation can be organized especially with Bureau (College representatives), end-users representatives or other EURAD WPs including KM WPs.

When a guidance document is developed in such details that the usability and applicability (whether the document meets the pre-defined goals) can be tested, the feedback from some potential end-users can be asked. Potential end-users of guidance documents can be representative of mandated actors (WMO, TSO, RE) from Advanced Stage Programme (AP), from Early-stage Programme (ESP), from Small Inventory Programme (SIMP) Member States in line with the scope and topic of the given guide. The potential ways of obtaining feedback concerning a draft guide could include asking independent views about the applicability of the given guide, organizing events for the end-users to identify collective viewpoints, compiling questionnaires for dedicated topics.

## 4 Pilot guide and lessons learned

### 4.1 Objectives of the pilot guide

The first guide produced (pilot guide) was on "Costing and Funding" for implementation of a radioactive waste disposal [10].

Cost estimations are needed for all projects, programmes and operations. Information on this topic is abundant, and guidance on various approaches and methods is widely available. However, the estimation of the costs of disposal programmes remains challenging due to their complex and societally sensitive nature and long implementation periods, and practical guidance on this issue remains insufficient.

Countries that are just starting to develop their disposal programmes and which have little or no experience in this area may have difficulties in finding the relevant advice on how to perform cost estimations. This guide aims to describe the cost estimation process specifically focusing on radioactive waste disposal programmes, and to provide practical advice on how to conduct this process to result in a consistent, reliable and well-documented cost estimation.

The guide suggests a stepwise approach to costing to make the whole process more transparent and easier to manage. The steps are interdependent and logically cover all the important phases in the cost estimation from defining the purpose and scope of the estimate, selecting the method and obtaining the input data, to performing the cost estimation and the consideration of, including suitable approach to, addressing cost uncertainties and risks management.

The guide also addresses possible mechanisms for financing disposal of radioactive waste. Since details on various financial mechanisms can be found in a number of documents this guide describes only the financing of RWM activities from a pre-collected fund, which is the most commonly applied method.

The intended end-users of this guide include primarily waste management organisations (WMO) or designated organisations if no WMO has yet been established in small inventory programme and early-stage programme countries (including countries that are initiating a new-build nuclear programme), which are, in most cases, responsible for conducting the cost calculations for their respective national programmes. The guide may also be beneficial for those entities (ministries, regulatory bodies and/or their technical support organisations) responsible for reviewing the cost calculations or those obliged to implement the "polluter pays" principle (e.g., waste generators).

The target audience may also include project managers and costing experts (who establish, revise and justify estimations) and those entities which are responsible for financing the national RWM programme.

### 4.2 Scope of the pilot guide

The guide focuses primarily on the cost assessment methodology for geological disposal, but with certain adaptations it can also be applied to near-surface or borehole disposal programmes since the principles are the same and, from this perspective, the guide may also be beneficial for small inventory disposal programmes.

The report provides general guidance on developing a cost estimation for radioactive waste disposal programmes, including more detailed advice on using a structured approach.

Initially, the guide explains the necessary prerequisites and boundary conditions for the disposal programme and its cost estimation, and emphasises the importance of a national RWM policy and national RWM programme, the existence of a national legislative framework and waste inventory, stakeholder engagement, etc.

The guide provides a brief description of each of these steps including information on additional literature that contains more detailed information.

In the guide the cost assessment of the disposal programme is described as a process consisting of several steps, starting with defining the purpose of the cost estimation, the scope of the work and the timing of activities included in the estimation, selecting the appropriate method for cost estimation, and preparing the Work Breakdown Structure (WBS) as a framework for a detailed cost estimation. After performing the cost estimation, the process also includes the analysis of uncertainties and risks in cost assessment and provisions for addressing them as well as thorough documenting of the whole process to provide traceability and performing an independent review of cost estimate to establish confidence in the estimate.

In the guide each of these steps is briefly described and wherever possible additional guidance referring to geological disposal provided. Specific attention is given to the development of the WBS as an essential and practical tool for performing the detailed cost assessment. Based on several disposal programmes and their respective WBSs an attempt was made to summarize the approaches and develop a more generic WBS for geological disposal that would be useful for countries and organisations that have just embarked upon or plan to launch the cost estimation process in the near future.

Similarly, when considering the uncertainties and risks in cost estimation of the disposal programme, the guide provides information on the most common uncertainties and risks in geological disposal (GD) programmes and suggests how they might be addressed.

The guide emphasises that the cost estimation is an iterative process that requires regular updates and improvements in the input data, as well as transparency and quality assurance in the cost assessment process and the data and information management systems.

### 4.3 Benefits for users of the pilot guide

Potential users of the guide may find beneficial the presentation of a practical example of how the work scope of the geological disposal programme could be broken down into smaller, meaningful elements and hierarchically organised in the form of a WBS, and a discussion on the possible cost uncertainties and risks related to the various WBS elements of geological disposal programmes.

The presentation of selected lessons learnt and experience obtained from the cost estimation processes in a number of national programmes may also be helpful for gaining a better understanding of the process.

The potential users may also find very useful several examples of cost estimations for various aspects of the disposal programme from different countries (e.g., Hungary, Slovenia, Czech Republic) that are included in Appendices as illustrations of how cost estimations are performed in practice.

### 4.4 Lessons learned

The crucial aspect of the guide production process is a mutual interaction with potential end users which can ensure a complementarity of selected topics and end users needs on guides development. With respect to this, the first short priority list of selected topics developed by WP12 has been communicated with a group of potential end users what provided a valuable contribution to the WP12 team when selecting topic for pilot guide.

Within the process of guidance development, an interaction with international entities is recommended (e.g., the IAEA and NEA) with special emphasis on already published or planned guides. Also, other relevant documents (technical, strategical, methodological, etc.) from publicly accessible sources has been considered and evaluated during a gap analysis leading to the topics selection.

This approach has been consistently applied within pilot guide topics selection and its subsequent development. The feasibility of the guide production process from a technical point of view and the expected timescale has been demonstrated, thus the process can be applied for the next guide production. In addition to the urgency criterion, the accessibility of the experts contributing to the guides must be seriously taken into account when selecting the next topics for guide production. With respect to the demanded experts limited availability, the EURAD cooperation with PREDIS can be highly recommended for planning further RD&D programmes as both projects have available large spectrum of experts.

## 5 Conclusions

EURAD as a European Joint Programme in the field of RWM research is managing three Knowledge Management WPs (WP11, WP12 and WP13) contributing to the expected KM goals. Within PREDIS, there is one KM WP (WP3) for all KM, closely working with other PREDIS WPs. During implementation of both projects, we begin to coordinate our activities to avoid potential duplication (e.g. EURAD WP12 excluded guide on waste acceptance criteria from its list as it is foreseen in PREDIS activities). The initial informal coordination was developed to more formalized form as EURAD and PREDIS representatives signed Joint Statement on knowledge management in 2021 [11].

EURAD WP12 is contributing to the KM through developing a comprehensive suite of instructional guidance documents that can be used by every interested end user involved in the RWM programmes, preferably those in early stage of its implementation and/or dealing with small inventory, but guidance documents developed within WP12 could be beneficial for advanced programmes as well.

KM should represent an integral part of all RWM programmes in order to support their efficient establishment and successful implementation during all programme phases. The main goal is dedicated to the knowledge enhancement and transfer between involved stakeholders/institutions, possibly between national RWM programmes and, in particular over generation to contribute to the RWM programme sustainability. KM should be considered already from the phase of conceptual planning of the programme. It needs to be implemented as soon as feasible to be an integral part of radioactive waste disposal implementation process.

The necessity of KM integration into RMW programmes, including RD&D, is also identified through the EURAD Founding documents (EURAD Roadmap [1], Vision Document [5], Strategic Research Agenda [6], Deployment Plan [12]), in the field of radioactive waste disposal and complemented with PREDIS KM strategy dedicated to the pre-disposal activities.

The produced pilot Guide on Cost Assessment and Financing Schemes of Radioactive Waste Management aims to fill identified gap and orient the early stages RWM programmes including those programmes dealing with small inventories on how to plan budget activities with special impact on radioactive waste disposal. This pilot guide may contribute to the learning process on costing strategy and methodology as well as on establishing and operating a funding scheme. The experience gained during the drafting of the pilot guide can serve as a sound basis for the development of further guides the topics of which will be defined based on a systematic and transparent selection process.

## Conflict of interests

The authors declare that they have no competing interests to report.

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This article has no associated data generated.

## Author contribution statement

Mr. Peter Ormai prepared the basic version based on the initial discussion. The PREDIS detail were provided by Anthony Banford and Erika Holt. The EURAD details were provided by Bálint Nös, Peter Ormai, Nadja Železnik, Irena Mele, Paul Carbol, Jitka Mikšová and Jiří Faltejsek. The article was produced as teamwork with participations of all co-authors.

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Review Article

Open Access

# Training and mobility in EU projects EURAD and PREDIS

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**Abstract.** Knowledge management (KM) is critical to ensure safe and sustainable radioactive waste management. The European Commission is encouraging KM through the Waste Directive. EURAD and PREDIS are projects funded by the European Commission, including work packages devoted to Knowledge Management. EURAD has set up a “School of RWM”, launched in 2020. To establish a portfolio of training courses, currently existing training initiatives in the field of RWM were mapped. A gap analysis was carried out to detect current unfulfilled needs for courses on specific topics. The School of RWM has already organized two training courses responding to the perceived needs. Besides training courses, both projects regularly organize topical webinars, which are related to RWM & Predisposal-related themes. Both projects launched a dedicated mobility program, allowing their beneficiaries to perform technical visits to infrastructures, undertake internships and set up exchange programs between institutions within EURAD/PREDIS. In addition, PREDIS also financially supports participation in training courses and events. Finally, both projects support their respective student communities, including masters, Ph.D. students, and postdocs. In order to improve their efficiency, EURAD and PREDIS KM will be merged in the proposed upcoming EURAD-2 program.

## 1 Introduction

Knowledge management (KM) is critical to ensure safe and sustainable radioactive waste management throughout the lifecycle. Moreover, KM is recognized as a key part of the Radioactive Waste (RW) implementation process and has gained interest in the last few years.

The European Commission is encouraging KM, through the Waste Directive, in order to improve the progress of EU Member States' implementation of their national RW disposal programs. KM is crucial for implementing an RW disposal facility (licensing, constructing, operating, closing processes, and post-closure activities). Each individual phase of an RW management program, from waste generation through processing, disposal, and repository closure, will require continuous RD&D development with improved process understanding (inventory, handling, treatment, geoscience, disposal/material development, chemical, and physical interactions, long-term safety assessment, ...). These developments will form the knowledge base needed for waste processing, packaging, and storage during the pre-disposal phase. Finally, this knowledge base will be used by, for example, waste management organizations, technical support organizations, regulators, and civil society, for obtaining the disposal construction, operation, closure licenses, and post-closure activities (e.g. monitoring). There is a high motivation for logical and sustainable KM structures populated with publicly available, consistent, transparent, and up-to-date evidence-based state of knowledge. These KM structures are necessary to evaluate the waste disposability and predict the behavior of a disposal facility and RW with relatively small uncertainties on time scales of $10^5$–$10^6$ years.

The European Joint Programme on Radioactive Waste Management (EURAD; 2019–2024; grant agreement N° 847593) gathers European Waste Management Organizations, Technical Support Organizations, and Research Entities working in the field of radioactive waste management (RWM). The main goal of EURAD is to achieve a step change in the European collaboration towards safe RWM through developing a robust and sustained science, technology and KM program. Such a step change means a new era via more effective and efficient public RD&D and KM funding in Europe and deep cooperation between the Member States. The aim is to implement a joint Strategic Program of research and KM activities at the European level, which brings together and complements the EU Member State programs to ensure cutting-edge knowledge creation and preservation to deliver safe, sustainable, and publicly acceptable solutions for the management of RW across Europe, now and in the future.

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The main activities of EURAD consist of research, development and demonstration activities, strategic studies, and KM, including access to existing knowledge, guidance for less advanced RWM programs, and developing a training and mobility program for EURAD end-users. The EURAD KM program is led by three distinct work packages (WPs): (i) WP11-State of Knowledge, which will gather the current state-of-the-art knowledge on RWM, (ii) WP12-Guidance, which will develop guidance documents that can be used by the Member States at the early stage of developing a national RWM program, and (iii) WP13-Training and Mobility. The "Training and Mobility" WP supports its activities through the "School of Radioactive Waste Management", launched in 2020. In the first phase, this School focused on Training and Mobility. Later, we integrated actions to promote and support the EURAD Ph.D. student community and provide a panoramic overview of all disciplines and activities associated with a safe and sustainable RWM program. The latter is done via a diverse portfolio of training and mobility offers as well as via linking all the School's activities to the EURAD Roadmap (*in progress*). Together these integrated actions form the four main pillars (i.e. (i) training courses/webinars, (ii) the Mobility Programme, (iii) providing a panoramic overview, and (iv) supporting the Ph.D. community of the School of RWM.

The "Pre-Disposal Management of Radioactive Waste" project (PREDIS; 2020–2024; grant agreement N° 945098) focuses on the development and implementation of activities for predisposal treatment of RW streams other than nuclear fuel and high-level RW. Like EURAD, PREDIS' main activities consist of research, development, and demonstration activities and KM. All KM activities are coordinated by one WP. The main objective of this WP is to provide the PREDIS participants and the European pre-disposal community access to existing and newly formed knowledge in a systematic and structured way. The PREDIS KM work package focuses on developing a KM program, collecting State of Knowledge documents, and developing a training and mobility program.

The EURAD and PREDIS Training and Mobility WPs are closely interlinked and complementary. This is reflected in the EURAD-PREDIS Joint Statement on Knowledge Management, which summarized the KM approach of both projects and their collaboration [1]. This paper presents the Mobility and Training program developed by both projects as well as bi-directional support, collaboration in training activities, learning from experiences in both projects, etc.

KM is challenging to implement, however, both EURAD and PREDIS projects have a great potential for success and have access to experts with many years of experience and knowledge in the fields of RWM and KM.

## 2 Training program

### 2.1 Objectives

The School of RWM and the PREDIS KM WP act as the coordinating structures managing the entirety of the training activities of EURAD and PREDIS. Their end-users are defined as professionals and potential new professionals at graduated and post-graduated levels for EU and non-EU countries (via International Atomic Energy Agency (IAEA) and Nuclear Energy Agency (NEA) programs) and, in particular, the next generation of experts.

To facilitate the development of the training program, the training portfolio will be linked to the EURAD Roadmap. This represents a generic RWM program that allows end-users to access existing knowledge in RWM. The content of the Roadmap is focused on which knowledge and competencies are considered most critical for implementing an RWM program (for more information: https://www.ejp-eurad.eu/roadmap). The School of RWM and the PREDIS training program pay attention to the best-fitted training format and ensure that the scientific state-of-the-art is guaranteed by enlisting EURAD/PREDIS subject matter experts as lecturers for their training courses.

### 2.2 Setting up the training program

The training programs of EURAD and PREDIS were set up following the same methodology but focused on their own target topics (RWM and predisposal of RW, respectively). Firstly, it was important to identify the specific training needs that were present in the RW community. Complementary to this, a mapping of existing training initiatives needed to be conducted.

By combining these two inputs, the School of RWM and PREDIS KM WP could draft a priority list of training courses, which helps implement the training courses and related activities such as webinars. All information related to the available activities is gathered on their own dedicated web pages (https://euradschool.eu/ and https://predis-h2020.eu/knowledge-management/).

#### 2.2.1 Identification of training needs

EURAD and PREDIS launched a "survey on training initiatives" in their respective communities [2,3]. The aim was to get a clear overview of the training needs and the currently existing training courses in the field of RWM and predisposition.

The EURAD survey was answered by 80 respondents, identifying a total of 363 training needs. Respondents categorized 262 topics as "difficult to find". The identified existing training courses cover most of the topics within RWM, however, an analysis of the training needs indicated that there were still several gaps identified within the EURAD community (e.g. uncertainty management and safety case development and review).

Thirty-three organizations provided feedback through the survey distributed among the PREDIS partners and its end-user group. The PREDIS community identified several topics for which training is needed but is currently not available (to their knowledge) among the commonly offered training courses. It is important to highlight that about 80% of the proposed topics (e.g. geopolymer matrices, characterization, life cycle analysis, decontamination processes) can be covered by PREDIS partners.

The survey also included questions related to the preferred format of courses organized by PREDIS. These were included to help understand partners' preferences with regard to training formats and design. Based on that feedback, courses should be mainly focused on the needs of Ph.D. students, postdocs, and junior professionals. Furthermore, the respondents indicated that the preferred duration is 1–2 days or one week.

#### 2.2.2 Mapping of existing training courses

The available training courses (in Europe) in the field of RWM were mapped up to the year 2021. This task was done in close collaboration between the EURAD and PREDIS Training and Mobility WPs. Over 150 courses were identified [4]. A comparison between the mapped courses and the training needs from the EURAD/PREDIS community confirmed a lack of courses in specific themes. An example is the lack of available training on uncertainty management in RWM: this was a topic that was identified as an urgent training need, and the mapping showed that currently, there are no training courses available to cover this gap. This provided a good way for the School of RWM and the PREDIS Training and Mobility Programme to develop their training courses and thus fill the identified gaps.

#### 2.2.3 Implementation of training courses

For the newly developed training courses in the frame of EURAD, the School of RWM considers the Systematic Approach to Training [5]. This approach consists of cycled implementation containing the following steps:

1. analysis of the required competencies (knowledge, skills, and attitudes).
2. Design of a training program based on a translation of competencies into learning outcomes and objectives.
3. Development of training materials to meet the predefined learning objectives.
4. Implementation of the training.
5. Evaluation of the training effectiveness, which serves as feedback to step 1 “Analysis”.

Based on the Systematic Approach to Training, EURAD developed quality criteria by which the newly developed training courses will be appreciated [6]. This also includes evaluation, which can be performed on several levels (e.g. learner satisfaction, knowledge/skills gained). Furthermore, these criteria also ensure uniform quality of the School of RWM's training courses.

PREDIS is currently developing its strategy for the training course program, but general lines are presented in Deliverable 3.4 [3].

In addition to implementing training courses, the School of RWM and the PREDIS KM Program also host online webinars. These are short and informal sessions providing information on a specific topic to a broad audience. They are recorded and made publicly available online.

#### 2.2.4 Developing a dedicated webpage

All information on the activities of the School of RWM is collected and organized on a dedicated webpage: https://euradschool.eu/. The aim is to make this webpage a centralized place where people, from both in- and outside of EURAD, can find all relevant information on the four main pillars of the School of RWM: training courses (including webinars), the Mobility Programme, panorama (providing an overview and insight into all aspects involved in RWM), and the EURAD Ph.D. community. Furthermore, the website also includes a discussion forum to bring together all members of the EURAD community. In addition, the webpage contains information about the outcome of the Mobility program, related publications, and a link to the EURAD Roadmap.

Similarly, PREDIS developed a specific section within its project webpage devoted to Knowledge Management Activities, including all the information related to the Training and Mobility Programme. In this section, the PREDIS community and the general public have access to the materials developed by PREDIS and all existing training material identified as relevant for the PREDIS community.

#### 2.2.5 Engaging the Ph.D. community

Both projects actively support their respective student communities. Note that this is not limited to Ph.D. students but includes Master's students, Postdocs, and the next generation working in the radioactive waste management sector. They are the future key figures in the field of RWM, and as such, they benefit from the possibility to network with their peers and established senior RWM experts early on in their careers.

To this end, an overview of all Ph.D. students working within EURAD and PREDIS is collected. In the case of EURAD, this overview is made publicly available via the School of RWM's website. This allows the Ph.D. students to easily find each other's contact data and be informed about the research topics of their peers. PREDIS uploads the updated overview of students at their internal system of document sharing, and all students have access to it.

The following actions are done to improve the students' integration within the project community and improvement of their knowledge and experience in the field; as well as enhance their networking:

- a list of events that are of special interest to Ph.D. students are available for them, not only training courses but also interesting conferences, summer schools, workshops ... in the field of RWM;
- publications made by Ph.D. students are gathered and published. This way, the scientific achievements of the Ph.D. community can easily be tracked by both the EURAD/PREDIS community and the general public;
- organization of Ph.D. student events;
- “Ph.D. corner” in the EURAD newsletters to highlight the work done by the Ph.D. students.

Finally, the School of RWM also hosts an open, interactive forum, which is available through the School of RWM webpage. The primary aim of this forum is to improve the cohesion and interaction between participants in the EURAD community. As such, it provides an ideal platform for students and junior researchers, senior experts, civil society members, etc., to discuss diverse topics in the field of RWM.

## 3 Mobility programme

### 3.1 Objectives

With the organization and coordination of a Mobility Programme, the projects allow its beneficiaries to perform technical visits to dedicated infrastructures associated with the EURAD/PREDIS partner organizations, undertake internships, and set up exchange programs between institutions within the project. In addition, it also offers Mobility actions to attend a course or a conference.

These activities serve as enhanced training as well as collaboration between all members of the EURAD/PREDIS community. The mobility actions can complement a training program and/or be part of a Continuous Professional Development program of experienced personnel involved in RWM.

### 3.2 Setting up the mobility programme

The School of RWM hosts the EURAD Mobility Programme. It was developed to complement existing initiatives (e.g. ENEN+ Mobility Fund). The intention is to financially support junior and senior professionals as well as Ph.D. students and postdocs from EURAD beneficiaries to:

- visit dedicated infrastructures from EURAD partner institutions;
- undertake internships and/or exchange programs between EURAD partner institutions.

EURAD opted for a tiered approach in developing its Mobility Programme. The Mobility Programme can evolve to include students (M.Sc and B.Sc) and support their mobility actions. Based on the performance of the Mobility Programme and end-user feedback, it will be extended regularly throughout the EURAD lifetime. Currently, the EURAD Mobility Programme operates at Stage II of its predefined stages. A proposal was submitted in April 2022 to extend the Mobility Programme to allow financial support for attending training courses and conferences.

For PREDIS end-users, knowledge transfer through mobility actions is a priority. As such, the Mobility Programme is intended for those who want to improve their knowledge and skills in the field of predisposal treatment of RW streams, other than nuclear fuel and high-level radioactive waste. The PREDIS Mobility Programme mostly targets Ph.D. students, postdocs, and junior scientists out of PREDIS beneficiaries. It will support them to:

- visit partners institutes or industrial partners;
- perform internships and/or exchange programs;
- participate in (inter)national training courses;
- attend events (e.g. conferences, workshops).

Both Mobility Programmes are open to all partner institutions affiliated with EURAD or PREDIS who would like to improve their knowledge and skills in the field of RWM and predisposition to RW. Moreover, they follow a similar methodology as PREDIS takes to profit from the previous experience of EURAD.

The application process is as follows:

1. applications submission to an online portal (https://pro.evalato.com/2185 or https://pro.evalato.com/3346 for EURAD and PREDIS, respectively).
2. Evaluation of the applications: the evaluation depends on the type of mobility action. On the one hand, there are internal WP mobility actions. In this case, the WP Leader, together with two members of either the EURAD WP Board or the PREDIS WP3, will perform the evaluation. On the other hand, there is cross-WP mobility. In this case, the application will be evaluated by an Evaluation Committee. The evaluation itself applies predefined criteria.
3. Acceptance of the Mobility action: based on the scores, a ranking will be made, and applicants will be selected.
4. Reporting: upon completion of the mobility actions, beneficiaries are asked to submit a detailed mission report, which will be assessed on the completeness, language, and compliance with the proposed mobility action. These mission reports will be stored and made available online as they are valuable outputs from the Mobility Programme. They also allow for evaluating the success and effectiveness of the performed mobility actions.

To successful applicants, a mobility grant will be provided, which is intended exclusively to cover mobility-related costs (i.e. travel, daily allowance, and accommodation). In the case of PREDIS, the registration fee for a conference or training is also covered. The grants will be provided as lump sums.

Applicants' practical information (e.g. how to apply, deadlines, lump sums) is summarized in a "Mobility manual" document elaborated by each project [7,8].

## 4 Current achievements of the EURAD School of Radioactive Waste Management and PREDIS Training and Mobility programme

### 4.1 Launch of the webpages

On December 21st 2020, the webpage of the School of RWM (https://euradschool.eu/) was launched. The landing page allows for easy navigation between information on courses, mobility, Ph.D. students, webinars, and general information about the School of RWM (Fig. 1). Additionally, it allows access to the discussion forum and a list of publications by the EURAD Training and Mobility work package. Furthermore, it contains news items and a calendar of upcoming events.

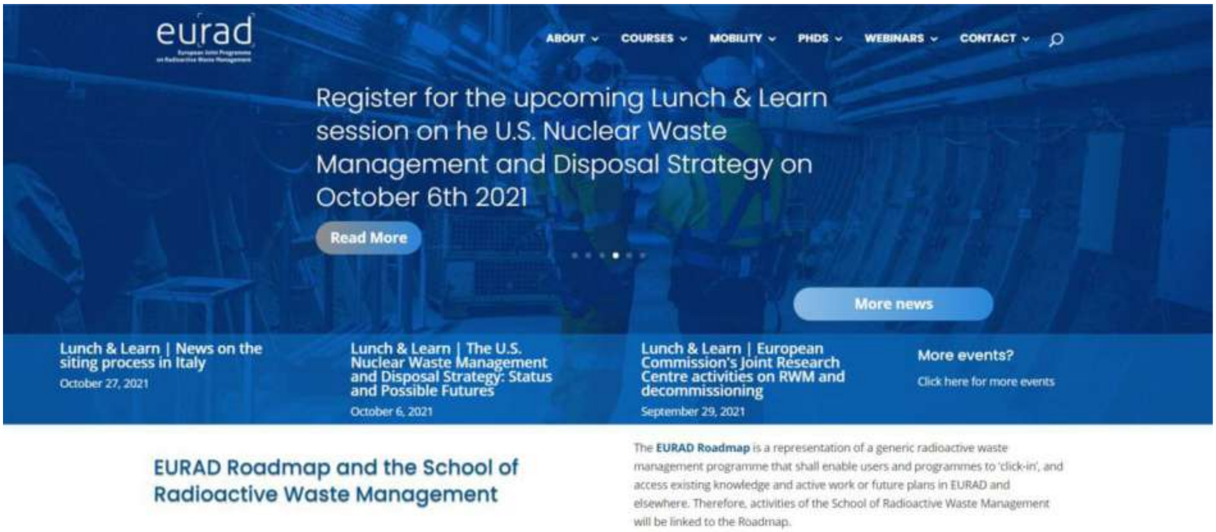


**Fig. 1.** Home page of the School of Radioactive Waste Management's webpage (https://euradschool.eu/). The home page allows navigating between information on courses, mobility, Ph.D. students, webinars, and general information on the School of RWM. Additionally, it allows access to the discussion forum and a list of publications by the EURAD Training and Mobility work package.

As of March 31st 2022, 2322 new users have visited the webpage. Eight thousand seven hundred and two page views were registered. The most viewed pages are (i) the home page (1343 views), (ii) the upcoming events page (1084 views), (iii) Mobility Application guidelines (493 views), and the (iv) list of EURAD partner infrastructures (434 views).

In June 2021, the discussion forum was launched, accessible through the School of RWM's webpage. The aim is to foster discussions, ask questions, and network with all EURAD partners. In order to create posts, registration is required. It contains sub-forums to support discussions concerning the School of RWM and the EURAD Roadmap.

The PREDIS webpage was launched on September 1st 2020. It includes a section focused on KM activities. The team is now working to implement a new design to improve the interaction of the beneficiaries and the general public with the relevant information.

## 4.2 Organization of training courses and webinars

Currently, the School of RWM has organized two training courses: a training on multi-physical couplings in geomechanics, in collaboration with EURAD WPs 6 and 7, and an introductory training on EURAD and RWM.

The EURAD Training on "Multiphysical couplings in geomechanics" was organized from January 22nd 2020 to January 24th 2020, at the University of Liège (Belgium). The course allowed the 70 participants to improve their understanding of heat transfers, water and gas migration, stress, and strain evolution in a repository. It addressed both experimental and numerical investigations at small (lab) and large (in situ) scales. In the end, participants obtained a broad view of the state-of-the-art and the challenges related to EURAD WP 6 and 7. They met several key researchers in the field, fostering information exchange and cooperation within the geomechanics community.

On September 14th 2020, the "Introductory course to EURAD and radioactive waste management" was organized. The aim was to give a comprehensive overview of the activities of EURAD, as well as an overview of the state-of-the-art in RWM. The target audience was primarily Ph.D. students, postdocs, and young professionals in the field of RWM, but the training course was open to all EURAD partners as well as people from outside EURAD. Two hundred sixty participants attended (at least part) of the training course. This course was organized online, and the lectures were recorded. The recordings of lectures are available online (https://www.youtube.com/playlist?list=PLahXOQn-bremYbN7GA8H9YN_m8AlVHCz1) and were viewed 587 times as of March 31st 2022. Some presentations are also available online on the general EURAD website (https://www.ejp-eurad.eu/publications).

The School of RWM is planning three more courses for 2022: one on uncertainty management, one on the EURAD Roadmap Domain Insights and the State of Knowledge, and one on safety case production and review. PREDIS will organize its first training course in May 2022.

As of February 28th 2022, the School of RWM has organized twelve webinars, all part of the EURAD Lunch & Learn sessions. These are short and informal sessions, 30 min of presentation followed by 30 min of discussion, providing information on a specific topic to a broad audience. All Lunch & Learn sessions are open to all and free of registration costs. The recordings of these webinars are made available online afterwards (https://www.youtube.com/playlist?listPLahXOQn-bremN911IEnOw8yAzQyuUR3ky). Table 1 provides a brief overview of the hosted webinars.

PREDIS launched its program of webinars in 2021. Webinars are a good opportunity for people to learn and

**Table 1.** Overview of webinars hosted by the School of Radioactive Waste Management.

| Title | Date | # attendees | # views (YouTube)* |
|---|---|---|---|
| Synergies of EURAD with the PREDIS project addressing predisposal waste treatment | 28/10/2020 | 30 | 62 |
| News from the German Site Selection Procedure | 25/11/2020 | 19 | 77 |
| Celebrating 20 years of the IGSC | 27/01/2021 | 45 | 34 |
| Knowledge Management in Nuclear Organizations | 24/02/2021 | 22 | 23 |
| The IGD-TP: European waste management organizations coordinating international R&D activities | 31/03/2021 | 19 | 57 |
| The next-generation scientific research for the safe management of radwaste – EURADSCIENCE | 28/04/2021 | 75 | 9 |
| Steps for Sharing (ERDO Association) | 26/05/2021 | 44 | 18 |
| The SITEX.Network | 30/06/2021 | 53 | 16 |
| EC-JRC activities on RWM and decommissioning | 29/09/2021 | 51 | 11 |
| US Nuclear Waste Management and Disposal Strategies | 06/10/2021 | 107 | 17 |
| News on the siting process in Italy | 27/10/2021 | 57 | 10 |
| Methods of information and knowledge transfer regarding final disposal of radwaste | 23/02/2022 | 133 | 5 |

(*) As of March 31st 2022.

discuss various topics related to predisposal. They are open to partners and stakeholders, have a duration of 3 hours, and are organized every 2 months, approximately.

As of March 1st 2022, 11 webinars have been organized. The number of attendees varied between 70 and 120. Approximately half of the attendees in each event came from outside the PREDIS community. The webinar topics were aligned with the subjects of the PREDIS work packages, covering both strategic and technical WPs. The topics are summarized in Table 2.

Videos and summary memos are available on the PREDIS webpage (https://predis-h2020.eu/events/).

### 4.3 Organization of Ph.D. events

Three events were organized specifically for the about 60 Ph.D. EURAD students: the EURAD Ph.D. Event N° 1 and a specific Ph.D. session during the first and second EURAD Annual Event.

The EURAD Ph.D. Event N° 1 was organized on September 15th 2020, adjoining the "Introductory course on EURAD and RWM". For this event, all Ph.D. students contributing to EURAD were invited to present themselves and their research to the wider EURAD community. This event was the first opportunity for EURAD Ph.D. students to get to know each other and network with other Ph.D. students as well as experts in the field. During this event, 22 Ph.D. students presented their work.

In a follow-up to the EURAD Ph.D. Event N° 1 a specific session highlighting Ph.D. research in EURAD was organized during the first EURAD Annual Event on March 17th 2021. During this half-day online session, six Ph.D. students presented the Ph.D. research (including their own) performed in their technical EURAD WP. These presentations were followed by a short debate during which EURAD experts could discuss the work that was performed with the Ph.D. students directly.

Recently, during the second EURAD Annual Event (March 30th 2022), there was also a Ph.D. student session. This was a hybrid session in which 15 EURAD and 3 PREDIS Ph.D. students presented themselves and their research to the wider EURAD community. These presentations were followed by an informal networking event where the students had the opportunity to discuss amongst themselves and experts in the field of RWM. For the online attendees, an online networking platform was provided.

Up to now, more than 30 students have joined the PREDIS students' community. Three events have been organized up to March 2022. At the PREDIS 2nd Consortium meeting, held online in May 2021, most students introduced themselves and gave summaries of the technical work they are undertaking within PREDIS.

The first student workshop was held in October 2021. The workshop aimed to discuss with the students how they could organize themselves, gather their expectations from the KM work package, obtain ideas on how to organize their participation in future workshops, and ask for their views on the best communication tools to use in order to reach their generation.

The second student workshop was held virtually in February 2022. The meeting started with an update on WP3 activities and a presentation on new students. It was followed by an ice-breaker session to talk about issues

**Table 2.** Overview of webinars hosted by the PREDIS EU project.

| Title | Date | # registrants | # attendees* | # views (YouTube) |
|---|---|---|---|---|
| Innovations in cemented waste package monitoring and storage | Jan, 2021 | 127 | 135 | |
| Innovations in metallic material treatment and conditioning | Feb, 2021 | 138 | 106 | 10** |
| Innovations in solid organic waste treatment and conditioning | Mar, 2021 | 168 | 113 | 8** |
| Innovations in liquid organic waste treatment and conditioning | Mar, 2021 | 205 | 124 | 3** |
| Waste Acceptance Criteria (WAC) 1 – information and resources | Apr, 2021 | 208 | 177 | 20** |
| Waste Acceptance Criteria (WAC) 2 – needs, challenges, and opportunities | May, 2021 | 173 | 119 | 19** |
| Gap Analysis and defining the baseline Strategic Research Agenda | Sep, 2021 | >100 | 96 | |
| Metallic and organic waste characterization (together with CHANCE project) | Oct, 2021 | 120 | 106 | 7** |
| Development of geopolymers for pre-disposal waste management | Oct, 2021 | 129 | 99 | |
| Knowledge Management | Nov, 2021 | 126 | 86 | |
| Digital Twins for Waste Management | Feb, 2022 | 150 | 147 | |

(*)At maximum, not necessarily for full webinar. (**)At date 10th March 2022.

not related to PREDIS, i.e., the festivities in the period December 2021–January 2022. Three students gave a presentation, one of them on his work within the project and the other two on their mobility actions.

### 4.4 Launch of the Mobility Programme

The EURAD and PREDIS Mobility Programmes were officially launched on April 8th 2020, and September 1st 2021, respectively.

Applications are filed in an online platform, allowing easy application and evaluation (see https://pro.evalato.com/2185 and https://app.evalato.com/program/3346/). As of March 31st 2022, eight applications have been approved in EURAD (one is still under review) and nine in PREDIS. In the case of EURAD, two mobility actions have been completed. Unfortunately, due to COVID-19, both Mobility Programmes have not been exploited to the expected extent.

To support the Mobility Programme and to encourage potential applicants, a list of available infrastructures at EURAD partner organizations was published on the School of RWM website (https://euradschool.eu/infrastructures/). This list aims to provide an overview of the available infrastructures and associated expertise within EURAD, which should facilitate applying for the Mobility Programme.

## 5 Conclusions

Adequate and effective Knowledge Management is crucial to ensure safe and sustainable radioactive waste management from pre-disposal disposal to the post-closure period. Therefore, KM is also an essential part of the PREDIS and EURAD projects, which both dedicate several training and mobility initiatives to enhance KM and competence building, as described in this paper.

The EURAD School of Radiation Waste Management was successfully launched in December 2020, and the Knowledge Management Team of PREDIS started in September 2021.

Their main deliverables are:

(i) to compose a diverse portfolio of tailored basic and specialized training courses for the end-users within EURAD and PREDIS, taking stock of and building upon already existing courses and creating new courses to bridge the identified gaps, and

(ii) to organize a mobility program that provides access to dedicated infrastructures associated with the Mandated Actors/Linked Third Parties/End-Users within the projects. These mobility actions can be seen either as a complementary action after one or more training course(s) (enabling hands-on training related to the experimental program executed within EURAD and PREDIS) or can be part of the Continuous

Professional Development (CPD) of experienced personnel involved in RWM and predisposal of RW.

Furthermore, actions towards students and junior researchers, being the future workforce and management in the PREDIS and EURAD communities, enhancing networking and integration in and between their respective communities, are given great attention. Public websites providing easily accessible information are set up and serve as a general entry point for further guidance.

As such, EURAD and PREDIS assist their end-users, students, and partners in acquiring, developing, disseminating, using, sharing, and preserving knowledge and skills. Its initiatives are based on their needs to assure effective knowledge transfer and competence building. As its initiatives are needs-driven, the scope of both programs is dynamic and can be broadened in the future based on the changing needs. These similar initiatives and harmonized approaches in both projects will facilitate future common actions. In the future EURAD-2 proposal, PREDIS will be taken up in the European Joint Programme EURAD, and thus all training and mobility activities in the field of RWM will become unified. Finally, both projects could focus more on online courses and content. This allows them to reach more learners and spread knowledge more efficiently for training activities.

## Conflict of interests

The authors declare that they have no competing interests to report.

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## Data availability statement

This article has no associated data generated and/or analysed.

## Author contribution statement

NB, AV, and VH wrote and reviewed the manuscript. MC reviewed the manuscript. All authors agree on the publication of this manuscript.

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FISA 2022
EURADWASTE'22

# JOINT CONCLUSION FISA 2022 / EURADWASTE ’22

Co-chair: Philippe STOHR (FR, CEA)

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# KEYNOTE: JRC'S ROLE IN EURATOM RESEARCH AND TRAINING AND HORIZON EUROPE

**Bernard MAGENHANN** (EC, DG JRC), Deputy Director-General of the Joint Research Centre

Monsieur le Président de la Région Auvergne-Rhône-Alpes ,

Monsieur le Président de la Nuclear Valley,

Honorables invités,

Mesdames et Messieurs:

Je suis très heureux de **co-présider avec Philippe Stohr du CEA** cette **session de clôture conjointe** des conférences FISA et EURADWASTE 2022.

Je suis convaincu qu'il est **essentiel de réunir la communauté scientifique** dans le cadre de ces conférences pour façonner <u>l'avenir de la recherche nucléaire européenne.</u>

Je voudrais remercier en particulier **la région Auvergne-Rhône-Alpes** pour l'accueil de cet événement, le **Commissariat pour l'énergie atomique** et à la **Société française d'énergie nucléaire** pour la qualité de l'organisation en coopération avec les services de la Commission européenne, ainsi que tous les participants qui y ont assisté.

**Je voudrais débuter mon intervention avec qq mots sur Centre Commun de Recherche de la Commission européenne – qui nous sommes et ce que nous faisons**

D'une manière très simplifiée, je dirais que nous sommes la Direction Générale scientifique de la Commission européenne. Nous délivrons aux directions générales de la Commission qui sont en charge de l'élaboration des politiques européennes, **des évidences scientifiques** qui leur permettent de développer des politiques plus pertinentes (mais cela est peut-être un peu prétentieux) en tout cas « mieux informées ».

Notre direction générale à aujourd'hui plus de 60 ans. Elle a été créée en tant que **Centre Commun de Recherche nucléaire par le traité Euratom. Elle est plus communément connue sous l'abréviation CCR (ou JRC en**

**anglais).** Au fil du temps, le CCR a élargi son champ de recherche initial – qui était à l'origine purement nucléaire - aux disciplines non nucléaires, qui couvrent **aujourd'hui plus ou moins 3/4 de notre programme de recherche.**

Nos activités scientifiques couvrent un **large éventail de politiques** telles que la croissance et l'innovation, L'énergie, les transports, le climat, l'espace, la sécurité et la migration, la santé… je vais m'arrêter là, je souhaitais simplement - par cette liste non exhaustive - montrer l'étendue de nos activités aux CCR. Et bien sûr je dois ajouter à cela la sûreté et la sécurité nucléaires.

Comme je l'ai dit notre rôle est le soutien des politiques européennes **sur base de données scientifiques, et ce** tout au long du cycle politique – de leur conception à leur implémentation.

Dans un monde, une Europe ou certaines politiques dans un même domaine peuvent être conflictuelles (entreprises, l'environnement ou l'agriculture pour donner quelques domaines ou des frictions peuvent apparaître), **nos analyses scientifiques et les résultats de notre recherche** se veulent indépendants et permettent d'éclairer les concepteurs de nouvelles politiques européennes sur les grands défis auxquels nos sociétés sont aujourd'hui confrontées. ET si vous etes intéressés, en allant **sur internet**, vous constaterez que nos études, rapports et résultats scientifiques ont une reconnaissance européenne, mais aussi internationale.

Le CCR est **financé** par le programme-cadre de l'UE pour la recherche et l'innovation: **Horizon Europe**, et par son **programme Euratom** de recherche et de formation pour toutes nos activités dans le domaine nucléaire. Je souhaiterais également mentionner le nouveau programme de démantèlement nucléaire et de gestion des déchets, programme qui a été initié dans le dernier cadre financier pluri-annuel

## Quel est le rôle du CCR dans le programme Euratom de recherche et de formation ?

Le traité Euratom charge la Commission de **promouvoir et de faciliter la recherche nucléaire dans les États membres et la mise en œuvre d'un programme communautaire** de recherche et de formation, ceci au travers d'actions dites directes et indirectes.

Les actions indirectes représentent des financements octroyés par la Commission européenne par exemple à des projets d'institutions de recherche dans les états membres. Ces actions indirectes sont gérées par nos collègues de la direction générale « Recherche et innovation ».

Les actions directes sont nos propres activités de recherche, celles du CCR, réalisées au niveau européen.

Et bien entendu, nous travaillons « main dans la main » avec nos collègues de la Direction Générale « recherche et innovation » pour optimiser l'impact de la recherche qu'elle soit financée sous forme d'actions directes ou indirectes.

S'agissant de nos propres activités de recherche (je parle ici des actions directes), nous disposons de notre propre capacité de recherche – avec un large spectre d'experts dans le domaine nucléaire qui travaillent de façon supranationale et indépendante et par conséquent ne sont pas liés aux intérêts par exemple des opérateurs privés ou nationaux.

Au sein du CCR, nous employons environ 350 scientifiques, techniciens et personnel administratif sur nos quatre sites de Petten (NL), Karlsruhe (D), Geel (BE) et Ispra (IT).

Si j'en viens à présent aux principaux objectifs de nos travaux de recherche, ils peuvent être regroupé en trois blocs principaux :

- **améliorer et soutenir la sûreté, la sécurité, les garanties et la radioprotection nucléaires.** Il s'agit là d'applications qui vont au-delà du domaine de production d'énergie, et qui par exemple touche des domaines comme la santé ou l'espace.

- **Le deuxieme bloc sera de Maintenir et développer l'expertise et les compétences dans le domaine nucléaire** au sein de la Communauté;

- **Le troisieme de Soutenir la politique de l'Union et de ses États membres** dans ce domaine

Actuellement, notre programme de travail 2021-2022 est structuré en quelque 5 portefeuilles composés de 58 projets, répartis comme suit:

- 38 % de nos ressources sont dédiées à la sûreté nucléaire, la gestion des déchets radioactifs, le démantèlement et la préparation aux situations d'urgence *(emergency preparedness)*;

- 32 % pour la sécurité nucléaire, les garanties et la non-prolifération,

- 19 % aux normes de référence, à la science nucléaire et aux applications non énergétiques

- **Et enfin 11 % pour l'éducation**, la formation et la gestion des connaissances.

Une bonne partie de ces ressources (comme je l'ai mentionné précédemment) est consacrée à apporter un **soutien direct et indépendant** aux politiques de l'Union en matière de sûreté nucléaire, de gestion des déchets radioactifs et de radioprotection.

Enfin, je souhaiterais également mentionner la contribution du CCR au rapport d'évaluation technique de l'énergie nucléaire au regard du critère «**ne pas causer de préjudice important** » (do not significant harm) du règlement sur la taxonomie, qui a conduit la Commission européenne à proposer l'inclusion de l'énergie nucléaire dans la taxonomie.

**Je voudrais à présent dire quelques mots d'introduction sur une nouvelle Stratégie nucléaire du CCR qui est actuellement en cours d'élaboration.**

Pourquoi développer une stratégie nucléaire?

Une première bonne raison est que nous n'en avions pas ! Ceci est devenu nécessaire dans un contexte politique et j'ajouterais géopolitique qui évolue rapidement et requiert toute notre attention au niveau européen. Aussi développer une telle stratégie aujourd'hui est une **opportunité pour revoir ce que nous faisons, comment nous le faisons et comment optimiser l'impact de notre travail.**

La deuxième raison est que malgré le **« nouveau *momentum* Nucléaire** » que nous connaissons  aujourd'hui, le législateur a décidé d'une réduction budgétaire significative du programme Euratom de recherche et de formation pour la période 2021-2025. Et cette réduction aura de profondes répercussions sur les ressources disponibles et la capacité opérationnelle de recherche nucléaire du CCR.

Notre stratégie vise donc à définir ou recadrer les priorités de nos actions de recherche au niveau européen et d'assurer que nous faisons « ce qui est utile » et ce qui a un impact » au niveau européen.

Notre stratégie se bases sur 5 piliers que nous pensons essentiels et qui d'ailleurs sont souvent interdépendants :

- **Une réorientation de nos activités** tenant compte de nos obligations – notre mandat règlementaire – mais aussi des applications nouvelles à la fois dans le domaine classique de l'énergie, mais également dans les autres domaines politiques (j'ai mentionné tout à l'heure « la santé »)

- Une **rationalisation et utilisation plus efficace de nos infrastructures** de recherche : nous souhaitons notamment permettre aux organisations de recherche nationales de les utiliser davantage sur des projets que nous aurions définis ensemble.

- **Les compétences** et l'alignement de ces dernières aux activités clés de notre nouvelle stratégie

- Une gestion / connexion plus **stratégiques à nos principaux partenaires**

- Une meilleure communication de qui nous sommes et ce que nous faisons.

Comme je l'ai mentionné précédemment, cette stratégie est en cours de développement et devrait être finalisée dans les tous prochain mois. Elle supportera notre programme de travail 2023/2024.

**Je souhaiterais à présent vous donner quelques informations sur nos Collaboration / Activités / infrastructures**

Cette **collaboration** avec les partenaires extérieurs est essentielle.

Elle nous permet notamment de nous assurer **nos activités sont bien alignées aux les activités de recherche et de formation menées dans les États membres** et qu'elles les complètent. Pour ce faire, nous interagissons et travaillons en permanence avec les principaux instituts et réseaux scientifiques et de recherche dans l'UE et à l'étranger.

- Par exemple, nous:

– Nous concluons ou faisons partie d'accords avec des instituts de recherche des États membres, de pays tiers, ainsi qu'avec des organisations internationales, telles que l'Agence Internationale de l'Énergie Atomique;

– Comme nous sommes aujourd'hui à Lyon, et sous la présidence française du Conseil, je voudrais mentionner ici la collaboration longue et fructueuse avec le Commissariat pour l'énergie atomique, tant dans le domaine de la sûreté nucléaire que dans celui de la sécurité nucléaire, ainsi que l'excellente collaboration avec l'Institut de radioprotection et de sûreté nucléaire, que nous prévoyons de poursuivre.

– Mais il y a beaucoup d'autres accord de collaboration avec les etats membres de l'UE

Ces initiatives de collaborations sont – pour nous – **fondamentales.** Elles contribuent à enrichir nos approches et choix stratégiques et influencent notre programme de travail au niveau européen.

**S'agissant maintenant de nos activités, je souhaiterais vous donner 5 exemples concrets**

- Nous travaillons dans **la recherche sur le vieillissement et la dégradation des matériaux**, dans le contexte de l'exploitation à long terme des centrales nucléaires;

- Nous sommes en charge du **système européen de surveillance de la radioactivité dans l'environnement** (EURDEP) et le **système européen de notification rapide et d'échange d'informations en cas d'urgence radiologique** (ECURIE),

- Nous contribuons à garantir la **sûreté du cycle du combustible nucléaire en étudiant les combustibles tolérants aux accidents;**

- Dans le domaine des conceptions innovantes, nous travaillons sur **la sureté des petites filières de réacteurs modulaires** et sur les systèmes et combustibles de nouvelle génération

- Enfin, nous sommes également actif dans les domaines de la gestion des connaissances, de l'éducation et de la formation comprennent également des initiatives telles que:

    - Des intervention dans les écoles internationales et conférences;

    - Des initiatives européennes d'apprentissage en matière de démantèlement nucléaires et de restauration environnementale (ELINDER),

    - Nous gérons le Centre européen de formation à la sécurité nucléaire (EUSECTRA), où nous dispensons un enseignement et une formation aux agents de première ligne et aux inspecteurs nucléaires d'Euratom et de l'AIEA.

Enfin s'agissant de nos infrastructures dont l'utilisation dans un proche avenir – je l'espère – pourra être plus amplement partagé avec la communauté nucléaire. Certaines de ces installations sont uniques au monde. 3 exemples

Nous disposons en effet

- des laboratoires de matériaux sur notre site de Petten (aux pays bas), qui **permettent de tester les matériaux dans des environnements défavorables,**

- les accélérateurs linéaires et tandem qui font de notre site de Geel (en Belgique) l'un des rares laboratoires au monde capables de produire des données neutroniques exactes.

- **les cellules chaudes ou les laboratoires d'actinides mineurs**, à Karlsruhe, qui permettent de mener des recherches sur des échantillons de combustible nucléaire irradié «réels»;.

## Un mot à présent sur la Participation du CCR aux actions indirectes

L'objectif principal de cette conférence est de présenter les progrès réalisés et les principales réalisations des projets Euratom de recherche et de formation menés au cours des dernières années, ainsi que d'explorer les perspectives d'avenir.

Les **actions indirectes** du programme ont soutenu environ 90 projets de fission nucléaire dans le dernier programme-cadre 2014-2020**. Le JRC a participé à 39 de ces projets.**

Les thèmes les plus importants des projets auxquels nous avons participés sont la **sécurité des systèmes conventionnels et la sécurité des systèmes avancés.** Nous avons également participé à des projets dans le domaine de **l'éducation, de la formation et des données nucléaires.**

L'objectif de la participation du CCR aux actions indirectes est de **compléter les initiatives des États membres et d'obtenir des synergies pour le programme d'actions directes du CCR afin de maximiser l'impact obtenu.**

Je souhaiterais conclure mon intervention en vous donnant un aperçu de nos Principaux défis

Compte tenu des défis croissants et de l'évolution rapide du contexte politique, je pense qu'il est nécessaire d'investir davantage dans la recherche nucléaire à plusieurs niveaux:

- le changement climatique,
- l'autonomie énergétique,
- la sécurité européenne et mondiale
- l'innovation technologique dans les domaines non énergie comme par exemple la santé

Pour garantir que l'utilisation de l'énergie nucléaire dans les États membres qui ont décidé de l'intégrer dans leur bouquet énergétique soit sûre, sécurisée et durable à long terme**, l'Europe doit garantir une approche cohérente en matière de sûreté, de sécurité**. Cela doit reposer sur des données scientifiques solides, des mesures et des méthodes nucléaires fiables et des outils appropriés.

En même temps, cela ne peut être garanti que si les compétences et le leadership technologique sont maintenus au sein de l'UE par le biais de la recherche, de l'éducation, de la formation et de la gestion des connaissances.

J'arrive à la fin de ma présentation et souhaiterais très chaleureusement vous remercier pour votre attention.

**Hans FORSSTROM (Sweden), Expert, General Rapporteur**

FISA 2022
EURADWASTE'22

# Participation & Audience

*30 May – 3 June 2022, Lyon, France*



## A global audience

**550+** Participants, **49** Nationalities

**Euratom4U** iOS Android App. & desktop version

FISA 2022
EURADWASTE'22

**51** Companies

**35** Universities

**29** Gov. Organisations

**28** Research Centres

**13** NGOs

## Young Generation goes nuclear!

FISA 2022
EURADWASTE'22

ENS-YGN **High-Level Opening**

**+150** participants

Open Call MSc/PhD/R&D Awards Competition, Nuclear Innovation Prize, Poster Exhibition, and ENEN PhD Event & Prize

**3** ENS-YGN Workshops, Meet & Match, **+500** Attendees



EURADWASTE'22

30 May - 3 June 2022
Lyon, France

# EURADWASTE´22
# KEY MESSAGES AND FUTURE PERSPECTIVES

Hans Forsström, SKB International AB

## Developments since EURADWASTE´19

- Radioactive waste disposal remains a challenge in many countries
- Good progress in GDR development
  - Finland, Sweden, France close to operation or start of construction
  - Site selection process developing in Switzerland, UK, Czech Republic, Canada
  - Progress in the restarted siting programme in Germany
- EURAD joint programme and PREDIS project up and running






## Success factors in a DGR program

Governance and interactions between stakeholders

Why ? Who? How ? ...

Roadmap and milestones

Clear decisional process, What and When

R&D programme

Research and Development Programme to follow the roadmap

## Research, development and demonstration

- Instrumental for the development of GDR designs and their safety assessment. Scientific-technical basis exists.
- Mainly funded from the WMO with clear RD&D programmes
- Much international cooperation since the 70ies (Stripa project)
- Cooperation between WMO on RD&D within IGD-TP
- International projects tend to have more trust than national
- EC-supported activities from several small projects (until 2018) to one large joint project EURAD (and PREDIS)



## European Joint Programme on Radioactive Waste Management - EURAD

- Research needs identified through three colleges, WMOs, Expertise organizations and Research entities.
- Roadmap, Theme overviews and Strategic research agenda (to be updated)
- Broad participation from advanced and less advanced programmes, and from research organisations and civil society
- Step change compared to earlier EC co-funded projects
  - 10 R&D WPs, 2 Strategic studies WPs and 3 Knowledge management WPs within one EJP
- Administrative structure well developed and works well. Important to keep the momentum
- Project selected in two waves, the 2nd within EURAD
- EURAD complemented with a project on Pre-disposal waste management, PREDIS to be merged into EURAD-2
- Results from EURAD WPs and from PREDIS presented at this conference

## European Joint Programme on Radioactive Waste Management EURAD
## Advantages to earlier EC-projects

- Increased cooperation and enhanced information exchange.
- Better understanding of the role of specific R&D in the total system (Specialists – system perspective)
- Good interaction between different disciplines
- Excellent platform for early-stage programmes to participate and learn
- Possibilities for transfer of knowledge from advanced programmes to less advanced programmes
- Potential synergies between countries with small inventories and those with large
- Involves many young researchers
- Enhances the mutual understanding and trust between partners
- More efficient management. Simpler for the WP-leaders



## EURAD Colleges

- To provide input to the definition of the EURAD programme three separate colleges are organized.
  - IGD-TP (Implementing geological disposal – technology platform)
    Many WMOs and other organisations sharing the vision First GDR in operation 2025
  - SITEX (Sustainable network for Independent Technical EXpertise on radioactive waste management)
    Organisations providing expertise to regulators and Civil Society.
  - EuRadScience
    Research entities involved in RWM R&D
- Each college prepares it's own SRA as input to the preparation of EURAD SRA

## EURADWASTE´22 –Three sessions

1. Collaborative Research, Development and Demonstration in Radioactive Waste Management
2. Strategic Research Studies in Radioactive Waste Management
3. Knowledge Management in Radioactive Waste Management



## Collaborative Research, Development and Demonstration in Radioactive Waste Management

- The progress of the RD&D projects within EURAD and PREDIS and some earlier projects were briefly presented, covering e.g. waste characterization, near field retention of radionuclides, evolution of engineered barriers over time and spent fuel management.
- Appetizers for posters.
- Interesting and useful results
- The connection to the needs of the safety assessment and design was not obvious in most presentations
- Important for the revised SRA to bring this connection back

## Strategic Research Studies in Radioactive Waste Management

- Broad presentations were given on the EURAD strategic studies on uncertainty management (UMAN) and cradle-to-grave management of odd wastes or small inventories (ROUTES), and of the work of DG ENER and IAEA, as well as the ERDO project.
- UMAN tries to identify uncertainties at different stages of programme development and find methods to deal with them, including being prepared for the unknown. Important to connect the uncertainty to the risk.
- Strategic studies are based on networking and the networking works well when common needs can be identified.
- An important component of the strategic studies is the involvement of the Civil Society providing good and critical input. But who are the Civil Society. A challenge for EURAD to involve a broad cross section.
- Good steps were shown towards close cooperation and coordination between IAEA and EURAD and possibly with NEA. Complementarity in their work.



## Knowledge Management

- The time period for a GDR is more than 100 years (plus long term)
- Ensuring knowledge over this period is thus of paramount importance
- KM has two components, information and know how. Information can be documented. Know how requires continuity and successive transfer.
- Each WMO will have it’s own KM focused on the implementation and long-term safety case, and background material
- But how to develop at an international level a broader KM available for other users

## Knowledge Management (continued)

- The three components of KM in EURAD and PREDIS were presented and discussed:
  - Training and mobility
  - State of knowledge documentation
  - Guidance based on experience

Roadmap for RWM implementation

7 Themes to be covered

Many scientific domains needed

Guidance documents. How to

State of knowledge documents. What do we know

- IAEA and NEA presented similar work at a different level. Opportunity for synergies.
- How to maintain information base. IAEA?



## Future RD&D

- Although some programmes are close to licence approval future research will be needed to:
  - Improve and optimize designs and operation. Simplifications
  - Adapt to the conditions of new facilities
  - Take new and improved developments in other fields into account
  - Keep a watching brief on new scientific knowledge
  - Ensure availability of capable staff and availability of R&D capacity
- Some areas will be deemphasised. Position papers or common opinion from EURAD based on State of knowledge reports?
- WMO funding might decrease over time.

## Looking ahead

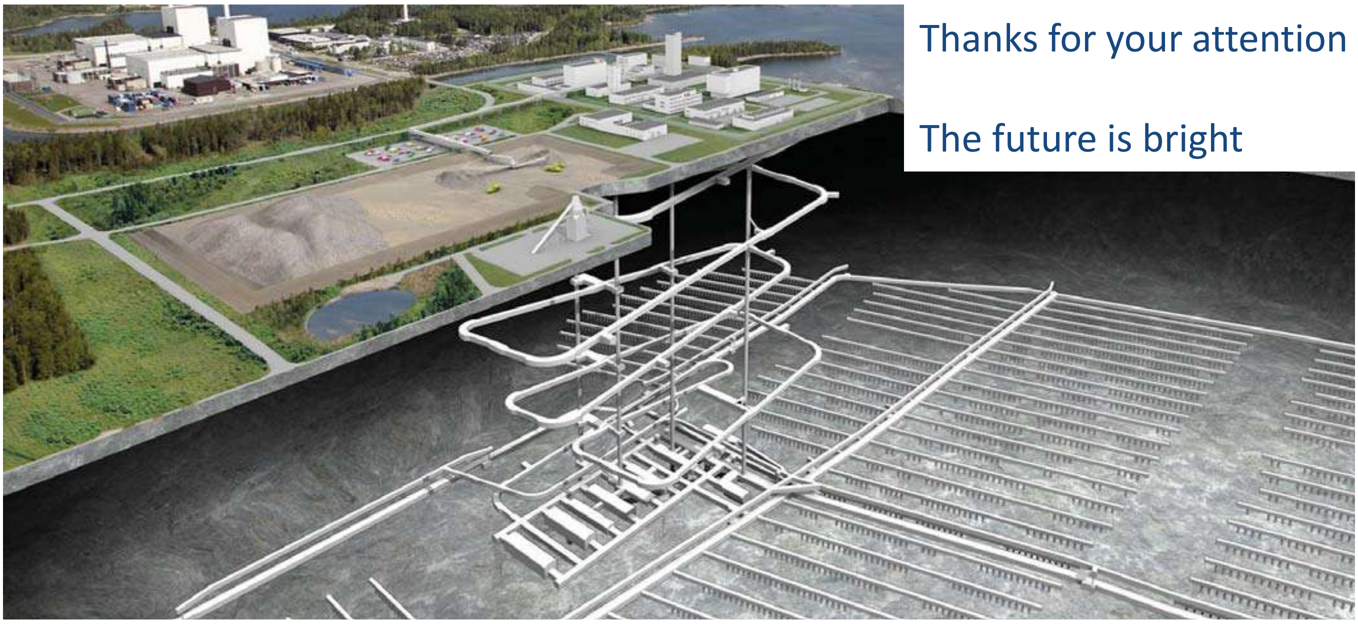
- EU-supported R&D will continue to be of importance
- EURAD-2 will include EURAD and PREDIS, i.e. cradle to grave approach
- Input for shaping EURAD-2:
  - Basic structure
  - Updated SRA with strong input from the different users, based on understanding the detailed needs of different MS, including advanced and early/medium stage programmes and small inventory programmes.
  - Close some areas based on “how good is good enough for implementation”
  - New areas, e.g. IT-based technologies for repository implementation
  - Ensure inclusiveness, new-comers to the programme, waste producers, regulators
- Stimulate even more active engagement by advanced programmes, not least in developing KM and guidance and becoming drivers within communities of practice.



## FISA - EURADWASTE

- Excellent that the two communities meet at the same time
- Did we really meet?
- Apart from the political opening session this is the only session where we are both in the same room.
- New reactors and systems have been discussed in FISA – even their impact on waste management – but not with RWM people.

- A clear message from EURADWASTE:
  Don’t develop new systems without ensuring beforehand that the waste can be taken care of .



Thanks for your attention

The future is bright

# KEYNOTE: RÉGION AUVERGNE-RHÔNE-ALPES, PROMOTING INNOVATION ECOSYSTEMS AND STRATEGIC CLUSTERS

**Jean-Louis GUYADER** (FR, AURA) on behalf of **Laurent WAUQUIEZ** (FR, AURA), President of the Region Auvergne-Rhône-Alpes

Bonjour à toutes et à tous, au nom du Président Wauquiez j'ai le plaisir de vous accueillir à l'hôtel de région. Je m'appelle Jean Louis Guyader, je suis conseiller régional élu dans le département de l'AIN et président de la commission enseignement supérieur, recherche, numérique et innovation.

Hello everyone, on behalf of President Wauquiez I have the pleasure to welcome you to the hotel de Region. My name is Jean Louis Guyader, I am president of the higher education, research, digital and innovation commission.

La Présidence française de l'Union Européenne permet que, de nombreuses manifestions européennes soient organisées en France. Je m'en réjouis !

C'est le cas de la 10ème édition des conférences FISA et EURADWASTE c'est l'occasion de faire le point sur les résultats des recherches scientifique, des innovations associées et de formations soutenues par le programme de recherche européen Euratom, sur la sûreté des systèmes de réacteurs nucléaires fission (FISA 2022, Fission SAfety) et sur la gestion des déchets radioactifs (EURADWASTE '22).

The French Presidency of the European Union allows many European events to be organised in France. I am delighted about that!

This is the case of the 10th edition of the FISA and EURADWASTE conferences it is an opportunity to present results of research, associated innovations, supported by the European research program Euratom, on the safety of fission nuclear reactor systems (FISA 2022, Fission SAfety) and on the management of radioactive waste (EURADWASTE '22).

VOUS NE VOUS ETES PAS TROMPES de LIEU: Auvergne Rhône-Alpes est la première région productrice d'électricité nucléaire de France et d'Europe. Elle fournit 22,4% de l'électricité nucléaire française avec 4 sites de production (Tricastin dans la Drôme, Saint-Alban en Isère, Cruas en Ardèche et le Bugey dans l'Ain) et 14 réacteurs nucléaires.

YOU ARE NOT MISTAKEN in choosing Auvergne Rhône-Alpes; it is the leading nuclear Electricity power producing region in France and Europe. It supplies 22.4% of French nuclear electricity with 4 production sites (Tricastin ôme, Saint-Alban, Cruas and Bugey), 14 nuclear reactors are working in this region.

The headquarters of the strategic decision-making centres of major players such as EDF and Framatome, but also of the largest nuclear site in Europe with ORANO Tricastin, are present in the Region.

Les sièges des centres de décisions stratégiques de grands acteurs tels qu'EDF et Framatome, mais également du plus grand site nucléaire d'Europe avec ORANO Tricastin, sont présents en Région. Orano Tricastin est entre autres reconnu à l'international sur le cycle du combustible nucléaire notamment son recyclage. Notre région est donc au cœur des enjeux et projets pour l'avenir de la filière.

Près de **1 200 entreprises** travaillent pour cette filière en région. Pour **près de 650 d'entre elles**, le nucléaire est une activité cœur de cible. Cela fait d'Auvergne-Rhône-Alpes la 2e région française en termes d'emplois dans la filière nucléaire, avec **plus de 48 000 emplois.**

Nearly 1,200 companies work for this sector in the regions. For nearly 650 of them, nuclear power is a core target activity. This makes Auvergne-Rhône-Alpes the 2nd French region in terms of jobs in the nuclear sector, with more than 48,000 jobs.

Auvergne-Rhône-Alpes est une des régions européennes de premier plan en matière d'enseignement supérieur, de recherche et d'innovation.

La région dispose de sept universités et d'une quarantaine de Grandes écoles publiques et privées.

350 000 étudiants poursuivent leurs études en Auvergne-Rhône-Alpes, dont près de 230 000 dans les universités et plus de 70 000 dans les Grandes écoles.

**18 formations, du Bac au Bac+5, sont dédiées au nucléaire en Auvergne Rhône-Alpes.**

Auvergne-Rhône-Alpes is one of Europe's leading regions in terms of higher education, research and innovation.

The region has seven universities and about forty public and private grandes écoles.

350,000 students continue their studies in Auvergne-Rhône-Alpes, including nearly 230,000 in universities and more than 70,000 in Grandes Ecoles.

18 graduates courses programs are dedicated to nuclear power in Auvergne Rhône-Alpes.

The Region supports local actors to cover the needs of the nuclear sector in terms of recruitment, particularly in the context of the Grand Carénage. I am more particularly the Grand Carénage de Bugey it is an industrial program focusing on investments and large-scale works

La Région accompagne les acteurs locaux pour couvrir les besoins de la filière Nucléaire en matière de recrutement notamment dans le cadre du **Grand Carénage**. Je suis plus particulièrement le Grand Carénage de Bugey c'est un programme industriel portant sur des investissements et des travaux de grande envergure. Les quatre centrales régionales sont concernées. La Région participe notamment aux groupes de travail proposés par les centrales nucléaires sur l'emploi/formation regroupant des représentants tels que la Préfecture, de la DREETS et le Pôle Emploi. Par ailleurs, la Région finance des formations et prend en charge la rémunération des demandeurs d'emploi et des futurs embauchés des entreprises de la filière nucléaire.

Auvergne-Rhône-Alpes concentrates 14.3% of the national scientific production, it has more than 62,000 research staff, or 14.4% of the national workforce. In addition, the regional territory hosts 2 European organizations CERN and EPN, European Photon and Neutron Sciences Campus.

Several engineering schools and universities have research programs dedicated to nuclear power.

Auvergne-Rhône-Alpes concentre 14,3% de la production scientifique nationale, elle compte plus de 62 000 personnels de recherche soit 14,4% des effectifs nationaux. De plus, le territoire régional accueille 2 organisations européennes le CERN et l'EPN, European Photon and Neutron Sciences Campus.

Plusieurs écoles d'ingénieurs et universités ont des programmes de recherche dédiés au nucléaire.

Par ailleurs, la Région bénéficie d'un écosystème de soutien à la Recherche-Développement-Innovation, composé de pôles de compétitivité dont **Nuclear Valley**, de Sociétés d'Accélération de Transfert Technologiques, de vingt-trois Instituts Carnot, ….deux Instituts de Recherche Technologique, deux Instituts pour la Transition Energétique, et de nombreux clusters et centres d'excellence.

The Region supports the development of "training-research-innovation" continuums. The Region's main tools in terms of support for collaborative R&D are based on calls for projects such as the R&D Booster system (the ViDeNS project - Vibration Device Network on Structures - labeled by Nuclear Valley, aims to control structures),

La Région soutient le développement de continuums de compétitivité « formation-recherche-innovation ». Les principaux outils de la Région en matière de soutien à la R&D collaborative reposent sur des appels à projets tel que le dispositif R&D Booster (ex : le projet ViDeNS - Vibration Device Network on Structures- labellisé par Nuclear Valley, a pour objectif de contrôler les structures).

Enfin, la Région intervient également via le soutien à des programmes de transfert de technologie tel que le programme Usine Numérique Régionale. Ce programme est financé grâce à la Région et l'Union Européenne (Fonds FEDER). La région anime le réseau des partenaires de la transformation numérique, représentant près de 200 collaborateurs de terrain issus de différents organismes afin de cibler différents types d'entreprises : CCI, CMA, MEDEF, CPME, ENE, Minalogic, Digital League et Agence Auvergne-Rhône-Alpes Entreprises.

**Conclusion**

Dans le cadre de la transition énergétique, la France doit produire plus d'électricité décarbonée. Le nucléaire est en effet une source d'énergie bas carbone qui contribue à la production d'une électricité très faible en CO2. Il émet ainsi **70 fois moins de CO2 que le charbon, 40 fois moins que le gaz, 4 fois moins que le solaire, 2 fois moins que l'hydraulique** et **autant que l'éolien.**

As part of the energy transition, the France must produce more carbon-free electricity. Nuclear power is indeed a low-carbon energy source that contributes to the production of electricity that is very low in CO2. It emits 70 times less CO2 than coal, 40 times less than gas, 4 times less than solar, 2 times less than hydro and as much as wind.

Deux nouveaux EPR2 sont attendu en Région Auvergne-Rhône-Alpes, avec une mise en service prévue en 2035 et le début des chantiers en 2028. Il est aussi probable que les deux sites candidats Bugey et Tricastin soient pourvu à termes.

I wish you rich and fruitful work because the nuclear sector is absolutely vital in the coming world where electricity needs will be increased tenfold either in direct consumption or in the production of carbon-free hydrogen.

Je vous souhaite des travaux riches et fructueux car la filière Nucléaire est absolument vitale dans ce monde où les besoins en électricité seront décuplés soit en consommation directe soit en production d'hydrogène décarboné.

Thanks for attention

**Philippe FRANTZ (FR, NUCLEAR VALLEY), President of Nuclear Valley**

# NUCLEAR VALLEY

The French Nuclear competitiveness cluster

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Centre d'affaires du Pont Jean Richard
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L-B7.05 – 7è étage
196 Avenue Thiers - 69006 Lyon

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## Nuclear Valley : The only competitiveness cluster of the French nuclear industry

- **Who we are :** A parapublic organization financed by the "Direction Générale des Entreprises", "Direction Générale de l'Armement" and local authorities (Auvergne Rhône Alpes and Bourgogne Franche Comté Regional Councils, "Grand Chalon" and "Communauté Urbaine Creusot-Montceau")

- **Our status « Competitiveness cluster » :** label granted by the Prime Minister to an association based in region, for 4 years, regarding to the goals of the Public authorities and the industrial sector related to the structure

- **Our missions :**
  - Encourage innovation, particularly in SMEs, by means of collaborative research projects which qualify for public funding
  - Expand synergy and business cooperation between Nuclear Valley members
  - Work towards the setting up of training courses aligned with the Nuclear sector requirements

2

## Nuclear Valley today


**+370** MEMBERS

**+ 320** Labelled projects

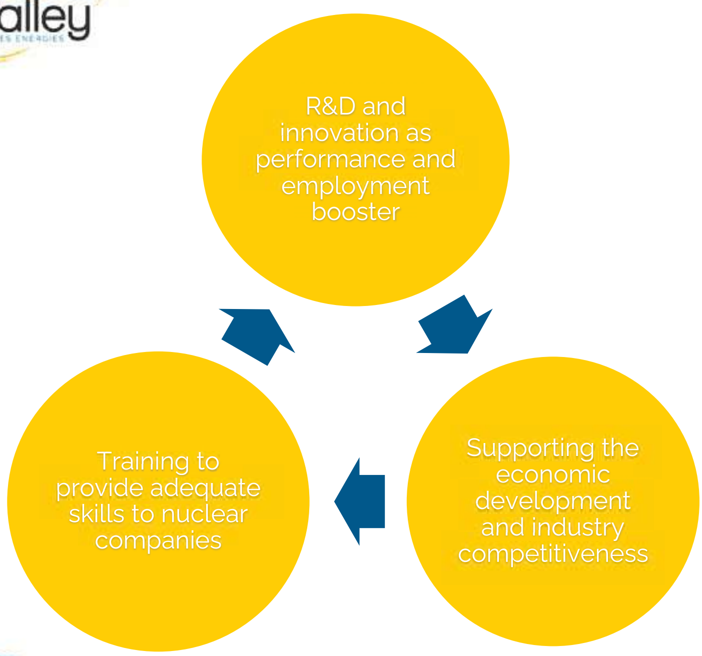
**+200** Financed projects

**+2500** BtoB meetings

- ✓ 48% SMEs
- ✓ 17% medium-sized companies
- ✓ 16% large companies
- ✓ 7% training schools
- ✓ 12% others (associations, competitiveness clusters, foundations, etc.)

3

## Our project « Ambition 2022 »




- A project and actions for R&D, innovation, development, growth and training
- Three pillars & service offers to achieve this ambition.

4

# A R&D roadmap based on 6 technical topics

Engineering, process & Equipment supply

Operation and maintenance

Back-end nuclear cycle : decommissioning, recycling and waste storage

Newbuilds and Civil Works

Medical Nuclear - Radiation Protection

Digital

# « France-Relance » final assessment :

- *Modernisation, R&D*
- *Nuclear skills strengthening*

# "Modernisation- R&D " and « Nuclear skills strengthening » Results of the recovery plan : France Relance

- More than **240 projects** submitted (over €1 billion )
- **141 winning projects** (40% in the AuRA and BFC regions)
- **472 M€ of investments** supported including **146 M€** from the State
- A total of **€1.18 billion** profits (€1 invested generates €2.5 for the ecosystem)

Investment amounts of the two support funds France Relance by region and the funds received (in EUR million)


| | |
|---|---|
| Total investment amount of the winning projects of the Call for Projects « Modernisation - R&D » | Total investment amount of the winning projects of the Call for Project « Nuclear skills strengthening » |
| The funds obtained for the Call for Projects « Modernisation - R&D » | The funds obtained for the Call for Project « Nuclear skills strengthening » |

Number of winning projects by region


**Winners** of the Call for Proposal « Modernisation - R&D »

**Winners** of the Call for Proposal « Nuclear Skills strengthening »

## Key figures of the nuclear section of "France Relance" from the Nuclear Valley's perspective

**Number of projects labelled by NV**

**57**

total investment amount of the labelled projects

184 M€

**Number of France Relance projects instructed by NV**

103

**Number of projects supported**

**18**

total investment amount of the projects supported

76 M€

*These figures exclude all data from the Call For Proposal "Innovative solutions for the management of radioactive materials and waste and the search for alternatives to deep geological storage" included in the directed component of the fourth "Investments for the Future program".

## A cluster at the heart of the French nuclear ecosystem


## GIFEN : who are we ?

**The trade association of the French civil nuclear industry**

- **Bringing together French companies related to the nuclear energy production life cycle** : the 5 French nuclear operators (Andra, CEA, EDF, FRAMATOME, Orano), the supply chain from large groups to SMEs and other partner organisations
- **Covering all strategic issues**
- **Providing** common interest **services**
- **World Nuclear Exhibition's organiser**
- Working closely with French and foreign **public authorities**

**→ With the aim of achieving excellence in the nuclear industry**

**+ 310** **Industrial members**

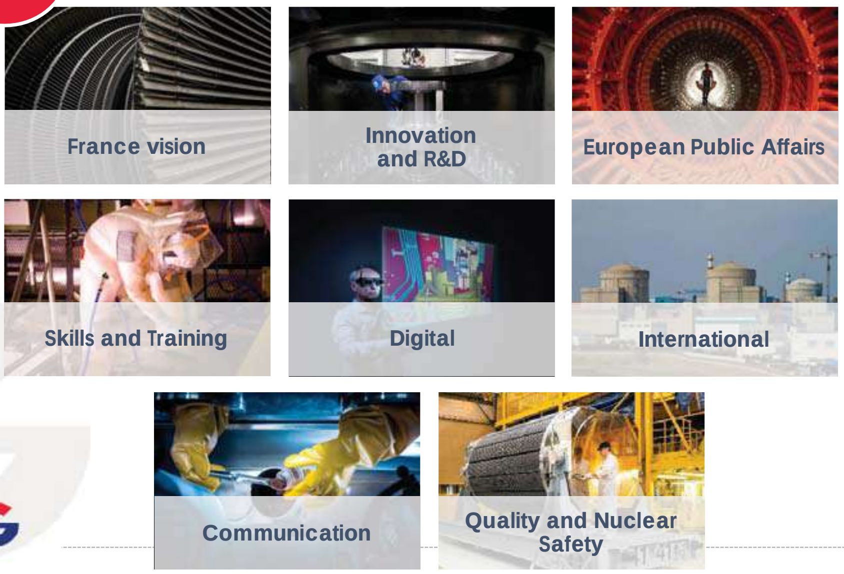
**+ 1 200** **Contributors**

**Collaborative mode**

2

# Gifen's strategic activities and major events

## 8 Committees




**Perspectives France Day**

- Once a year
- Annual presentation of major clients' projects over 10 years in the 16 business families
- Analysis of the load/resource balance

**French pavilions at international trade fairs and International roadshows**

- Meetings with targeted international countries

**Foreign Trade "Rendez-vous"**

- 3 times a year
- Presentation of the major international projects carried out by French and foreign operators

# CLOSING REMARKS FROM THE FRENCH PRESIDENCY

**Philippe Stohr** (CEA, France), Director of the Direction of Energies

Mesdames et Messieurs,

Chers collègues

Clore une conférence de l’ampleur de la conférence FISA-Euradwaste n’est jamais chose facile, tant il est vain de vouloir chercher à formuler en quelques mots des conclusions reflétant la richesse des échanges et l’énergie qui a pu se dégager durant les trois jours de la conférence. Aussi je vais m’employer à vous donner quelques messages que j’espère concis et clairs et que je veux porteurs d’espoir et d’enthousiasme.

Tour d’abord, ainsi que plusieurs d’entre vous l’ont déjà fait, je voudrais rendre un hommage à Bernard Bigot. Au travers son remarquable parcours et avec son engagement qui marquait tous ceux qui ont pu travailler avec lui ou simplement le rencontrer, Bernard Bigot a été un acteur majeur pour le développement de l’énergie nucléaire et la recherche dans le domaine.

Je voudrais aussi formuler les remerciements d’usage :

- à la commission européenne pour avoir organisé avec le CEA cette 10ème édition conjointe aux programmes FISA et EURADWASTE, sous le label de la Présidence française du Conseil de l’Union européenne,

- à la région Auvergne Rhône-Alpes, pour nous avoir permis de tenir cette conférence ici à Lyon, en l’ayant accueilli au sein de l’hôtel de région,

- à tous nos partenaires ensuite, trop nombreux pour les citer tous, mais dont vous avez pu voir à plusieurs reprises les logos sur les visuels, et sans lesquels cette conférence n’aurait pu se tenir,

- et enfin et surtout, à tous les orateurs, chairmans, participants des conférences et des évènements qui ont marqué ces trois derniers jours.

Trois jours, c’est peu, nous l’avons vu, pour résumer tous les travaux de recherche qui ont été effectués ces dernières années dans le cadre Euratom.

Mais cela aura été, j’en suis convaincu,

- suffisant pour confronter les points de vue et susciter des débats d’idées,

- utile pour faire émerger de nouveaux projets de collaboration,

- nécessaire pour se retrouver, enfin, après une période de crise sanitaire qui a pu, parfois, distendre des liens ...

Cela aura aussi permis, je l'espère, de susciter des vocations parmi les jeunes qui ont participé à cet évènement.

Car, comme cela a été signalé par plusieurs d'entre vous, dans les sessions d'ouverture et aussi dans les sessions techniques, nous vivons un moment particulier ... une période charnière.

L'urgence climatique est là.

Et les efforts à faire pour atteindre le « Net Zero Carbone » en 2050 sont devant nous. Le défi pour nos sociétés est d'y répondre avec le niveau d'engagement requis, et ce dans la bonne temporalité, c'est-à-dire dès maintenant.

Pour cela, toutes les énergies bas carbones doivent être mobilisées, de façon coordonnée, qu'il s'agisse de nucléaire ou de renouvelables.

Le système énergétique bas carbone doit être pensé de manière intégrée, qu'on parle d'électricité, de chaleur ou de gaz et d'hydrogène, d'énergie pour les procédés industriels ou pour les mobilités, qu'elles soient terrestres, maritimes ou aériennes.

« Des synergies de toutes natures », pour reprendre les propos de Rosalinde van der Vlies, doivent ainsi être mises en oeuvre.

La situation géopolitique est par ailleurs complexe.

Cela a été évoqué à plusieurs reprises et l'Europe s'accorde aujourd'hui sur la nécessité de renforcer sa souveraineté énergétique. L'énergie nucléaire peut et doit avoir un rôle à jouer pour cela.

Comment y parvenir ?

Tout d'abord en considérant bien l'énergie nucléaire dans toutes ses composantes, et sur l'ensemble de son cycle de vie : de la construction d'une centrale à son démantèlement. De l'extraction de l'uranium à la gestion des déchets ultimes de façon raisonnée et sûre, quel que soit le concept retenu, comme l'a évoqué Pierre-Marie Abadie dans son propos.

En utilisant ensuite cette énergie pour tout ce qu'elle peut proposer : production d'électricité et de chaleur, production d'hydrogène, ou comme outil direct pour décarboner certaines d'industries fortement émettrices de carbone.

En changeant aussi notre regard sur cette énergie, en l'envisageant de manière différente :

- comme solution disponible pour remplacer des centrales à charbon ou à gaz et décarboner des mix électriques qui s'appuient aujourd'hui sur ces énergies,

- pour des usages hybrides, couplant différents vecteurs énergétiques,

- pour des besoins locaux où la petite puissance des « Small Modular Reactors » peut être un atout, également pour développer des boucles énergétiques locales.

En allant finalement jusqu'à concevoir le nucléaire autrement, en le réinventant, que ce soit techniquement ou industriellement, ou dans notre approche de sûreté ou de normalisation – bien entendu en lien fort avec nos autorités de sûreté respectives.

Ce qui m'amène à un autre sujet clef, celui de l'innovation.

L'Agence Internationale de l'Energie indiquait l'an dernier dans son rapport Net Zero 2050 que près de 50% des technologies qui doivent nous permettront d'atteindre cet objectif restent encore à développer, à industrialiser et à déployer dans nos sociétés.

C'est bien dans ce domaine de l'innovation que vous avez, que nous avons, tous, un rôle à jouer.

Des conférences comme FISA, comme Euradwaste, des appels à projets comme ceux lancés par Euratom sont le terreau de l'innovation.

Au cours de ces derniers jours, vous avez échangé, proposé, discuté : il est absolument nécessaire de poursuivre ainsi pour innover encore et même d'ouvrir le champ des possibles au-delà de ce qui est traditionnellement le domaine d'Euratom.

La révolution numérique, les nouvelles méthodes de fabrication, ouvrent de nouvelles possibilités, que nous devons explorer, non seulement pour l'industrie nucléaire mais pour tout notre système énergétique.

L'innovation passe par du ressourcement :

- Depuis quelques années, des start-up du nucléaire émergent, avec des concepts dont il convient naturellement d'apprécier la solidité scientifique et technique, mais qui innovent, avec souvent des approches originales, des choix radicalement différents. En France, un nouveau programme a été lancé en février 2022 pour permettre à certains de ces projets de mûrir, de s'y développer. Le CEA accompagnera ce programme et entend y prendre une place comme acteur majeur de l'innovation dans le nucléaire. Je veux espérer aussi que cela conduira aussi à d'enrichir l'innovation de toute la communauté européenne du nucléaire.

- Le ressourcement, c'est aussi la question des infrastructures de recherche, des moyens nécessaires aux activités expérimentales dans le domaine du nucléaire, qu'il s'agisse de moyens d'irradiation, de laboratoires chauds ou de plateformes technologiques spécifiques. Nous le savons tous, ces infrastructures vieillissent. Leur renouvellement, ainsi que le développement de nouvelles capacités, est un sujet clef pour l'attractivité et le maintien d'une recherche d'excellence en Europe.

- Le ressourcement passe aussi par l'attractivité de notre filière pour les jeunes professionnels, et je salue à cet égard les initiatives lancées par Euratom pour promouvoir nos métiers.

C'est pourquoi je veux terminer sur une note positive et d'espoir : lors de ces conférences, nous avons vu et rencontré de nombreux jeunes professionnels, enthousiastes, curieux, bouillonnants d'idées et convaincus que le nucléaire peut et doit jouer son rôle dans notre avenir énergétique.

Ils sont à la fois porteurs de la place de cette énergie dans l'agenda de décarbonation de nos économies et le futur de la filière nucléaire dans toutes ses composantes. Je suis confiant qu'ils sauront proposer des idées en rupture, enrichir notre communauté. Ils représentent l'avenir, et les voir aussi nombreux et passionnés est dynamisant et enthousiasmant.

Bien sûr, le chemin à parcourir est encore long. Les conférences de ces trois derniers jours n'étaient qu'une étape sur ce chemin, avec ces rencontres se poursuivront dès aujourd'hui lors du forum SNETP.

Pourtant je retiens que cette conférence FISA – Euradwaste aura été un jalon : je suis certain que de nombreuses idées y ont vu le jour qui porteront leurs fruits et qu'il en résultera de futurs projets qui nous seront présentés à la prochaine édition de la conférence FISA-

Euradwaste, qui est envisagée au premier semestre 2025, sous présidence polonaise de l'union européenne.

D'ici là, je nous souhaite à tous, collectivement, des années riches en innovation, en rencontre, et des projets européens fructueux.

Bon futurs échanges et bon forum SNETP à tous !

# CLOSING REMARKS FROM THE EUROPEAN COMMISSION

**Bernard MAGENHANN**-EC, DG JRC

Mesdames et Messieurs, nous vivons des temps difficiles.

Nous devons réduire nos émissions de gaz à effet de serre en fixant des objectifs ambitieux de réduction de 55 % pour 2030 et de neutralité CO2 pour 2050 dans l'UE.

Malgré les différentes options nationales pour atteindre ces objectifs, tous les scénarios envisagés dans les stratégies prospectives pour une économie à faible intensité de carbone en Europe incluent l'énergie nucléaire en tant que source de production d'électricité à long terme.

L'agression russe contre l'Ukraine a - je crois – rebattu les cartes et mis en évidence certaines de nos faiblesses dans nos modes d'approvisionnement énergétique. L'autonomie énergétique européenne se construit aujourd'hui, avec moins de dépendance aux importations de pétrole et de gaz et reposera sur un mix énergétique nouveau ou le nucléaire peut avoir un rôle important à jouer dans la transition vers 2050.

Et il nous faut également considérer l'innovation technologique dans d'autres applications nucléaires, par exemple dans le domaine de la santé, de l'espace et de l'intelligence artificielle. Et à l'heure où nous parlons ces secteurs se développe rapidement.

Il est donc important que l'ensemble de l'UE continue à développer son leadership technologique afin de garantir les normes les plus élevées en matière de sûreté, de sécurité, de garanties et de radioprotection, ainsi que la gestion responsable et sûre des déchets nucléaires et radioactifs, afin d'éviter d'imposer des charges excessives aux générations futures.

L'un des aspects clés de l'utilisation sûre et sécurisée de ces technologies est la recherche nucléaire, l'éducation et la formation dans le domaine nucléaire et la gestion des connaissances nucléaires.

C'est pourquoi ces conférences sont si importantes: la rencontre de nos communautés de recherche de l'UE sur la sûreté nucléaire et sur la gestion des déchets radioactifs permet la diffusion des résultats du programme de recherche et stimulent les échanges sur ce que nous faisons, comment nous le faisons, les défis à venir et leurs opportunités et risques.

De notre côté, les résultats serviront de base à l'élaboration des futurs programmes, qui seront améliorés, seront plus utiles, plus efficaces et plus synergiques.

Et de votre côté, les présentations et les discussions de ces jours ont certainement donné lieu à des collaborations et à des échanges d'idées qui, à terme, auront une incidence positive sur les futures recherches.

Mesdames et Messieurs, j'espère que cette conférence vous aura été fructueuse et personnellement je souhaite que ces échanges se poursuivent au sein du Forum SNE-TP qui aura lieu immédiatement après et à d'autres occasion par après.

Je remercie tous les organisateurs de cette conférence pour leur travail remarquable et vous remercie également pour votre participation.

Merci beaucoup et à bientôt.


FISA 2022
EURADWASTE’22

# SIDE EVENTS

# OVERVIEW OF AWARDS AND PRIZES

# Prize pitches

*31st of May, 16:30-18:30*

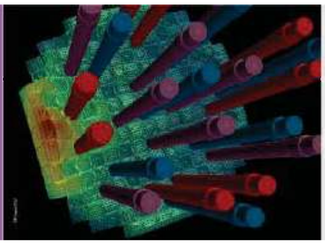
## Nuclear Innovation Prize in safety of reactors systems

- 1st Prize – MultiProtectFuel - Multicomponent Nuclear Fuel Cladding with Safety and Operational Benefits - Martin SEVECEK
- 2nd Prize – MitMAT - Mitigation and Real Time Monitoring of Acoustic Resonances in Main Steam Systems of Nuclear Reactors - Jesus HERNANDO
- 3rd Prize – GUARDYAN - GPU Assisted Reactor Dynamic Analysis - David LEGRADY
- 3rd Prize – DH-LDR - Passive decay heat removal function for the LDR-50 low-temperature nuclear reactor - Jaakko LEPPANEN

# Nuclear Innovation Prize in waste management

- 1st Prize - ARCTERIX - Advanced radwaste characterization based on tomographically enhanced radiation imaging without X-rays - Bo Wilhelm CEDERWALL
- 2nd Prize – QUANTOM - Non-destructive measurement system for verifying the content of radioactive waste packages - Laurent COQUARD
- 3rd Prize – ROBBE - ROBOT-aided processing of assemblies during the dismantling of nuclear power plants - Joerg RECKNAGEL

European Commission



FISA 2022

30 May - 3 June 2022
Lyon, France

**PhD Prize**

**R&D Prize**

**Euratom project**

10th European Commission Conference on EURATOM Research and Training in Safety of Reactor Systems
30 May - 3 June 2022 | Lyon, France

## PhD Prize

- MODEL BASED SYSTEM ENGINEERING, AN INDUSTRIALIZATION PATH FOR DECOMMISSIONING PROJECTS BY ASSYSTEM – Brice ROFFINO - **not registered?**
- PARUPM: A SIMULATION CODE FOR PASSIVE AUTOCATALYTIC RECOMBINERS – Araceli DOMINGUEZ-BUGARIN
- AN INNOVATIVE SUPERCRITICAL CARBON DIOXIDE CYCLE FOR DECAY HEAT REMOVAL IN EXISTING AND FUTURE NUCLEAR POWER PLANTS – Markus HOFER
- TURBULENCE-INDUCED VIBRATIONS PREDICTION: THROUGH USE OF AN ANISOTROPIC PRESSURE FLUCTUATION MODEL – Nout VAN DEN BOS
- INVESTIGATION OF A HYPOTHETICAL CORE DISRUPTIVE ACCIDENT SCENARIO IN MYRRHA – Dorde PETROVIC
- APPLICATION OF THE TRANSPOSITION METHOD INVOLVING EDF NUCLEAR PLANTS MEASUREMENTS: CASE OF REACTIVITY – Eric-Karson NJAYOU-TSEPENG – **back up if ROFFINO not represented?**



## R&D Prizes

- REACTOR SAFETY ANALYSIS TOOLBOX RESA-TX – Alejandra CUESTA
- DIPSICOF, DIAGRID INTEGRATED PASSIVE SYSTEM LIMITING CORE FLOWBYPASS IN ACCIDENTAL CONDITION FOR ADVANCE FBR REACTOR – Florian VAIANA

## Euratom project

- HEALTH EFFECTS OF CARDIAC FLUOROSCOPY AND MODERN RADIOTHERAPY IN PAEDIATRICS – Isabelle THIERRY-CHEF



EURADWASTE'22

30 May - 3 June 2022
Lyon, France

## PhD Prize
## R&D Prize
## Euratom project

## PhD Prizes

- The impact of the compaction and mineralogical composition on the water retention behavior of Opalinus Clay – Qazim LLABJANI
- INNOVATIVE OXIDATIVE TREATMENT AND GEOPOLYMER ENCAPSULATION OF SPENT MIXED BED ION EXCHANGE RESINS – Francesco GALLUCCIO
- Retention of redox-sensitive TcVII on FeII/FeIII bearing clay minerals – Yanting QIAN
- IMMOBILIZATION OF SPENT NUCLEAR GRADE RESINS IN LOW CARBON CEMENT: STUDY OF THE REACTION KINETICS – María JIMENA DE HITA
- A multi-scale insight into Boom Clay self-sealing ability after gas experiments – Laura GONZALEZ-BLANCO



## R&D Prize

- In-Can Vitrification of ALPS slurries from Fukushima Daiichi Effluent Treatment using DEM&MELT Technology – Aliénor VERNAY
- Presentation of the expertise activities carried out in CHICADE – Olivier DAVID

# ENS Prize

- ENS Prize

# NUCLEAR INNOVATION PRIZE

**Description of the event**

https://ec.europa.eu/info/research-and-innovation/funding/funding-opportunities/prizes/nuclear-innovation-prize_en

The ‘Nuclear Innovation Prize’ (call closed) is meant to give visibility to the most dynamic, forward-looking and innovative researchers, research teams or industrial contestants, with a prize planned to be delivered by European Commissioner Mariya Gabriel for Innovation, Research, Culture, Education and Youth (tbc).

Nuclear Innovation Prize in safety of reactor systems

1st place: EUR 50,000 / 2nd place: EUR 30,000 and 3rd place: EUR 20,000 Nuclear Innovation Prize in radioactive waste management

1st place: EUR 50,000 / 2nd place: EUR 30,000 and 3rd place: EUR 20,000 Six (seven in 2022) awarded Nuclear Innovation Prizes related peer-reviewed papers should be published within the international Open Access Journal (EPJ-N) topical issue on FISA 2022 – EURADWASTE ’22 Awards and later within the conferences proceedings.

Euratom funded research in fission safety, waste management and radiation protection benefits from consistent success in pursuing excellence across a broad range of nuclear science and technologies.

Together with EU countries the programme has continuously helped maintain a high-level of competences, underpinned by sound and advanced research.

Nuclear researchers and engineers are constantly challenging state-of-the-art in the field and improving evolving technologies thereby creating conditions for innovations beyond technologies and scientific breakthroughs, towards a more dynamic and competitive European industry for the benefit of every citizen and the whole of society.

Side Events - Nuclear Innovation Prize

EPJ Nuclear Sci. Technol. **9**, 8 (2023)

https://doi.org/10.1051/epjn/2022037

EPJ Nuclear Sciences & Technologies

Available online at:
https://www.epj-n.org

**Euratom Research and Training in 2022 : the Awards collection, Roger Garbil, Seif Ben Hadj Hassine, Patrick Blaise and Cécile Ferry (Guest editors)**

Regular Article

Open Access

# A novel 3D-imaging and characterisation technique for special nuclear materials in radioactive waste

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**Abstract.** A novel technique for non-destructive assay (NDA) of radioactive waste called ARCTERIX (Advanced Radwaste Characterisation based on Tomographically Enhanced Radiation Imaging without X-rays) is presented. The concept is based on a 3D-tomographic imaging technique for special nuclear materials – neutron-gamma emission tomography (NGET). ARCTERIX takes the NGET principle from its original application area of nuclear security systems into the realm of radioactive waste assay with its special characteristics and challenges. By adding localisation and imaging of SNM inside shielded waste containers to the array of existing techniques used for radioactive waste characterisation, ARCTERIX complements the state of the art in passive and active NDA interrogation methods. It is aimed primarily at the class of mixed, long-lived radioactive waste that is commonly called "legacy" or "historic" waste which has special safety, security and safeguards concerns due to its mixed composition, commonly poor documentation, and the frequent presence of SNM. The ARCTERIX concept provides rapid imaging and characterisation of nuclear materials in radioactive waste with a high degree of automation and high throughput capabilities, making it possible to quickly scan large radioactive waste inventories for the presence of special nuclear materials with minimal manual intervention. The first ARCTERIX prototype system has demonstrated a high technological readiness for the implementation of the technique in a commercial stand-alone system for rapid assessment of radioactive waste drums or in a system operating in conjunction with established techniques.

## 1 Introduction

The safeguarding of radioactive materials is by necessity a continuous process, starting from its generation to the final decommissioning stage. This is of special importance for nuclear materials for which uninterrupted tracking is needed to minimise the risk of nuclear proliferation and terrorist threats resulting from illegal trafficking. Critical links in the nuclear safeguards and security chains are therefore the implementations of systems for detecting, identifying and localising radioactive materials using radiation sensors and radiation imaging techniques.

There are currently several techniques available for the characterisation of radioactive waste which are either implemented in the state of the art or under development, for a recent review, see, e.g., reference [1]. High-energy photon transmission imaging (radiography, tomography) can reveal essential information on radioactive waste packages, such as density, position, and structure of the waste inside a container, but provides no information on the radionuclide content. Radiological assessment is therefore needed using passive or active non-destructive assay (NDA) techniques such as gamma-ray spectroscopy, which allows for characterising a wide range of radioactive and nuclear materials. Passive NDA measurements (utilising spontaneous emissions from the radionuclides present in the waste) are often preferred for initial assessment [2] since they typically entail a lower complexity and cost, as well as a lower risk of radiation exposure to personnel. For a complete characterisation, both destructive assay (DA) and NDA measurements are required.

An imaging system for ionising radiation requires either physical or electronic collimation of the incident radiation or otherwise exploiting correlations between detected particles emanating from the same initial physical process, such as a radioactive decay event. Passive tomographic 3D-gamma-ray imaging of radioactive waste is available commercially but suffers from low spatial resolution due to instrument limitations and effects of scattering of gamma rays in the waste matrix and its shielding [3] and is limited to radionuclides with relatively penetrating (high-energy) gamma emissions. Special nuclear materials (SNM) like plutonium, with their notoriously feeble and low-penetrating gamma emissions, are exceedingly difficult to image using passive gamma techniques to meet assay goals. For such

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materials a key signature is neutron emission. Neutron imaging systems have been developed with physical collimators using the traditional transparent channel approach or based on coded apertures, as well as in the form of neutron scatter cameras [4]. Each approach has its drawbacks, such as the tradeoff between angular resolution and detection efficiency in physically collimated systems and neutron scatter cameras. For this reason, passive neutron coincidence counting, used for identifying SNM, does not provide practical means to find its location inside the waste matrix. Active neutron interrogation with the differential die-away technique, or active photon interrogation with high-energy photons (photofission), can be used to achieve a relatively high degree of quantitative accuracy for assessing the presence of nuclear materials in radioactive waste [1,5] but they are cumbersome and costly procedures that also do not provide means of accurate localisation of such materials inside the waste containers.

In order to facilitate compliance with regulatory requirements and to avoid unnecessary radiation exposure to personnel or risk of contamination, the initial characterisation of legacy waste would benefit greatly from high-spatial-resolution 3D imaging of the radionuclide content. This is particularly important for waste containing SNM, which have feeble emissions that make localisation using established techniques exceedingly difficult. Preferably, the imaging task would be carried out with a high degree of automation and without opening sealed and shielded containers. There is currently no established NDA technology for high-spatial-resolution imaging of SNM in radioactive waste.

## 2 Aims and methods

ARCTERIX is based on a novel 3D radiation imaging modality for SNM – neutron-gamma emission tomography (NGET) [6,7], which was inspired by methods developed in fundamental nuclear physics experiments [8]. The method has similarities with emission tomographic techniques used in medical imaging, such as positron emission tomography (PET) [9,10] and its variant time-of-flight PET (TOFPET) [11], which also use the physics of the emission process as a means to locate radioactive sources with high precision. The NGET technology has been recognised by the Royal Swedish Academy of Engineering Sciences (IVA) as one of the top 100 most important Swedish innovative research projects in 2021, aiming at sustainable preparedness for future societal crises [12].

Our main partner for the implementation of the NGET approach to radioactive waste characterisation and one of the end users of the technology is the company AB SVAFO. SVAFO are tasked with decommissioning nuclear facilities in Sweden in a safe, environmentally responsible, and sustainable manner and the management of the Swedish long-lived intermediate-level radioactive waste at the Studsvik nuclear decommissioning and radioactive waste handling site, preparing for the future construction of a final repository called SFL [13]. The operations are conducted on a non-profit basis under the supervision of the Swedish Radiation Safety Authority, SSM. An important part of this task entails characterising the thousands of legacy waste drums present at the facility with high sensitivity, aiming for imaging capabilities with relatively high spatial resolution. This situation is not unique to Sweden. Orders of magnitude larger quantities of such waste are placed in similar temporary storage worldwide. Such waste, often of unclear composition and shortcomings in the original documentation, requires initial characterisation to accurately determine the inventory before it is processed for final disposal. SVAFO provides the ARCTERIX project access to its nuclear decommissioning and radioactive waste handling facility in Studsvik, around 100 km south of Stockholm, Sweden. The collaboration between KTH and SVAFO, which is funded by the Swedish Foundation for Strategic Research (SSF) [14], has defined the following main goals:

- A high-precision characterisation and imaging system for radioactive waste with a focus on special nuclear materials under safeguards.
- High spatial resolution and image processing in real-time by leveraging recent advances in machine learning.
- An automated approach to waste drum characterisation with minimal human intervention.
- Easily optimised detection geometries and scanning methodologies using a specially developed numerical simulation package.
- Optimised quantitative isotopic characterisation in combination with high- or medium-resolution spectroscopic gamma-ray detectors and 3D-densitometry based on gamma-ray transmission scanning.

While the current ARCTERIX implementation is focused on the class of radioactive waste called "historic" or "legacy" waste, a detection system featuring the NGET imaging modality might also be applied to radioactive waste characterisation in general, potentially including verification of spent nuclear fuel and other types of high-level waste suspected of containing SNM.

### 2.1 Technical overview

The ARCTERIX prototype system has been developed in an integrated approach combining experimental studies with numerical simulations using the Monte Carlo radiation transport codes Geant4 [15] and MCNP6 [16]. The fission process was modelled using the computational code FREYA [17]. The simulation codes are used to optimise the detection geometry for different types of radioactive waste configurations. The novelty of the ARCTERIX approach to visualising radiation from nuclear materials lies in the combination of rapid and sensitive detection of the radiation that they emit by using measured detailed time and energy correlations between detected particles [6]. The rapid, precise and automatic determination of the location of SNM in the waste matrix leads to key advantages in radioactive waste characterisation. Two alternative image reconstruction methods have been developed, both exploiting the properties of correlated gamma-neutron pairs originating from spontaneous fission events. Since we are primarily concerned with radioactive waste geometries with spatial dimensions of the order of 1 m, the detected time differences between correlated gamma rays and fast neutrons are a few to 100 ns. This "prompt" time window is of primary interest for the imaging capabilities.

The rapidly developing field of machine learning (ML), a part of the wider field of artificial intelligence (AI), is based on computer algorithms that can improve and learn automatically through experience and by using data [18]. ML is an analysis approach that is especially well suited for solving multidimensional problems with a variety of applications in radiation detection, including pulse shape discrimination [19], radioisotope identification [20,21], and radiation source localisation based on relative flux measurements [22,23]. In the development of ARCTERIX, it has been found that ML algorithms can favourably be used to analyse the complex correlations in the data obtained from the organic scintillators in the mixed radiation field of neutrons and gamma rays, in particular in combination with the more traditional analytical-statistical approach for radiation imaging using Bayesian methods. One implementation of the image reconstruction employed in ARCTERIX is based on a ML algorithm operating on the time difference distributions (within the prompt time window) recorded in the detector array. This imaging method is a simplified but still very efficient approach to the full NGET event-by-event image reconstruction (see below), providing rapid and accurate 3D localisation of SNM based solely on measuring the accumulated gamma-neutron arrival time difference distributions for different combinations of detector elements. For typical detection geometries relevant for radioactive waste characterisation (see Figs. 4 and 8 below), it may be readily assumed that the photon is detected before the neutron since the mean velocity of neutrons from nuclear fission is roughly an order of magnitude lower than the speed of light. Therefore, this cumulative NGET (CNGET) technique does not require gamma-neutron discrimination capabilities, nor does it require measuring energies. For a system of $N$ detector elements there are $N(N-1)$ unique time difference distributions, taking into account which detector element detected the first in a time-correlated pair of particles emitted from a fission event. The CNGET technique uses this complete set of cumulative time difference distributions to determine the location of SNM in 3D using an artificial neural network (ANN). These time difference distributions are updated and analysed continuously during a measurement, successively improving the accuracy of the localisation. This simplified method can be applied to imaging of single sources or multiple/distributed sources using iterative image reconstruction methods. Results obtained from measurements on a weak, 1.7 µCi, Cf-252 radioactive source, are shown in Figure 1. A ML algorithm based on a four-layer feed-forward ANN was used to process the data. See reference [6] for details.

The other image reconstruction technique that has been implemented for the first ARCTERIX prototype system uses a deconvolution algorithm based on Bayes' theorem [24]. The algorithm calculates event-by-event the probability distribution for the point of origin from the measured energy deposited by the neutron, the gamma-fast neutron time difference, and the positions of the detector elements that fired. The result is a spheroidal-like

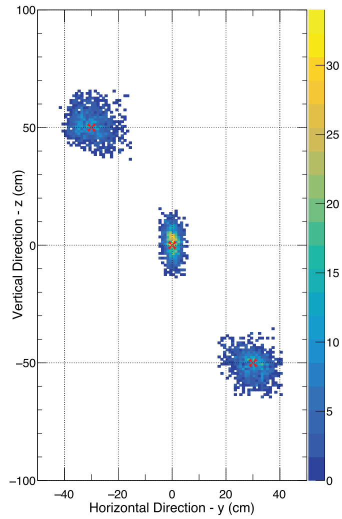


**Fig. 1.** CNGET imaging of a 1.7 µCi Cf-252 source. The plot shows the source positions calculated by the ANN for a total number of 1440 1-min measurements in each of three different positions (indicated by the red crosses) in the central plane of the detector system. The colour scale on the right indicates the number of measurement results per 1 cm$^2$ pixel. Taken from reference [6].

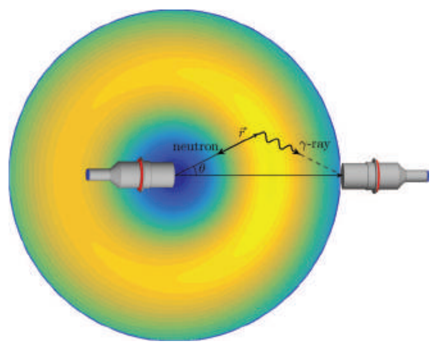


**Fig. 2.** Schematic illustration of the basic principle behind the Bayesian image reconstruction employed in ARCTERIX. The probability density function for the position of a fission event corresponding to the detection of a correlated neutron-gamma pair is mapped event by event. Taken from reference [6].

distribution as illustrated schematically in Figure 2. Differently from neutron scatter imaging (see e.g. Ref. [25] and references therein), only the detection of a single neutron interaction is required. Fast-neutron interactions in organic scintillators are dominated by elastic scattering on hydrogen atoms (protons). The probability distribution for the initial neutron energy can be estimated from the approximately known kinetic energy distribution of fission neutrons above the detected recoil energy, which is the minimum kinetic energy that could be carried by the incident neutron.

There are both similarities and major differences between positron emission tomography, widely used in nuclear medicine, and NGET. PET imaging relies on the fact that 511-keV photon pairs from positron annihilation are strongly correlated in space and time to deduce the

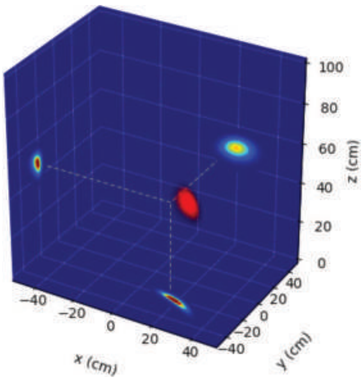


**Fig. 3.** 3D representation of the localisation of a 1.3 μCi Cf-252 source. The source was placed inside a lead cylinder with a 16 mm radial thickness and 105 mm height at a position $(x, y, z) = (20, -30, 52)$ cm and measured for 10 s. See text for details.

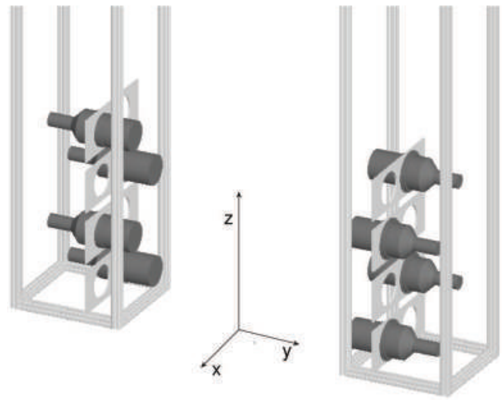


**Fig. 4.** Schematic drawing of the detector configuration in the test set-up employed at AB SVAFO showing the two detection assemblies and the mechanical support structure. The horizontal distance between the front faces of the detection assemblies is 1.0 m. Taken from reference [29].

distribution of positron-emitting isotopes within the field of view. A PET detector system with good enough (sub-nanosecond) time resolution can, additionally, exploit the relative time-of-flight (TOF) information for the detected photon pairs to improve on the 3D image resolution [11]. Differently from positron annihilation, the physics of the nuclear fission process does not provide easily deduced direct directional correlations between the emitted photons and neutrons. However, neutrons being massive particles have a velocity directly related to their kinetic energy. Furthermore, since neutrons emitted from spontaneous fission of SNM have rather well-established energy distributions, often approximated by a Watt spectrum [26] with parameters depending weakly on the nuclide, it is possible to estimate the probability that a detected neutron had a certain initial velocity based only on a partial energy measurement or even without measuring the energy at all. Using such estimates, the measured relative time-of-flight between the neutron and the photon in a correlated neutron-photon pair can be translated into information about their point of origin, i.e. the position of the radiation source. Similarly to a neutron scatter camera, this technique can be combined with standard image reconstruction techniques. An image obtained from a short measurement of a 1.3 μCi Cf-252 radioactive point-like source with the ARCTERIX prototype is shown in Figure 3.

As elaborated further below, the ARCTERIX technology can identify and precisely locate in three dimensions the presence of small amounts (grams or less) of SNM inside shielded waste containers.

## 2.2 Laboratory measurements

The ARCTERIX core hardware is a modular organic scintillator-based detection system with an easily modified geometry that can be adapted to different applications. Organic scintillators have high gamma-ray and neutron efficiencies as well as excellent neutron/gamma pulse shape discrimination and timing properties. Several test measurements have been carried out using the detection system geometry illustrated schematically in Figure 4. The geometry of the first ARCTERIX prototype system was adapted from the ANSI N42.35-2016 [27] industry standard for radiation portal monitors and consisted of two pillars, each holding four 127 mm diameter by 127 mm length cylindrical cells forming a zig-zag pattern (Fig. 4). Each detector cell, containing approximately 1.6 l of EJ-309 scintillator [28], was optically coupled to a Hamamatsu R1250 photomultiplier tube (PMT) [9]. Since the detection system is modular it is easily scalable. The support structure is designed to accommodate up to 20 horizontally oriented detector cells in each pillar and, additionally, ten detector cells at the top of the structure, making up a total of 50 detector cells. The current version of the prototype system, which is being integrated with an automatic waste drum scanning system, includes 12 additional 95 mm diameter by 76 mm length cylindrical cells.

The PMT anode pulses were read out by an 8-channel digitiser board featuring 14-bit resolution and 500 MHz sampling rate. The digitiser has pulse shape discrimination (PSD) capabilities for distinguishing between neutron and gamma-ray interactions in the scintillators based on field programmable gate arrays (FPGA). For further details concerning the detection assembly and readout electronics, see Reference [6]. The digitised signals ("traces") from the detector modules are processed in real time within the digitiser's FPGAs to extract charge integrals, pulse shape information and timing information. The PSD algorithm for distinguishing gamma-ray interactions from neutron interactions is based on the charge comparison method (Fig. 5), whereas sharp time stamp extraction is performed using a digital constant fraction discrimination algorithm. Energy information for each trace is extracted using a moving window deconvolution algorithm.

Figures 6 and 7 show the results of measurements carried out using an encapsulated californium-252 (Cf-252) radioactive source in different shielding configurations. The source had an activity of 1.3 μCi (mass $2.4 \times 10^{-9}$ g,

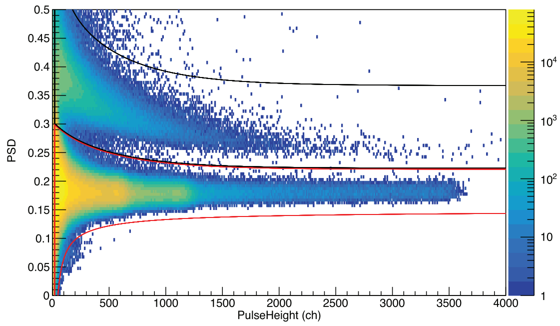


**Fig. 5.** Pulse shape discrimination between gamma rays and neutrons employed in the ARCTERIX prototype. The plot shows the distribution of tail integrals (taken over the last 73% of the signals) divided by the total pulse integrals ("PSD" parameter) vs the pulse height of the PMT signals. The vertical colour scale is indicated on the right. Neutrons and gamma rays were selected by choosing events within the regions indicated by the black and red lines, respectively. The signals saturate at around 6.5 $\mathrm{MeV_{ee}}$.

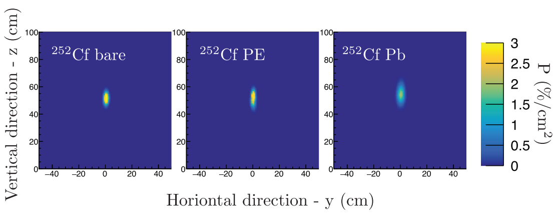


**Fig. 6.** Source localisation results based on Bayesian inference applied to event-by-event data. Each panel corresponds to a 10 s measurement of the 1.25 µCi Cf-252 source placed at $(x, y, z) = (0, 0, 52)$ cm. The deduced projected probability density distributions in the $y-z$ plane are shown for the bare source (left), inside the PE1000 shielding (middle), and inside the lead shielding (right). The calculated probability of finding the source per cm$^2$ pixel is indicated by the colour scale on the right. Taken from reference [29].

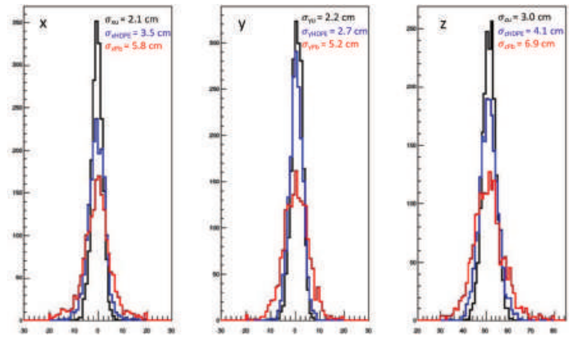

**Fig. 7.** Projections of measured source position distributions on the $x$-, $y$- and $z$-axis for different shielding conditions. A total number of 1800 10-s measurements were performed for each case. Black: bare source, blue: source inside a 4-cm radial thickness HDPE cylinder, red: source inside a 1.6 cm radial thickness lead cylinder. The Cf-252 source was placed at $(x, y, z) = (0, 0, 52)$ cm in the coordinate system indicated in Figure 4. Taken from reference [29].

**Fig. 8.** Set-up used in the test measurements on legacy waste at AB SVAFO. Photo by Fredrik Ekenborg.

neutron emission rate 5400 s$^{-1}$), around 27% of the ANSI N42.35-2016 standard Cf-252 source [28].

The Cf-252 material was embedded in a ceramic cylinder with dimensions 4.6 mm (diam.) by 6 mm and encapsulated in a double-welded stainless-steel cylinder with outer dimensions 7.8 mm (diam.) × 10.0 mm (ANSI classification code C66544) [30]. High-density polyethylene (HDPE) plastic and lead shielding was used to investigate the effect of fast-neutron and gamma-ray attenuation on the imaging performance, respectively. The obtained spatial resolution of around two up to a few cm ($\sigma$) is remarkable, considering the much larger dimensions of the detector cells. The results also indicate a robustness of the NGET imaging technique against the presence of moderate amounts of shielding materials of different types.

## 3 Measurements at the Studsvik nuclear decommissioning site

Radioactive waste in general and legacy waste in particular is commonly stored in drums with various passive shielding materials. The emitted radiation is also subject to intrinsic shielding from the radioactive materials themselves. Therefore, the performance in realistic conditions required further investigation, which was the purpose of the first ARCTERIX prototype system. At AB SVAFO, most of the radioactive waste is stored in drums of 200 to 300 l volume enclosing an inner drum with the waste form and typically a 5 cm concrete lining.

### 3.1 Preliminary results

Test measurements on radioactive waste drums were carried out at AB SVAFO in May 2021 using two detector assemblies. A photo of the measurement set-up is shown in Figure 8. Figure 9 shows horizontal slices through the 3D images of four of the investigated waste drums, each measured for approximately one hour. The slices were taken at the vertical position with maximum spontaneous fission activity in each drum. Estimates of their Pu-mass content were made by comparing the number of registered gamma/neutron-coincidences with Geant4 [15] Monte-Carlo simulations. In a typical case, the resulting estimate of the effective mass of Pu-240 in the drum was 0.9 g with a relative statistical uncertainty of 6%,

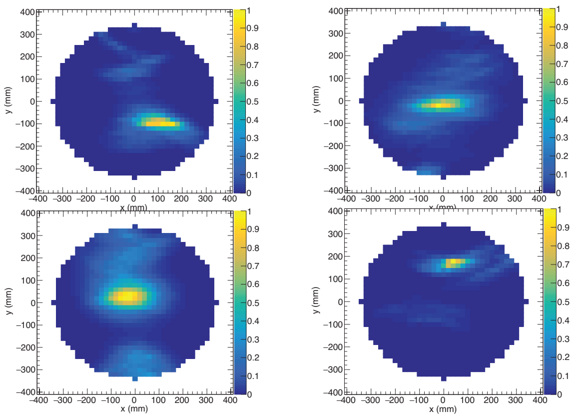


**Fig. 9.** Examples of projected 2-cm thick horizontal slices of the full 3D image for four different legacy waste drums at the SVAFO facility in Studsvik, Sweden. Each slice is applied at the vertical position of the maximum detected concentration of spontaneous fission activity. See text for details and reference [31].

in agreement with the rough assessment of the contents of the waste drum by AB SVAFO based on available documentation. The detailed sensitivity of the method, in particular when applied to other types of radiactive waste with different structure and characteristics, requires further studies.The systematic uncertainties of the quantitative estimates are complex and difficult to assess from the emission tomographic data. However, they can be significantly reduced by combining NGET imaging with standard transmission tomographic techniques (3D densitometry).

## 4 Conclusions and outlook

Using the recently developed neutron-gamma emission tomographic technique (NGET), ARCTERIX provides rapid and accurate localisation of SNM, enhancing current capabilities in nuclear security, safeguards, and radioactive waste management applications. The NGET imaging technique has so far been demonstrated using detectors based on large organic liquid scintillator cells, achieving a typical spatial resolution of a few cm in laboratory conditions, significantly less than the dimensions of the radiation sensors themselves. Even better spatial resolution than was obtained with the first ARCTERIX prototype system should therefore be possible by reducing the size of the detector cells. This is addressed in the current version of the prototype system which features twelve 0.5 l scintillator cells, in addition to the eight 1.6 l cells used in the first tests. The prototype system currently under development also features a high-resolution HPGe-based gamma-ray emission tomographic scanner and a transmission tomographic gamma-ray scanner for integrated 3D densitometry. Solid organic scintillators such as stilbene or plastic might also be preferable to liquid-scintillator-based systems in some applications since they are more robust and less sensitive to temperature variations. New developments in scintillation plastics have led to performance approaching or even exceeding the level of commercially available scintillation fluids [32], and we, therefore, are investigating the possibility of replacing or complementing the liquid scintillators with plastic scintillators in the next prototype version of ARCTERIX.

The development of a new generation of fast inorganic scintillators with moderate energy resolution for gamma rays, sensitivity to both thermal and fast neutrons, and PSD capabilities to discriminate between the two types of radiation is also promising for future developments. Examples are CLLBC [33] and CLYC [34,35]. Although these and similar inorganic scintillators have reduced cross sections for fast neutrons compared with organic scintillators, the energy transfer mechanism (primarily due to $^{35}\mathrm{Cl}(n,p)$ and $^{35}\mathrm{Cl}(n,\alpha)$ reactions) also enables neutron spectroscopic measurements [36]. The intermediate-resolution gamma-spectrometry made possible by these detector materials enables isotopic analysis of radioactive waste components, in particular for plutonium and uranium isotopic analysis [37,38]. An additional development direction we are following is to optimise the ARCTERIX detection system for Compton scatter imaging of pure gamma-emitting radioactive nuclides, in addition to the crude intensity-based localisation capabilities that are already present due to the granularity of the detector system.

## Conflict of interests

The author is the inventor of patent applications related to this work filed by KTH Holding AB, KTH Royal Institute of Technology (Nos. US 17/255143, EP 3811121, CN 201980043247.2).

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## Data availability statement

Data used for generating the figures in the paper can be made available upon request.

## Author contribution statement

The project was conceived and supervised by the author. Contributions from J. Vasiljević, A. Göök, and the SVAFO team led by A. Puranen and F. Ekenborg are gratefully acknowledged.

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# Non-destructive verification of materials in waste packages using QUANTOM®

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**Abstract.** The nuclear and non-nuclear industry has produced a considerable amount of low and intermediate-level radioactive wastes during the last decades. The material characterization of waste packages recently became more and more important in order to dispose of these waste packages in a final underground repository. Material characterization remains an indispensable criterion to prevent pollution of the groundwater with toxic materials and is usually required by the national licensing and supervisory authorities. Information on the nature of waste materials can be obtained based on existing documentation or, if the documentation is insufficient, on further destructive or non-destructive analysis. Non-destructive methods are to be preferred to minimize radiation exposures of operating personnel as well as costs. Existing non-destructive techniques (Gamma scanning, X-ray, active/passive neutron counting, muon tomography) do not allow the identification of non-radioactive hazardous substances. An innovative non-destructive measurement system called QUANTOM® (QUantitative ANalysis of TOxic and non-toxic Materials) has been developed. It is based on the prompt and delayed gamma neutron activation analysis (P&DGNAA). This technology is able to identify and quantify the elemental composition (Cd, Cu, B, Pb, Hg, Fe, Al, ...) in radioactive packages such as 200-l radioactive drums. This information helps waste producers verify the content of their radioactive wastes, especially regarding the presence of hazardous substances. Different reference materials have been analysed by means of the same technology (P&DGNAA) at the research reactor of BUDAPEST. A comparison of those results for five reference materials is presented. The results show a very good agreement between QUANTOM® and standardized reference analyses.

## 1 Introduction

Disposal of nuclear waste is one of the major challenges facing the nuclear industry. Commercial nuclear power plants as well as the non-power industry have already produced a considerable amount of low-level (LLW) and intermediate-level (ILW) radioactive waste. Waste acceptance criteria have been developed according to different requirements for final repositories in several countries in order to assure safe and sustainable storage of the waste.

Due to the phasing-out of the German nuclear power production and dismantling activities, a considerable increase of LLW and ILW is expected in Germany. LLW and ILW are currently stored in intermediate storage. Such wastes are destined to be finally disposed of underground in the deep geological repository called Konrad, which is planned to go into operation in 2027. The German federal company for radioactive waste disposal called BGE (Bundesgesellschaft fuer Endlagerung) is responsible for the approval of conditioning procedures and the qualification of radioactive packages for final disposal in Konrad. Strict waste acceptance requirements [1] were defined based on the results of a site-specific safety assessment. They include requirements on waste forms, waste containers, activity limitations, as well as mass limitations of non-radioactive harmful substances. The latter is required in order to preserve the groundwater according to the Water Law [2]. Thus, the masses of several non-radioactive toxic substances (94 in total) are limited in the repository Konrad (e.g., mercury, cadmium, copper, arsenic, aluminium, antimony, lead, cyanide, etc.). The mass of these hazardous substances needs to be tracked and quantified in the repository inventory. This requires each waste producer to quantify and declare the amount of those materials if they exceed a specified value, usually 1% of the whole container mass (drum + material content), while for legacy waste the threshold is typically 5% [1]. Only qualified packages regarding the radiological inventory and

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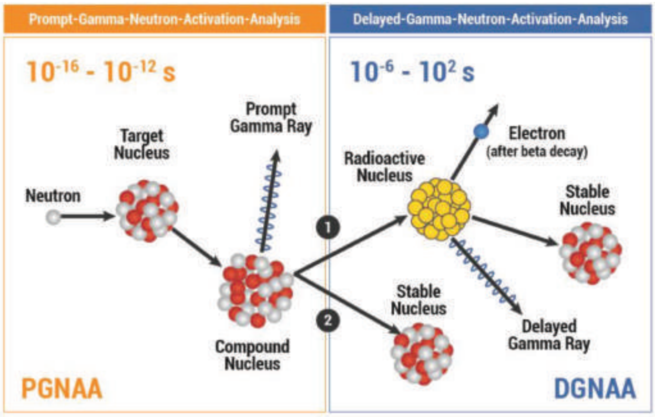


**Fig. 1.** Physical basics of Prompt and Delayed Gamma Neutron Activation Analysis (P&DGNAA).

the material composition can be received and subsequently disposed of in Konrad. Material characterization means that the materials in the drums need to be categorized into groups of substances (material vectors) and the mass fractions of these substances need to be quantified [1]. Waste producers declare their wastes based on these material vectors. Currently, more than 500 such material vectors have been declared and approved by BGE.

For material characterization, legacy wastes are usually problematic: the existing documentation is poor and not sufficient to satisfy the requirements. Besides, the documented material vector may be too conservative or erroneous compared to the real material composition in the drum.

Until today, the material characterization of legacy wastes was performed based on documentation, if it exists sufficiently and, if not, by using destructive methods. Such methods are time-consuming, expensive and cause radiation exposure to the operating personnel. Additionally, they will lead to a repackaging of the waste, which will increase the waste's total volume. Furthermore, in Germany, repackaged wastes are subject to even more restrictive requirements.

To overcome the limitations of the current approaches for material characterization, a non-destructive technology has been developed: a fully automated mobile measurement device based on prompt and delayed gamma neutron activation analysis called QUANTOM®.

## 2 Non-destructive technology

### 2.1 State of the art of Non-Destructive Assay (NDA) techniques

Worldwide, segmented or integral gamma-scanning as well as active or passive neutron counting are used as the standard non-destructive measurement methods for the radiological characterization and quality assurance of radioactive waste packages [3]. These techniques determine the isotope-specific activities of radionuclides in waste packages, but they cannot detect non-radioactive hazardous substances such as cadmium, mercury, aluminium, etc. In addition to these methods, radiography or tomography of waste packages using a radioactive gamma source or X-ray is particularly useful to investigate the contents of heterogeneous waste drums. However, these imaging methods only show the attenuation of intense radiation and do not allow direct identification of substances. The existing imaging procedures only distinguish between metal, organic compounds and concrete by density categories, but they do not distinguish between different materials with similar densities such as cadmium and copper. Since the chemo-toxic potentials of these elements differ a lot and cannot be determined by the abovementioned non-destructive technologies, an improvement in NDA techniques for waste characterization is needed.

### 2.2 Advanced methodology for scanning nuclear drums: P&DGNAA

In order to determine masses of non-radioactive substances in radioactive waste packages, especially drums, an innovative method based on Prompt and Delayed Gamma Neutron Activation Analysis (P&DGNAA) has been developed in Germany since 2007 [4–6]. P&DGNAA is a standard method at nuclear research reactors for the element mass analysis of small samples (mass range: mg - g). As described in Figure 1, PGNAA relies on the measurement of gamma radiation emitted promptly during the de-excitation of the compound nucleus after a neutron capture. These so-called prompt gamma rays are emitted within a time period of less than $10^{-12}$ s. Thus, the detection of these prompt gamma rays has to be carried out during neutron irradiation. Instead, DGNAA relies on the measurement of delayed gamma rays that are emitted later on from the activated radioactive products (see Fig. 1). The timing of this delayed emission is characterized by the half-life of the formed radioactive nucleus.

The main advantages of P&DGNAA for scanning waste packages are listed below:

- no need for conditioning or preparation of the waste matrix;
- the technology is applicable for any kind of waste form;
- the technology is non-destructive;
- high penetration capabilities of neutrons, which enable a full representative description of the entire waste package;
- a multi-element analysis with high sensitivity is achievable.

Current studies and analyses with QUANTOM® make use of PGNAA only, but DGNAA will be added as measurement mode in the future using the same equipment.

### 2.3 Measurement system

The QUANTOM® measuring system uses a deuterium-deuterium neutron generator as a neutron source, which emits neutrons isotropically with an energy of 2.5 MeV

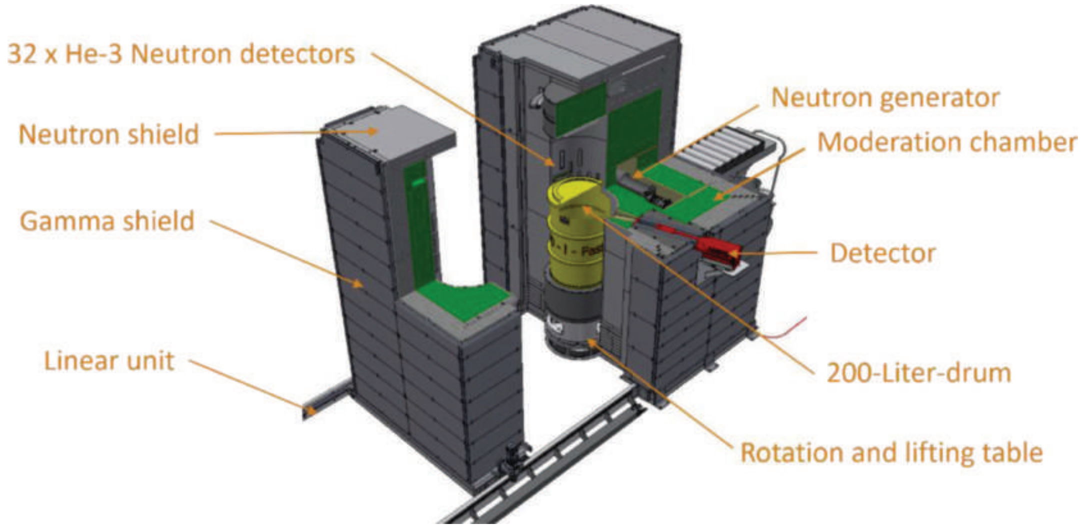


**Fig. 2.** Cut-view of the QUANTOM® measurement device. The measurement chamber can be opened by driving apart the left part of the facility using the linear unit.

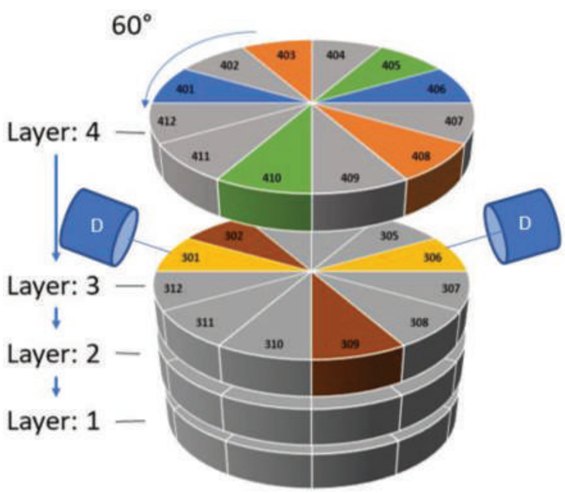


**Fig. 3.** Schematic representation of a segmented drum measurement.

**Fig. 4.** Overview of the measuring system QUANTOM®.

and yields a maximum source strength of $4 \times 10^9$ neutrons per second (model DD109.4 of Adelphi Technology Inc.). Inside the neutron generator, deuterium gas is ionized and accelerated towards a target by a high voltage of 130 kV. Fission reactions with a second deuterium nucleus take place inside the target, which emits free neutrons. The neutron generator can be operated either continuously or in pulsed mode. Figure 2 shows a cut-view of the facility and gives an overview of all installed components. For monitoring the source strength, a U-238 fission chamber is placed in the vicinity of the neutron generator. The fast neutrons are slowed down in a moderation chamber made of ultra-pure graphite and subsequently irradiate 200-L waste drum located inside the chamber. The graphite moderates and reflects the neutrons and thus maximizes the thermal neutron flux inside the waste drum. The neutron capture cross sections are high enough to induce a good signal-to-noise ratio only for thermal neutrons. The contents of the drum are activated, and the neutron-induced gamma radiation is measured by means of two N-type HPGe (high-purity Germanium) detectors with a relative photopeak efficiency of 60% each. The germanium detectors are electrically cooled which renders the handling of liquid nitrogen unnecessary. The two HPGe detectors are located on the sides of the moderation chamber shielded by collimators and thermal neutron shielding (see Fig. 2). Both detectors can be removed from the measuring position with little effort. The neutron flux surrounding the drum is monitored online by 32 $^3$He proportional counters with a low partial gas pressure of 50 kPa

**Fig. 5.** Universal drum adapter surrounding a drum to be measured.

of $^3$He and 100 kPa of Argon. The number and the positions of the neutron detectors have been optimized based on Monte Carlo simulations [7].

As part of the analysis process, collimated sectoral measurements are carried out. Therefore, the drum to be measured is virtually divided into 48 sectors (4 horizontal segments (layer) with 12 sectors each), as shown in Figure 3.

The drum is virtually divided into four horizontal segments (layers), which are further partitioned into 12 angular sectors. The gamma spectra are recorded individually for each sector at discrete positions. The measurement of two sectors is performed simultaneously in front of the collimated field of view of two HPGe detectors, avoiding double measurements of the same sector. The use of two detectors reduces the measuring time by a factor of two and increases the overall sensitivity of the measuring system. After two sectors with the same colour in Figure 3 were measured in parallel, the drum is automatically rotated (60°) by a rotating table and the next two sectors are measured. After the 12 sectors of a layer have been measured, the drum is lifted up and the next layer can be measured. The entire drum can be scanned within 24 single "sector"-measurement positions which yields a complete non-overlapping surface scan. The moderation chamber is surrounded by a neutron and a gamma shield. These shields consist of borated polyethylene plates and lead-steel composite plates. The QUANTOM® measuring system has been successfully set up and is currently being operated in Stolberg, Germany, in the AiNT Technical Center. A picture of the measuring system is shown in Figure 4.

# 3 Status of QUANTOM®

## 3.1 Building and commissioning

The measuring system shown in Figure 4 has been fully built and put into operation in 2020 after having been licensed according to §12 Para. 1 No. 1 of the German Radiation Protection Act (StrlSchG). In addition, this license was extended in accordance with §12 Para. 1 No. 3 (StrlSchG) for handling unsealed radioactive materials up to $3 \times 10^9$ times the exemption limit and for handling sealed radioactive materials up to $10^6$ times the exemption limit. The commissioning of the measuring system was authorized by a technical expert in 2020. Non-destructive measurements of radioactive waste drums using the current installation site have already been performed.

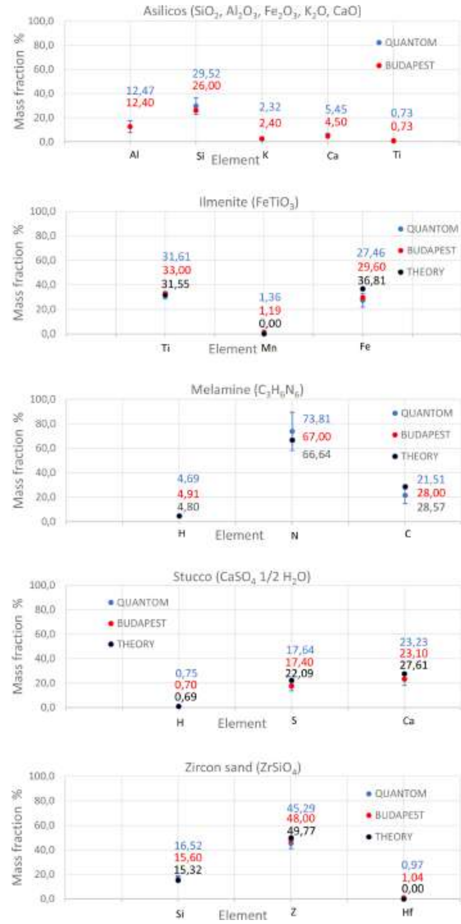


**Fig. 6.** Reconstructed mass fraction for five homogeneous drums filled with reference materials (QUANTOM®) and compared with the reference analysis made at the research reactor of BUDAPEST. The additional black points called "THEORY" show the theoretical mass fractions calculated by using the known molar masses and the stoichiometry.

## 3.2 Validation

To test and validate the measurement technology, reference drums were filled with various reference materials (e.g., zircon sand, melamine, stucco plaster, asilicos, etc.) and measured with QUANTOM®. The reference materials were selected as a function of their neutron affinity and gamma absorption properties. Diverse drum and cap types were used to simulate the real diversity of the waste drums used in the past. A universal adapter has been developed for handling all 200 l drum types with different drum caps (see Fig. 5). This adapter has been successfully tested and used so that all drum and cap types can be safely handled.

Samples of the reference materials used for the validation campaign were analysed at the research reactor in

BUDAPEST (neutron source intensity = $1 \times 10^{15}$ n/s) using the same technique (PGNAA) and standardized processes. In this paper, we present the results for five reference drums filled with different homogeneous materials (asilicos, ilmenite, melamine, stucco, and zircon sand). The integral measurement of a drum takes about 2–4 h. The data analysis process is explained in Section 4. The achieved sensitivity (detection limits) depends on the element to be analysed. For metals such as Al, Cr, Fe, Cu, Ni, Mn, Mo, etc., a detection limit of approx. 100 ppm can be achieved. These sensitivities are based on simulations studies with MCNP modelling a homogeneous concrete matrix (density = 2 g/cm$^3$) with a measurement time of 4 h for the entire drum. For other toxic elements such as Cd or Hg, an even lower detection limit of approx. 10 ppm can be achieved for a measurement time of 4 h. These low detection limits can be further reduced if, for example, the measurement time is increased.

The following Figure 6 shows the results of the analysis of the five reference materials. Overall element masses were calculated by summing over the spatially distributed masses. Note that with QUANTOM® the entire matrix is analysed (i.e. 200 L). At the research reactor of BUDAPEST, the sample volume analysed was about a few grams (i.e. ~1 cL). Due to this large difference in scanned volume, some discrepancies are expected since the materials contain impurities and are not perfectly homogeneous. With QUANTOM® major, minor and trace components can be detected. However, we plotted only the major components in Figure 6. In order to compare the results between QUANTOM and BUDAPEST, the mass fractions have been plotted in Figure 6. The uncertainties for the BUDAPEST values are very small (about a few %). In some cases, (ilmenite, melamine, stucco, and zircon sand) it is also possible to calculate the theoretical mass fractions by simply using the stochiometric ratio and the corresponding molar masses of the elements. This approach is called "THEORY" in Figure 6.

The evaluation of drum measurements includes a data-driven approach for the calibration of the fission chamber to determine the neutron generator's source strength. Measurement uncertainties were calculated using Monte-Carlo sampling with respect to all input quantities of the reconstruction method. The sources of uncertainties considered include, among others, calibration uncertainties, model uncertainties in the simulations and uncertainties regarding the positioning of the drum inside the measurement chamber. In addition, some gamma lines have to be corrected for a background signal in the active underground of the measurement (e.g., H, Al). This results in a significantly increased measurement uncertainty for the corresponding element mass.

All measurement results show a very good agreement with the known reference masses from BUDAPEST within the stated measurement uncertainties. The "THEORY" values show small discrepancies. This was expected and can easily be explained: the theoretical calculation does not consider any impurities (e.g. Mn in ilmenite), which, of course, does not correspond to reality. In the future, measurement uncertainties can be reduced by further studies and additional measurement campaigns which will yield more detailed information about the variability of measurement parameters.

### 3.3 Mobile drum inspection system

After the successful validation in 2021, the QUANTOM® measuring system will be integrated into a 25-Foot container. This mobile unit (see Fig. 7) can be brought directly to the site where the drums are stored or to the waste conditioner. In this case, the operation of the system only requires a notification notice according to §17 of the German Radiation Protection Act (StrlSchG), since the local dose rate at a distance of 0.1 m from the surface of the container is below 10 μSv/h. This significantly reduces the licensing efforts for commissioning the measuring system.

The entire system is fully automated. The final design of the mobile measurement device is shown in Figure 7 including an automatic drum conveyor and the container. The system can be loaded with at least up to 10 drums so that approximately only one loading per day is necessary. The measurement time for each drum is in the range of 2–4 h. The system automatically and autonomously transports one drum after the other into the final drop-off position for measurement, where it will be weighed by a high-precision scale (±0.03%). The drum is then automatically taken by a rotating crane and transported into the irradiation chamber on the lifting turntable.

## 4 Methods and software development

For the evaluation of the gamma spectra, a new gamma-spectroscopy software called PEAK® has been developed. It is especially suited for PGNAA and enables an automatic fingerprinting of the elements (see Fig. 8, which shows a typical PGNAA spectrum) using special algorithms coupled to current and verified nuclear physics databases of prompt and delayed gamma lines of the IAEA [8]. The net peak area is determined by fitting a physical model [9] to the data.

The gamma spectra are analysed individually for each sector measurement (48 in total) to calculate net peak areas. The mass reconstruction is then performed by jointly evaluating all measurements based on simulations which take into account signal contributions of all sectors within one measurement. This enables a spatial resolution for the element quantification in a discrete model. Thus, inhomogeneities can be taken into account within the drum.

The mathematical algorithm for spatial-dependent mass quantification is based on the virtual partitioning of the drum into four axial segments (layers) and twelve radial sectors per axial segment (see Fig. 3). In the data analysis, the sectors are additionally subdivided into seven radial partitions. The mass reconstruction algorithm takes into account the attenuation of the gamma radiation and absorption of the neutron flux within the waste matrix

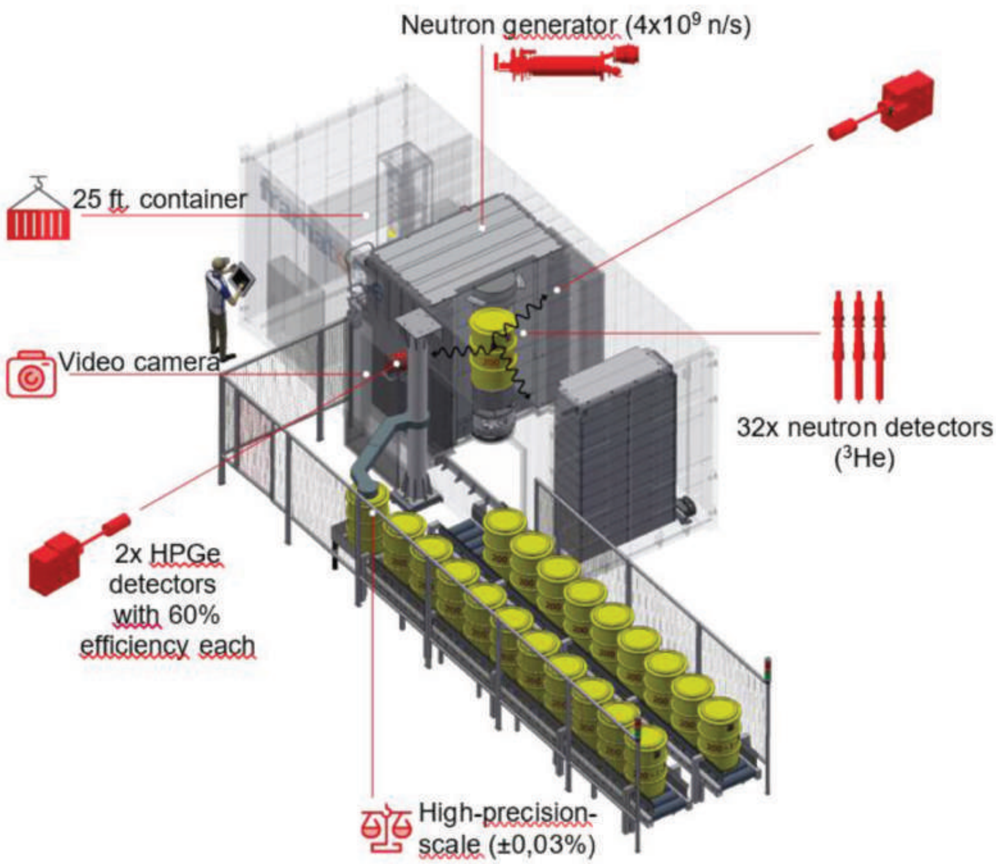


**Fig. 7.** Design of the mobile QUANTOM® measurement device integrated into a specially designed transportable container as well as the automatic drum loading system.

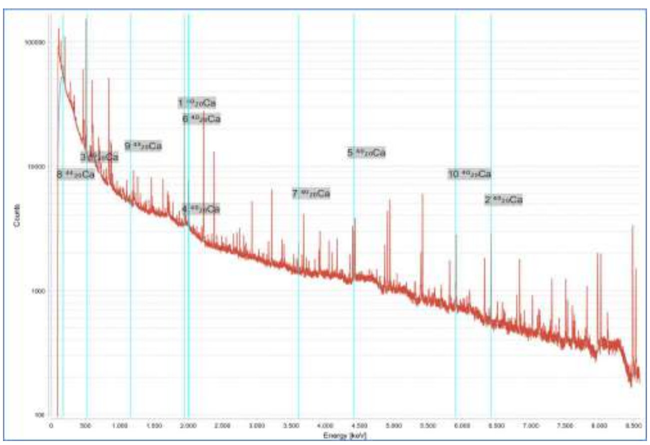

**Fig. 8.** Fingerprint of Calcium in a stucco sample, where the blue lines show the 10 most intense prompt gamma peaks from Calcium.

and the drum wall. The data analysis must be carried out iteratively because the measurement parameters depend on the material composition itself. Iterations with regard to the elemental composition of the drum are carried out until the computed composition of the partitions stabilizes within a range smaller than a predefined threshold value. The neutron flux within a respective partition and resulting partial cross-sections can either be calculated deterministically based on a diffusion approximation of the space and energy-dependent linear Boltzmann equation [10,11] or by using MCNP simulations [12]. This is done for each individual iteration step by considering the physical boundary conditions. The design of the measuring system and the data analysis algorithm have been successfully patented [13].

## 5 Conclusion

The qualitative and quantitative determination of elements (and in some cases the ruling out of some materials) in waste drums is possible with PGNAA. A full-automated drum measuring system called QUANTOM® has been developed and validated. It enables non-destructive verification of the plausibility of material descriptions of (radioactive) waste packages. QUANTOM® is a first-of-a-kind commercial system and will be ready as a mobile unit to be used directly where (legacy) wastes are stored or conditioned. The main benefits of QUANTOM® are summarized below:

- non-destructive multi-element analysis of the entire matrix;
- fast measurement process (2–4 h per waste drum) with high measurement precision;

– no repackaging and no increase in waste volume;
– reduction of costs (min. 50% per waste drum) compared to destructive analysis processes;
– minimizing the transportation of radioactive waste drums and radiation exposure of the operation staff.

## Conflict of interests

The authors declare that they have no competing interests to report.

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## Data availability statement

Analyzed Data associated with this article cannot be disclosed due to legal reasons.

## Author contribution statement

Laurent Coquard: technical lead and coordination of project, writing. Julian Hummel: mechanical design. Günter Nordhardt and Max Georgi: automation. Andreas Havenith: conception, technical lead. Kai Krycki: codes and methods development. Bo Fu: measurement and data analysis. Christopher Helmes: software development. Marcel Heidner: simulation & software development. Frederic Simons: software development. Theo Köble, Olaf Schumann: conception, neutronic measurement.

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Regular Article

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# ROBBE – Robot-aided processing of assemblies during the dismantling of nuclear power plants

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**Abstract.** For a successful decommissioning and dismantling of an NPP (Nuclear Power Plant), correct and controlled processing of all components is necessary, whereby a large part of the work relates to coated (mainly painted) steel components, which make up a significant proportion of the total inventory of the power plant to be processed. The contamination of these components is reduced by removing the surface coating using UHP (Ultra-High-Pressure) water jet blasting technology. Thus, the decontaminated material is released to be recycled conventionally after receiving clearance in accordance with Chap. 3 StrlSchV (German Federal Law Gazette 2018 No. 41: StrlSchV, 2018). The manual processing of these individual parts is cost-intensive, so that an autonomous, automated solution is more economical while increasing throughput at repeatable high quality. ROBBE aims at implementing a robot-assisted, automated and autonomous decoating procedure of component groups using UHP water jet blasting technology and implements it ata German NPP in Biblis on an industrial, productive scale.

## 1 Introduction

RWE Nuclear GmbH has already implemented the processing method based on UHP water jet blasting technology – initially with manual process control. The UHP water jet technology is used in such a way that the coating is completely removed from the entire surface of the components. This enables the complete removal of any contamination that may be bound in the coating itself, on its surface or underneath at the boundary layer to the substate and thus achieving a high level of process reliability. ROBBE builds up on the existing infrastructure for manual UHP waterjet coating removal and expands it to an autonomous processing facility automating the following steps:

- geometry recognition of the coated (steel) components.
- Coating removal with the UHP water jet process.

After dismantling assemblies into manageable components, they fit into Euronorm stackable steel boxes and are ready to be processed. Most of the components can be classified as parts of

- pipelines, fittings, valves, pumps, containers, etc.
- retaining profiles
- machinery
- diverse apparatus
- steel structures.

The component geometries can be of any dimension that fits into an Euronorm box ($1200 \times 8000 \times 600\,\mathrm{mm}^3$). Many components have free-form surfaces, so there typically are not repeating known component geometries. All objects exhibit unique geometric shapes including cavities and occlusions making the autonomous 3D scan of arbitrary objects one of the main challenges to overcome.

### 1.1 Technical and scientific goals

For component clamping and geometry recognition, the dismantled components are removed from the box and fixed on a zero point clamping plate with clamping tools. The clamping plate with the attached component is then placed on a turntable with a zero point clamping system in the UHP decontamination cabin. An embedded

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autonomous, robot-supported 3D laser scanner captures their individual geometry, the geometry of the used clamping tools and their spatial orientation on the clamping plate. Then a detailed and complete surface geometry model of the component as well as the clamps is calculated and, with knowledge of additional procedural parameters as well as the robot kinematics and taking into account reachability constraints, the best possible trajectories for the decoating process are determined which completely cover the component's whole visible surfaces minus those of the clamping tools.

The decoating process is carried out inside the decontamination cabinet by the robot-assisted UHP water jet blasting technology.

The machining process ensures that the required quality criteria are achieved and that the processed components can therefore be approved according to German Federal Law StrlSchV [1]. The outstanding feature of our technology is the autonomous and complete real-time capture of the 3D geometry of arbitrary components of any shape and size with multiple coatings, as well as the adaptive trajectory planning for the robot-assisted decoating process using UHP water jet blasting technology including repositioning of the component for complete coating removal, if required. In addition, we have implemented a sustainable, energy-saving, innovative filter and water circulation system further reducing radioactive waste and saving resources.

The scanning process chosen by ROBBE (Fig. 1) places high demands on the scan quality (complete and closed 3D models) and the recording and processing speed of the system. We developed a fully automated scanning system with an autonomous view planning that minimizes reflections of the laser on the component surface through a suitable choice of the wavelength range and the corresponding scan trajectories. As shown schematically in (Fig. 1), a control loop for the autonomous 3D detection of the surface geometry is put in place, which is based on dynamic scanning of the component using a real-time laser line scanner.

Each scan line is evaluated in terms of its quality allowing conclusions to be drawn, which area could be accessed poorly and which will be difficult to access later on during the decoating process. In addition, intelligent algorithms analyze the point cloud with the aim of eliminating surface reflections and points that do not belong to the object as well as possibly incorrectly recorded points (background reflections and other artifacts). The subsequent cleanup of the pointcloud is very efficient and leaves a smooth realistic surface model.

The focus of our R&D approach has therefore been on the development of a real-time laser scanner for the autonomous detection of individual and initially unknown component geometries as well as the development of a technology for the subsequent complete, autonomous, robot-assisted coating removal of these components using UHP water jet technology. This includes the calculation of the robot trajectories and complete control of its inverse kinematics, taking into account physical effect parameters and interfering geometries (e.g., from the clamps).

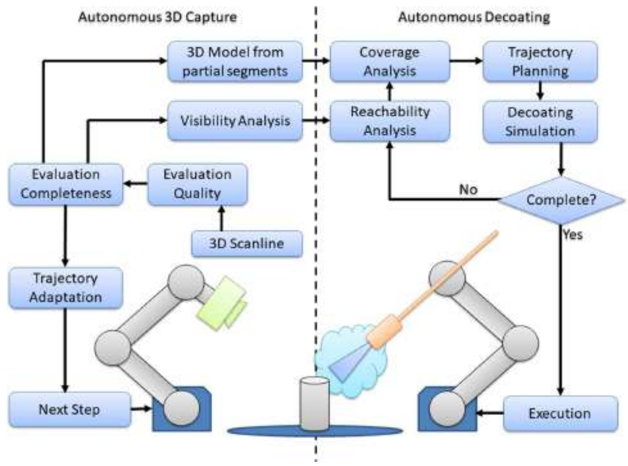


**Fig. 1.** Autonomous 3D geometry capturing and robot-assisted coating removal – shown here by two robot arms for the sake of clarity.

## 2 State-of-the-art

In preparation for this project, we evaluated the current state-of-the art, e.g., at the trade association for industrial parts cleaning in Hilden/Germany, at trade fairs and conferences such as the international trade fair Parts2Clean in Stuttgart (October 2018) and the Kontec in Dresden 2017 and 2021. Scientific institutes were also surveyed, such as the Fraunhofer "Cleaning Technology Alliance" (FAR) based in Berlin (Fraunhofer Gesellschaft, 2018). In industry, various process technologies for cleaning and decoating metal components are used in a wide variety of sectors. So-called blasting processes are among the most established techniques in industrial surface cleaning technology. They use the momentum exchange between blasting media and the workpiece surface to increase the removal rate, sometimes with the addition of abrasive substances. Based on a patent application in 1870, the blasting process was successfully and systematically further developed [2]. The result shows that in industrial applications a large part of the process is already automated when high numbers of similar items or large areas are to be processed.

The main difference to the current state of the art is that ROBBE needs to be able to capture the most diverse 3D object geometries, because there are no CAD models that could be used for the trajectory planning of a cleaning robot.

There have already been national funded projects [3], which also aimed at autonomous cleaning and decoating of components, but on a laboratory scale. They were based on the assumption that objects to be decoated can be reduced and approximated by basic primitives (CAD), calculating trajectories on these surfaces through simplified parametric paths.

In ROBBE we developed a more complex process for 3D acquisition working with dynamic view planning which independently selects the optimal scan trajectory during the 3D digitization of the objects. This ensures that the entire surface of the object is measured and ambivalences or unresolved surface areas are excluded.

At Fraunhofer Institute for Computer Graphics Research IGD, CultLab3D [4] funded by the Federal German Ministry for Economic Affairs and Energy (BMWi) laid the foundation for the first, fast, economical and fully automated approach to 3D digitization of cultural heritage objects. The CultLab3D is a 3D scanning pipeline, consisting of two scanning stations, an arc scanner that captures most of the surface of an object and a robotic arm scanner that takes care of all remaining cavities and occlusions that were not detected by the first scanning station. Unique to this autonomous scanning system are intelligent view planning algorithms for the robotic arm scanner, which allow it to capture every region the optical sensor can see on the surface of an object with the smallest number of perspectives and optimal depth of field [5–8]. In ROBBE these algorithms have been adapted to laser-based approaches for the autonomous real-time acquisition of arbitrary 3D surfaces eliminating manual post-processing of the resulting 3D models which are complete and closed.

A study from Hübner et al. [9] provides an up-to-date overview of the procedures mostly used in previous dismantling projects. It also analyzes the outcome of an expert survey on the status of the processes used and their future prospects. Mechanical processes, especially blasting processes, and above all the abrasive blasting processes, have therefore proven to be indispensable. High-pressure water jet processes are being commended for future applications, however pointing out, that the required water treatment might be demanding. However, this is one of the aspects solved in ROBBE already. In addition, in the aforementioned study, the ability to automate decontamination work is viewed rather skeptically. Currently, the automation of dismantling processes is almost impossible to implement, mainly because of arbitrary geometries of the components and the lack of adaptation capability of the processing machines to unknown geometries. Again, this is precisely what ROBBE overcomes.

## 3 Idea and implementation

The project idea of using a new, innovative and autonomous technology to achieve high throughput at repeatable high quality was developed at an early stage when the decontamination room at RWE was completely renovated and a new UHP water jet technology was installed, leading to a high level of motivation for the exploration team to research potentially suitable solutions and development approaches on the international industrial technology market. As is usually the case with such development projects, this process is lengthy and resource-intensive. An engineering office (TSE Wassmann) specializing in cross-sector technologies was called in to provide support. The project then got to a head start when the basic technical and industrial feasibility was clearly and tangibly demonstrated with the autonomous scanning approaches of the Fraunhofer Institute for Computer Graphics Research IGD.

### 3.1 The industrial prototype plant – technical implementation

The system design was significantly influenced by the process work flow and the existing physical space for the later implementation of the robot system. During the development process, it turned out that dividing the process into spatially different scan and work areas did not seem suitable for various reasons. A wide variety of design variants with different operating parameters were created and evaluated using CE matrices. Accordingly, the process variant with integrated geometry recognition and processing function with an articulated arm robot – without tool change – directly in the UHP processing box turned out to be the most suitable. The main reasons for this were:

- the work area is easy to control from a safety point of view.
- Saving resources (only one robot).
- Harmonizing well with component logistics.
- Processing time is not significantly longer.
- Sufficient protective measures for the optoelectronic systems are available.

**Industrial robots:** the existing space influenced the choices of the robotic arm. Due to the nature of the UHP blasting process used, only water and moisture-resistant industrial robots can be considered. In addition, it must be suited for its purpose and match all requirements for certification and integration in an NPP environment. The required gripping length and applied payload of around 60 kg limited the number of suitable robot providers. Also, the programming interfaces of the robots must be open to control each joint individually, as well as performing positional data read outs at high frequency. Using a UHP cleaning system with a robot also calls for appropriate precautions to ensure a stable data connection and UHP water supply to the end effector of the machine. Therefore, utmost importance was given to design all supply lines along and partially inside the robotic arm, so they would enable full integration of all necessary technical components (scanning and UHP waterjet technology) in a closed, watertight unit built on the end effector.

**UHP waterjet technology:** central to the work-flow is the management of the UHP water jet process. Currently, cleaning is still carried out manually. A manipulator-supported, but hand-guided lance is used for coating removal. The guidance of the jet pipe is based on the experience of the human worker. During operation, a direct view of the processing zone is only possible to a very limited extent due to the extreme formation of fog, despite the strong air circulation. The UHP system works at a nominal pressure of 2500 bar, at 24l/min and a water outlet temperature of 80 °C. The jet leaves the nozzle at about $1000\,\mathrm{m\,s^{-1}}$. This ultimately not only leads to the desired cleaning effect, but also generates large amounts of mist and aerosols. For automation, virtual modeling and simulation is necessary to reproduce this process. Therefore, we determined various physical process parameters needed to establish corresponding virtual 3D models of nozzles and

**Fig. 2.** Left: component sample from the dismantling. Middle: parts with a newly applied, resistant coating for removal tests. Right: experimental setup for determining the jet parameters of various nozzle tools.

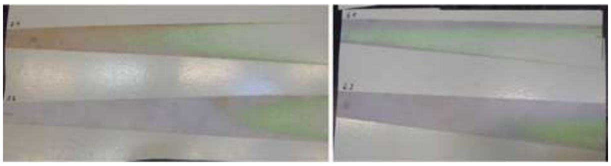

**Fig. 3.** Experimental results: quite abrupt transition between good and insufficient cleaning. Here, we increased the distance to the plate until colored and therefore still coated areas of the workpiece remained. Other parameters were determined in the same way, such as the angle of attack, etc.

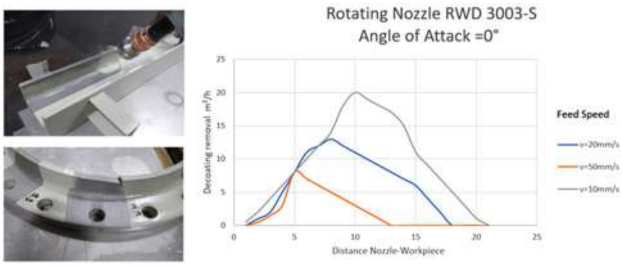


**Fig. 4.** Experiments on complex objects. It is easy to see that the angle of incidence is a critical parameter. The diagram on the right shows the removal rate on the $Y$ axis and the distance on $X$ at a given speed. One recognizes that a further approach to the workpiece surface of the nozzle does not necessarily produce a better cleaning performance – there are maxima.

optimize their cleaning trajectories in our virtual cleaning simulation.

A whole set of physical parameters had to be considered. In addition to the nature of the tool (nozzle configuration, angle of attack, speed and type of drive), the most important parameters are those describing the relationship between the tool and the surface, depending on the choice of tool. The distance allows to assess the trade-off between speed and cleaning effect. The same applies to the feed rate and the angle of attack on the surface.

To determine these parameters, a series of tests were carried out with the UHP technology on repainted component samples from the demolition process (Fig. 2). The newly painted elements were determined to be a "worst-case or heavy duty" scenario, as the adhesion of the new protective coating is ultra strong but becomes more brittle over time and can thus be removed more easily. Figure 3 shows typical test results by way of example.

Interestingly, the transition between successful and unsuccessful decoating was always quite abrupt in our experiments. Objects with more complex shape geometry have also been examined in order to obtain further key figures when machining curved surfaces, inside and outside corners as well as undercuts and bores (Fig. 4).

**Fig. 5.** CAD planning and development of final UHP waterjet nozzle with integrated and water protected laser scanner.

**Fig. 6.** IGD01 Prototype Setup featuring a Laserscanner and a true-to-scale UHP waterjet mockup.

Based on these tests, we designed and developed a high performance nozzle (Fig. 5). In addition to the scanner, the UHP blasting tool is an essential component of the robot end effector unit and significantly determines its shape geometry and the water supply through a hose guided along the robot arm.

**Research prototype:** the aim of the research prototype IGD01 was to simulate the industrial prototype in a collaborative environment located at the Fraunhofer laboratory in Darmstadt (Fig. 6). No high forces were to be expected on this prototype, as the focus here was on the development of the scanning technology and the simulation of cleaning. The research prototype works with a compliant, collaborative robot system and a dummy UHP waterjet tool at the end effector, but which already contains the real scan head. This prototype allows a simulation of the entire process, experiments with different end effector configurations and work in the immediate vicinity of the robot.

**Autonomous capture and cleaning:** in order to carry out an autonomous, robot-assisted cleaning of system parts, various sub-components are necessary (see Fig. 1). In addition to the hardware components such as robots, turntables, scanners and high-pressure cleaners, various software components are also necessary to make it possible. The process can roughly be broken down into three parts: The detection of the object on the turntable filtering out interfering geometry from fasteners and clamping, trajectory planning, simulation and optimization of the

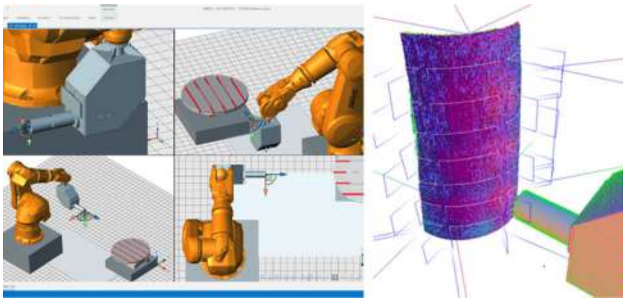

**Fig. 7.** Simulation of the cleaning process directly on the point cloud allows the cleaning tracks to be optimized with a focus on the areas that have not yet been decoated.

cleaning path and finally cleaning with optional repositioning of the object.

**Object capture – shape and surface recognition and modeling:** the detection of the objects on the turntable takes place performing adaptive scan runs. The scan head consists of a triangulation scanner with a (high speed) camera and laser line. In addition to the depth line, the scan head also provides information on the quality of the data obtained. This allows for direct readjustment/guidance of the scan head if the object gets out of focus or lighting is too bright or too dark. For the adaptive part of the scan, a mechanism is used that estimates the completeness of the 3D model obtained. At the end of the acquisition, the 3D model is cleaned in order to filter out artifacts (e.g., reflections between bare metal parts). In addition, an analysis is carried out to separate the component to be cleaned from interfering geometry from fasteners and clamping devices to limit cleaning to only the visible part of the component.

**Planning and optimization of the cleaning path:** the path planning algorithm uses the computed 3D model and the measurement data obtained from the UHP waterjet experiments. Various techniques are combined to get to the final cleaning path. The method starts with a group of pre-defined departure strategies and evaluates which one to choose. Based on the starting point, the geometric complexity of the component to be decoated and taking into account the best effective parameters of the UHP waterjet tool, the most efficient path is chosen. The method makes sure adequate spacing between the cleaning paths is observed and complete coverage of the object is achieved. Treated surface parts are marked on the 3D model as to know what has already been cleaned. Ultimately, this creates a complete cleaning program that includes the movements of the robot and the turntable.

The data obtained in the experiments represent the basis for using physical simulation to obtain a plausible virtual image of the nozzle under varying operating parameters. This means that the cleaning process can be reproduced virtually (Fig. 7) and the cleaning paths can be optimized with a view to optimal surface treatment. The optimized movement data are finally transferred to the industrial robot for coating removal and the UHP tool is guided over the assemblies to be processed according to these data, practically executing the generated cleaning program. Additional, non-optical protective functions (including collision and collision protection) monitor any errors in the calculation or operation.

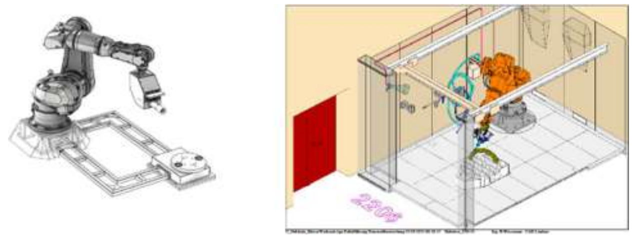

**Fig. 8.** Virtual planning and simulation of RWE01/RWE02 for the final decont cabin.

**Coating removal process:** the optimized cleaning trajectory data are finally transferred to the industrial robot for decoating, the UHP tool is navigated over the components to be processed according to these data, and the cleaning program is executed. The cleaning program may involve repositioning of the object (due to surface regions where clamping was performed in previous positions) to make sure coating of a component is fully removed. Additional non-optical sensors are used to complement vision-based collision protection and monitor any errors during operation.

**Multi-stage development and transition to productive operation:** ROBBE focussed very much on the research and development of all necessary next generation technologies required to achieve an autonomous coating removal process. This applied above all to the areas of real-time, autonomous laser scanning, path planning and simulation of the decoating process. The theoretical approaches have been transferred in terms of software and technology to microelectronic or mechatronic systems, tested and built as industrial components into first a research prototype built by Fraunhofer and now the final decont cabin (Fig. 8) built by a certified system integrator (manufacturer).

The latter is undergoing the last evaluation round until going into operation at Biblis NPP in a two-stage process named RWE01 and RWE02. RWE01 is first evaluated and tested in a washing bay outside of the controlled area of the reactor buildings at Biblis power station premises to make sure UHP technology and the decoating process with the integration of a mobile UHP pump unit as well as the safety-related functions are working as planned. This is also where all necessary control steps and the later required interconnection to the system control of the decontamination room are tested. A control-related simulator based on an adapted dummy PLC is used for the safety, signal and data technology, capable of exactly mimicking the subsequent installation situation and connection to the existing plant facility.

The whole complex autonomous decoating process involving 3D scanning of an arbitrary object followed by dynamic trajectory planning for the UHP waterjet

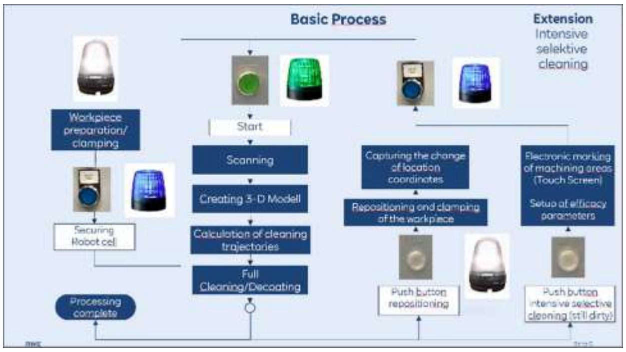


**Fig. 9.** Elegance lies in Simplicity: Final Process Workflow and User Interface.

**Fig. 10.** RWE01 prototype evaluation in washing bay prior to operational release into decontamination room as RWE02. The scan head is designed as part of the blasting tool with a humid and watertight protective flap protecting the sensible laser and camera optics during decoating operation.

treatment has been reduced to a simple and easy to use push button interface (Fig. 9).

RWE01 has been delivered and successfully set up in Mid November 2021. It is currently performing a series of operational tests as described above (Fig. 10). After successful conclusion of those tests, the system will be installed as RWE02 in the decontamination cabin inside the controlled area of Biblis NPP Block A. The transfer is being supported by an experienced NPP system manufacturer to ensure efficient and comprehensive trials as well as a short conversion process from RWE01 to RWE02. We expect RWE02 to go operational by the end of 2022.

## 4 Conclusion

We have presented the results of ROBBE which advances the current state-of-the-art by automating a once manual process in the dismantlement of NPPs increasing efficiency while enhancing workplace safety and health protectioncombined with a sustainable, energy-saving, innovative filter and water circulation system further reducing radioactive waste. ROBBE introduces autonomous digitization of arbitrary object geometries, generating dynamic trajectories for efficient decoating using UHP waterjet technology, based on physical evaluation results. Intelligent path planning algorithms allow robot-assisted laser scanners to capture arbitrary object geometries in repeatable high quality and to calculate a closed 3D surface model immediately after a scan is completed without manual post-processing. Neither CAD models are required for the 3D digitization of the objects, nor is it required to teach the scanning robot manually how to scan the component surface. The real-time laser scanner developed is capable of capturing highly reflective surfaces (stainless steel, chrome). The resulting 3D point cloud is examined for reflections and other faulty 3D measurement points through plausibility analysis. Object recognition distinguishes between clamping tools and object geometry. The machining process starts after an iterative object decoating simulation has been carried out determining the most efficient trajectory for the UHP waterjet nozzle. Among the optimization parameters considered are the accessibility of the object surface by the robotic arm, the achievable distance between jet nozzle and the workpiece surface, the range of adjustable angles of attack and the feed speed to ensure an optimized and complete decoating of the component. This may include the repositioning and re-clamping of the component to make sure all of its surface is thoroughly cleaned. The technical solution can also be transferred to other applications, such as alternative cleaning processes or subsequent processes (radiological measurements, quality assurance, component documentation) in dismantling, or to other industrial applications (surface processing of components with individual shape geometry in small batches).

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## Conflict of interests

The authors declare that they have no competing interests to report.

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## Data availability statement

Data associated with this article cannot be disclosed due to patents pending.

## Author contribution statement

The following authors have contributed to this paper and to the implementationof the ROBBE industrial prototype:
• Dieter Fellner – foundations of computer science for laser-based digitization
• Pedro Santos – autonomous robotic digitization and surface treatment.
• Martin Knuth – autonomous view and trajectory planning.

• Martin Ritz – robot calibration, robotic command interfaces.
• Jörg Recknagel – overall project coordination, requirements UHP waterjet technology, efficiency evaluation, collecting ground truth data, water treatment technology, system integration
• Klaus Steinbacher – workplace safety mechanisms, radiation protection, system integration.
• Burkhard Wassmann – industrial prototype engineering, system integration.

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Regular Article — Open Access

# In-Can vitrification of ALPS slurries from Fukushima Daiichi effluent treatment using DEM&MELT technology

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**Abstract.** After the accident at the Fukushima Dai-ichi Nuclear Power Station, a large amount of contaminated water was treated using several decontamination systems with different natures of adsorbents and chemicals. The resulting wastes, called Fukushima Effluent Treatment Wastes (FETW), were stored at the Fukushima Dai-ichi site. Vitrification could be the most promising treatment method to package these wastes. The consortium gathering CEA, Orano, ECM Technologies and ANDRA, implemented an in situ, robust, simple and versatile In-Can vitrification process, the DEM&MELT technology. Since 2018, the applicability of this technology for FETW treatment and conditioning has been evaluated. In 2021–2022, studies focused on one particular waste, coming from the ALPS system (Advanced Liquid Processing System-Multi Radionuclides Removal) generating around 70%vol. of FETW. This waste is composed of two co-precipitation slurries: one mainly composed of iron hydroxide, and one of calcium carbonate and magnesium hydroxide. The purpose of this article is to highlight the feasibility of ALPS slurries vitrification with DEM&MELT, relying on tests performed from laboratory-scale to full-scale. Macroscopically homogeneous glasses were produced using the DEM&MELT demonstrator, with a waste loading of 60 wt.% (expressed as waste dry mass) and microstructural analyses were performed. It gives promising results for FETW conditioning with the DEM&MELT process.

## 1 Introduction

A large amount of waste, called Fukushima Effluent Treatment Waste (FETW), has been stored on the Fukushima Daiichi site. Among this waste, ∼80%vol. consist of sludge and slurries that have been generated by three decontamination systems: ACTIFLO®, ALPS and evaporative concentration apparatus. Among the volume, about 70% is generated by the ALPS system which produced two types of co-precipitation slurries: an iron hydroxide slurry and a calcium carbonate/magnesium hydroxide slurry. For now, ALPS slurry is stored in liquid form, but a dewatering process by filter press is planned for the stabilization of the slurry. The pasty and sticky texture of the dewatered slurry (after filter press operation) as well as its chemical composition make this waste very challenging to treat.

Vitrification is a promising method to condition such waste. A dense and durable final wasteform is produced thanks to a thermal treatment with the addition of vitrification additives to the radioactive waste [1–3]. Atomistic bonds are created between the elements of the radioactive waste and the glass formers, which enables to reduce the waste reactivity and enhances passive safety. Vitrification is already implemented by many countries, especially for high-level waste, and the glassy wasteforms long-term behaviour with regard to the deep geological repository that has been studied since the 1950s.

The goal of the study reported in this article is to highlight the feasibility of the vitrification of ALPS slurries with the In-can vitrification process [4–6] DEM&MELT. The DEM&MELT technology has been developed by the consortium gathering CEA (French Alternative Energies and Atomic Energy Commission), Orano, ECM Technologies and ANDRA (French national radioactive waste management agency, acting as the operator of the French call for proposals resulting in the DEM&MELT pilot construction), and is an in situ, robust, simple and versatile In-Can vitrification process (see scheme in Fig. 1) [7]. This study was performed through funding from the Japanese Ministry of Economy, Trade and Industry as The Subsidy Program “Project of Decommissioning and Contaminated Water Management”.

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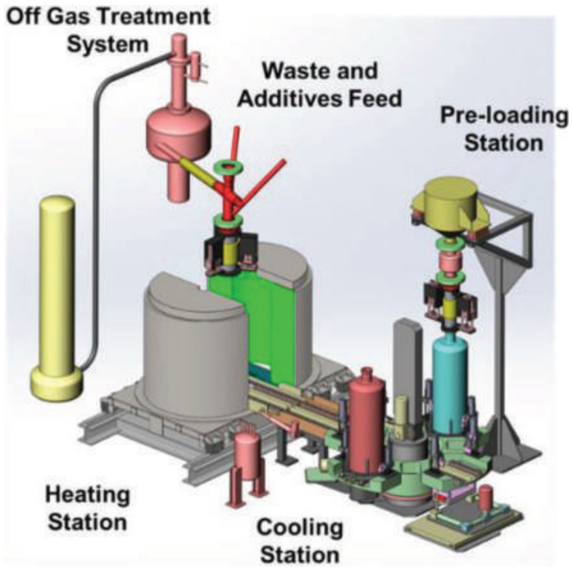


**Fig. 1.** Schematic diagram of the DEM&MELT process.

The applicability of the In-Can vitrification to the FETW is evaluated following some baseline treatment objectives [8]:

- the production of a solidified and dense vitreous matrix, in which the presence of non-labile crystallizations is accepted,
- the production of a waste form which is not subject to radiolysis,
- a significant volume reduction,
- chemical stabilization of radionuclides in the waste form,
- a suitable treatment capacity regarding the amount of waste.

This article aims to present the study of the In-Can vitrification of ALPS slurries, from laboratory-scale to full-scale, to produce inactive industrial canisters of vitrified ALPS slurries (as non-radioactive surrogates) using the DEM&MELT demonstrator operated on the CEA Marcoule site.

## 2 Experimental method and data

This experimental program is performed in a non-radioactive environment [9]. This is a classic and important methodological step in the vitrification study of any radioactive waste stream. Indeed, it is a powerful tool for increasing the technical and economic efficiency of studies. Although the radioactive nature of the waste is important, the major challenges related to its vitrification can be studied, and at least partly solved, in a non-radioactive environment. After the non-radioactive studies, studies with radionuclides using the CEA facilities can be considered, if necessary, to verify the results obtained on the materials and their evolution under irradiation. This methodology has been successfully applied to the qualification of various vitrification processes and glass matrices.

**Table 1.** Composition in wt.% of mixed ALPS slurries surrogates.

| Dry composition (wt.%) | Surrogate ALPS slurry mix (5:1) |
|---|---|
| $CaCO_3$ | 47.30 |
| $Mg(OH)_2$ | 29.47 |
| $Na_2CO_3$ | 3.52 |
| $SiO_2$ | 2.98 |
| $SrCO_3$ | 1.90 |
| $FeO(OH)\cdot H_2O$ | 11.97 |
| $Al_2O_3$ | 0.94 |
| $Co(OH)_2$ | 0.50 |
| $Ti(OH)_2$ | 0.45 |
| $Zn(OH)_2$ | 0.38 |
| $Ca(OH)_2$ | 0.32 |
| Cl | 0.26 |

First, representative surrogates of both ALPS ferric slurry and ALPS carbonated slurry were manufactured by a co-precipitation process. In order to be physically representative of the real waste, filter press operations were used to obtain a water content close to 50 wt.%. Although these two slurries can be vitrified independently, preliminary scoping studies (not shown) demonstrated the interest in mixing these two slurries for vitrification. Therefore, the waste studied is a 5:1 mix of carbonated and ferric surrogate slurries expressed as dry mass (Tab. 1). Slurries are doped with non-radioactive Sr, a surrogate of their main radionuclide.

To vitrify these ALPS slurries, borosilicate glass additives were selected because the properties of borosilicate glasses are recognized in the nuclear field. They enable high Waste Loadings (WL: waste fraction in the final wasteform) while meeting processability requirements such as chemical reactivity with the waste, appropriate melting temperature, limitation of the volatility of some species and corrosion issues.

In order to ensure the course of full-scale tests with the DEM&MELT demonstrator, various experimental steps were implemented. First, the study started at a laboratory scale (≈100 g of glass) in order to test some of the main parameters and search for an acceptable final wasteform, using a muffle furnace. Then a test at bench-scale was made (≈1 kg of glass) with a furnace integrating an Off Gas Treatment System (OGTS) to evaluate the volatility of species during the glass production and consolidate operational parameters. The last step was the full-scale tests with the DEM&MELT demonstrator (≈300 kg of glass). The present article focused on laboratory-scale and full-scale tests.

One of the goals of the study was to obtain a high WL to reduce the volume of waste and so the number of containers to be produced and stored while having a suitable final wasteform. In the following, the waste loading is

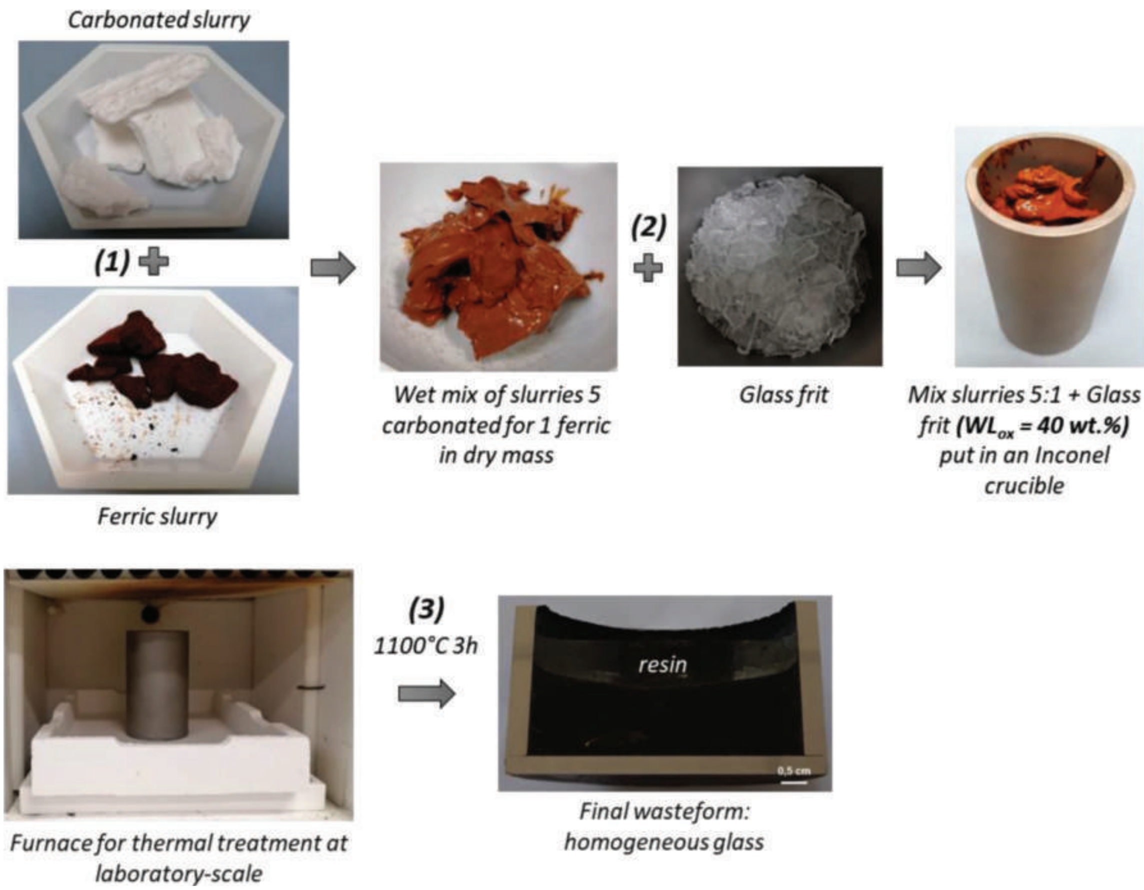


**Fig. 2.** (1) Mixture of the two slurries, (2) mixture of mixed slurries with the glass frit placed in a crucible (3) thermal treatment in a muffle furnace and crucible cut in the height direction to see the material. An epoxy resin is poured after the thermal treatment to maintain the material during cutting.

expressed in two ways: (i) as a function of the masses of dry waste and final wasteform ($WL_{dry}$, Eq. (1)), remembering that there is 50 wt.% of water inside the slurries, or (ii) as a function of the masses of oxides forming the waste and final wasteform ($WL_{ox}$, Eq. (2)). $WL_{ox}$ calculation requires the conversion of the waste mass into an equivalent mass of oxides (e.g. $CaCO_3$ converted in CaO) so that chemical species discharged to the OGTS (e.g. water, carbonates, nitrates, etc.) are not taken into account. To calculate the mass of slurries in oxide form, a batch of slurry is heated to 1000 °C to remove all gases, and masses before and after thermal treatment are compared.

$$WL_{dry}\,(\%) = \frac{\text{mass of dry waste (kg)}}{\text{mass of wasteform (kg)}} \times 100 \qquad (1)$$

$$WL_{ox}(\%) = \frac{\text{sum of oxide masses composing the waste (kg)}}{\text{mass of wasteform (kg)}} \times 100. \qquad (2)$$

## 3 Laboratory-scale tests

After previous investigations (not shown), a glass frit additive composed of $SiO_2$, $B_2O_3$ and $Na_2O$ was selected for the vitrification of ALPS slurries surrogate. It can be noted that this study was not focused on glass frit formulation, so a deeper material study could have led to a higher WL than the one found in the presented study. The laboratory-scale study focused on sensitivity tests covering the process main parameters:

- refining temperature,
- reactivity between the glass frit and the slurries as a function of the shape of each component and their mixing procedure,
- reactivity at high temperature of a mix of slurries and glass frit put into a high-temperature molten glass,
- WL.

### 3.1 Nominal tests – glass production and characterisation

The different preparation steps of a typical test are shown in Figure 2. The mixture of slurries and glass frit is placed into a crucible. The crucible is then put inside a muffle furnace and follows a thermal treatment up to 1100 °C, with dehydration and decarbonation steps due to the quantity of water and carbonates composing the slurries. After the thermal treatment, the crucible is gently cooled at 60 °C·h$^{-1}$. The glass sample shown in Figure 2 is the

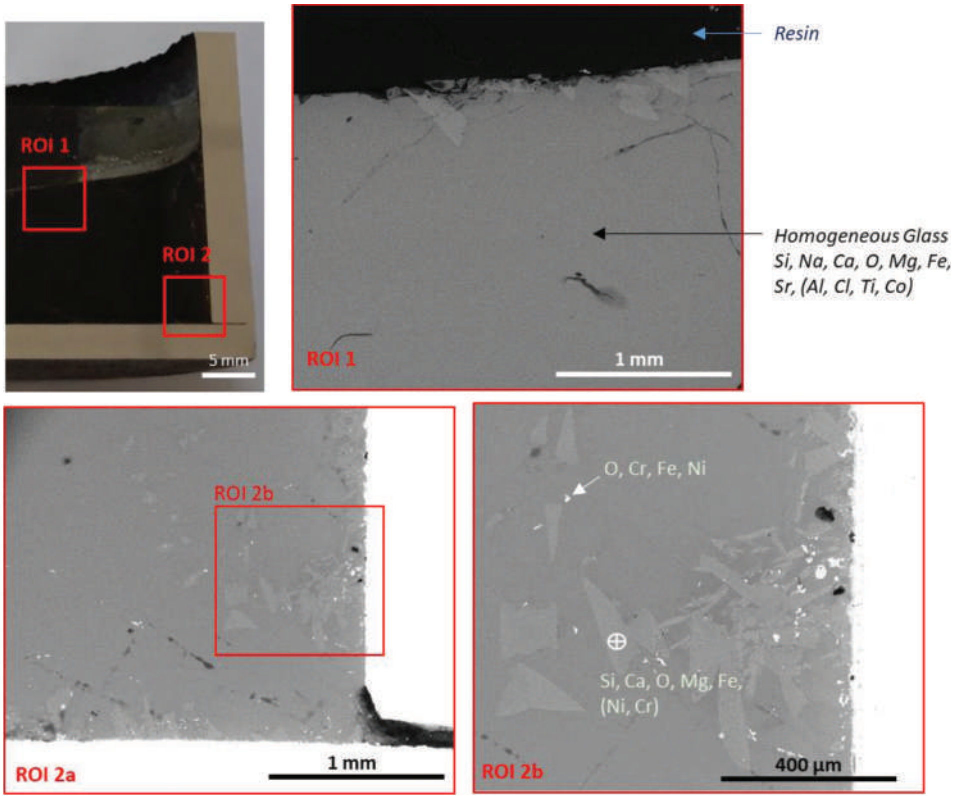


**Fig. 3.** SEM imaging of the wasteform, $WL_{ox} = 40$ wt.%.

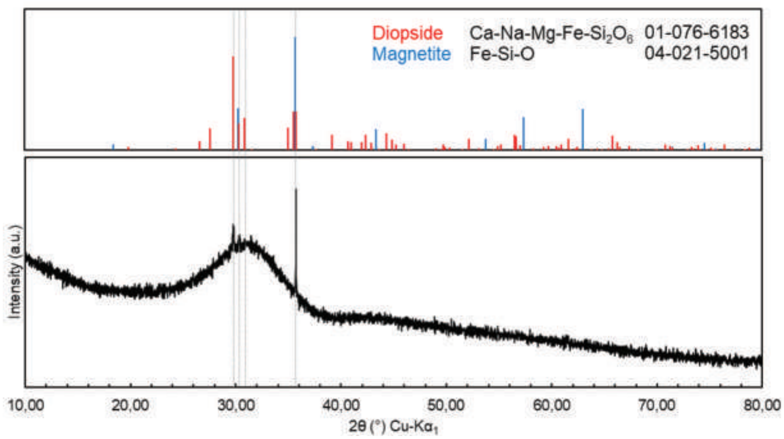


**Fig. 4.** X-Ray diffractogram of the wasteform $WL_{ox} = 40$ wt.%.

wasteform obtained with the nominal parameters selected for the study: $WL_{ox} = 40$ wt.%, a homogeneous mixture of ALPS slurries with the glass frit supplied as flakes, and a refining temperature of 1100 °C. After each test, the crucible is cut to characterise the vitrified material. Visual and microstructural analyses are performed.

Scanning electron microscopy (SEM) (Fig. 3) and X-ray crystallography (Fig. 4) are performed and are presented here for the nominal sample shown in Figure 2. The SEM observations of the cross-section show a homogeneous glass in a major part of the sample, composed of Si, Na, Ca, O, Mg, Fe, Sr, Al, Cl, Ti, Co, and B. The amorphous state of the wasteform is also confirmed by the X-ray diffractogram. Very few grey crystals are visible on the surface and especially near the metallic crucible wall. These crystals are silicates of Ca, Mg, Fe, a diopside phase according to the X-ray diffractogram, and contain also some Ni or Cr. These two last elements are not present in the initial material composition, they come from the crucible. Some small crystals, in white colour, are present near the big grey crystals and contain Cr, Fe, and Ni. These particles, coming from a very slight crucible corrosion, could act as nucleating agents for the silicate crystals, favouring their growth, and are localized in the

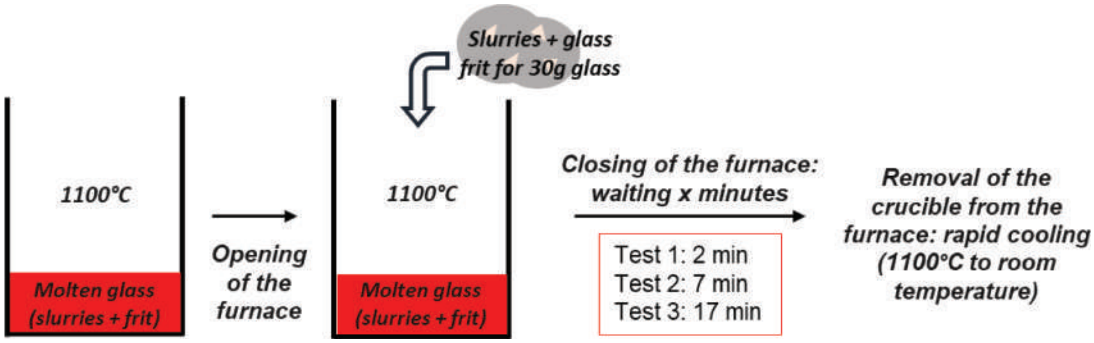


**Fig. 5.** Principle of the reactivity tests at high temperature.

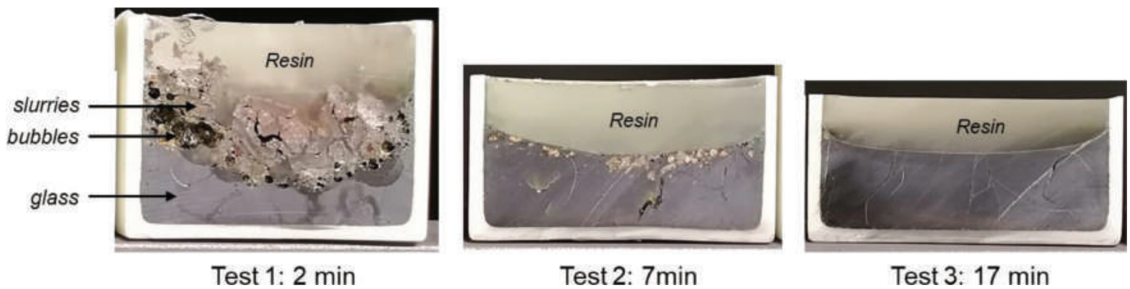


**Fig. 6.** Half-cut crucibles after the tests to see the evolution of the material with the time of digestion.

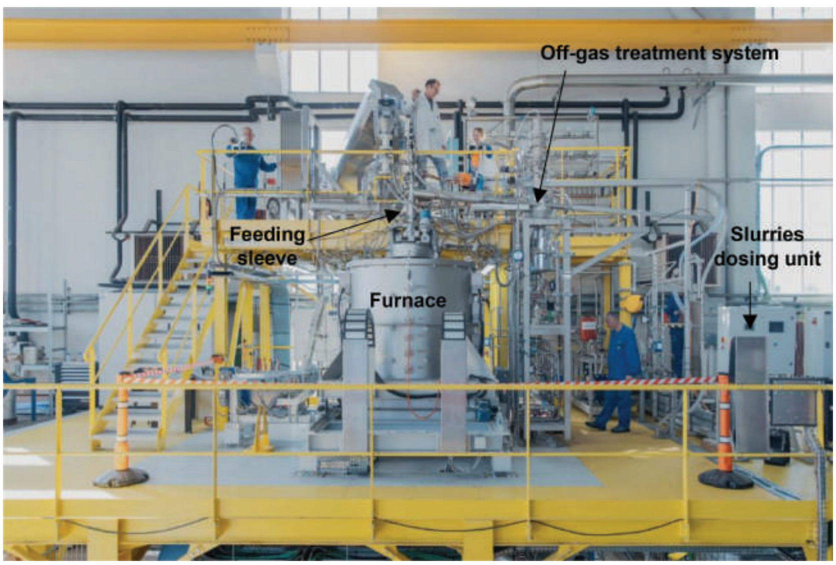


**Fig. 7.** Photo of the DEM&MELT inactive pilotdemonstrator at CEA Marcoule (© Y. Audic/CEA).

interface areas which favour heterogeneous nucleation. So a glass matrix is obtained with very few crystals which do not impact the durability of the matrix and which are not containing Sr.

### 3.2 Study of the reactivity between slurries and glass frit

During the course of an In-Can treatment, raw material (waste and/or glass additive) is first preloaded into the canister at ambient temperature and then heated until the selected treatment temperature. Then, waste and/or glass frits are usually fed on the molten glass in order to fill the canister. At the laboratory-scale usual tests in muffle furnaces are made under static conditions, with no material feeding during the thermal treatment. The so-called "reactivity tests" at high temperatures described in the following aimed to mimic material feeding and to estimate the time of fed material digestion in the molten glass.

The principle of the test is described in Figure 5. A mix of slurries and glass frit ($WL_{ox} = 40$ wt.%) is poured on a molten glass (corresponding to a $WL_{ox} = 40$ wt.% wasteform) at 1100 °C. After waiting $x$ min ($x = 2$ min for Test

1, 7 min for Test 2 and 17 min for Test 3), the crucible is removed from the furnace to "freeze" the state of the material by rapid cooling from 1100 °C to the room temperature. The goal is to follow the reactivity steps between the fed material and the glass bath as a function of time and to look at the evolution of the microstructure at the interface between the molten glass and the added mixture.

Visual observations presented in Figure 6 show fast digestion of the slurries under static conditions (<20 min at 1100 °C). After two minutes at 1100 °C, the addition of mix slurries + glass frit is not assimilated. Large bubbles are visible at the boundary between the glass and the added material, coming from the decomposition process of the slurries. After 7 min at 1100 °C, the reaction of slurries + glass frit with the molten glass has begun but some fragments of slurries are still present on the glass surface, associated with the presence of very small bubbles. After 17 min at 1100 °C, the added slurries + glass frit are completely digested: a homogenous glass is visible at the macroscopic scale.

Reactivity tests at high temperatures showed fast digestion of the slurries inside the molten glass bath, meaning that a good reactivity between constituents at 1100 °C can be expected at full-scale.

### 3.3 Results of the sensitivity tests

The other tests made in the sensitivity study are not shown in detail but they showed that a homogeneous glass was obtained with a $WL_{ox}$ of 40 wt.% in a temperature range between 1050 and 1130 °C. The glass frit shape, tested with three different shapes (flakes, beads and fine powder), did not affect the wasteform quality.

Therefore, the feasibility of the vitrification of ALPS slurries was validated at the laboratory scale and nominal operation parameters were selected for the full-scale test.

## 4 Full-scale

### 4.1 DEM&MELT In-Can vitrification demonstrator

Test at full-scale was performed on the DEM&MELT demonstrator located at the CEA Marcoule site. A picture of the prototype is shown in Figure 7. In the In-Can vitrification process, the canister is directly used as a melter and renewed after each batch. The container is first preloaded with waste and/or glass additives, then placed into the resistive furnace composed of two half shells. During the heating, glass frit and slurries are added. A special feeding system was developed to be able to continuously feed this constraining waste. Indeed, slurries are very hard to process regarding feeding function: their rheology is penalizing (high viscosity) and it has a high tendency to stick. An OGTS enables stopping volatilized species released from the melt and recycling them into the melter in order to increase the radionuclides trapping in the glassy confinement matrix.

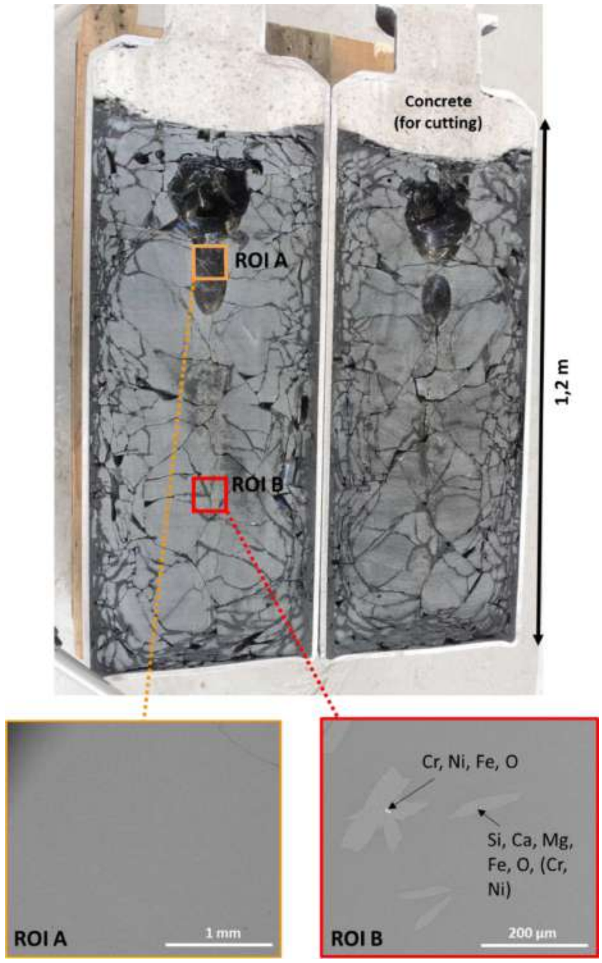


**Fig. 8.** Half-cut container obtained after vitrification of ALPS slurries using DEM&MELT prototype ($WL_{ox}$ = 40 wt.%) and SEM pictures of its microstructure.

### 4.2 Vitrification of ALPS slurries

A vitrification test of ALPS slurries surrogates was performed on the DEM&MELT full-scale demonstrator at a melting temperature of around 1100 °C. A full container was produced (∼280 kg of material) containing ALPS slurries with a $WL_{dry}$ of 60 wt.% (corresponding to a $WL_{ox}$ of 40 wt.%). The measure of Sr volatility gave very good results with a low value of $7 \times 10^{-3}$ wt.%. A picture of the container cut in two parts is shown in Figure 8.

Such as observed at the laboratory scale, the final wasteform is a black homogenous glass. Microstructural SEM analyses on different locations of the canister were performed: results are consistent with the laboratory scale result. As confirmed also by X-ray diffraction (not shown, but similar to laboratory-scale), the wasteform is an amorphous glassy material. Very few crystals are visible inside the glass matrix for some locations and are composed of Si, Ca, Mg, Fe, O and a bit of Cr and Ni, such as diopside crystals seen at the laboratory scale. No Sr was identified in these crystals, it was located in the glass matrix.

## 5 Conclusion

The feasibility of ALPS slurries conditioning into a borosilicate glass wasteform was studied using the DEM&MELT In-Can process. The upscaling methodology enabled us to find the best parameters such as the optimal waste loading or the melting temperature before operating full-scale tests using the DEM&MELT demonstrator.

The vitrification demonstration of ALPS slurries was successfully performed, with a high waste loading. Good homogeneity of the glass melt was ensured with the DEM&MELT In-Can vitrification process, thanks to the natural thermo-convection loop triggered inside the molten glass that ensures a good reactivity between the waste and the glass additives.

The final wasteform is a homogeneous, monolithic and dense vitrified material exhibiting only a few isolated crystallizations. The high waste loading achieved of 60 wt.% (in dry mass of slurries) leads to a significant volume reduction of ALPS slurries: volume of waste reduced close to 1/12 considering ALPS slurries in the liquid form before the filter press process. The volatility of Sr was low, less than 0.007%, meaning that nearly the whole amount of Sr coming from slurries was confined into the wasteform. A formulation study could still allow for increasing this WL.

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## Conflict of interests

The authors declare that they have no competing interests to report.

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## Data availability statement

This article has no associated data generated and/or analysed.

## Author contribution statement

Aliénor Vernay performed laboratory-scale tests and material analysis and wrote the manuscript. Hélène Nonnet supervised laboratory-scale tests with Aliénor Vernay and reviewed the manuscript. Caroline Michel and Jean-François Hollebecque performed the full-scale test and reviewed the manuscript. Maxime Fournier and Régis Didierlaurent performed the project management and reviewed the manuscript.

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Regular Article — Open Access

# CHICADE nuclear facility: a collaborative technological platform, dedicated to the expertise and characterisation of nuclear wastes

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**Abstract.** CHICADE (CHimie CAractérisation DEchets – Chemistry CAracterization Wastes) is one of the nuclear facilities of the Energy Division of the French Alternative Energies and Atomic Energy Commission (CEA/DES). The CEA/DES is responsible for structuring and piloting the research programmes on energy at CEA. It involves its own institutes of research and those of other divisions. CHICADE is part of the Directorate for Nuclear Dismantling, Services and Waste Management. The Laboratory of Expertise and Destructive characterization is set up in the Basic Nuclear Facility – N° 156 called "CHICADE" where heavy equipment is used. The laboratory brings together both skills and means of characterization, using destructive methods on nuclear waste packages. It also carries out measurements on the whole waste package (gas release measurements, leaching tests). After a short presentation of the CEA and the Cadarache Centre, this publication aims to present the CHICADE facility and present the types of expertise on nuclear waste that are conducted there, i.e., measurement of the diffusion coefficient, inventories, leaching test, permeability measurement, gas measurements, radiochemistry, imaging. In conclusion, CHICADE is a nuclear facility with unique equipment, allowing exhaustive expertise to be carried out in a single location, benefiting from cross and complementary methods.

## 1 Introduction

The CHICADE facility is located in the CEA centre of Cadarache (Cf. Fig. 1), which is one of the CEA's historic centres as it is celebrating its 63rd anniversary. This centre was home to the first experimental fission reactors for electricity production and also for naval propulsion, but Cadarache is also a platform for fusion, solar energy and life sciences.

The CEA is made up of several directorates: the Directorate of Military Applications, the Directorate of Fundamental Research, the Directorate of Technological Research, and the Directorate of Energies (DES), of which the CHICADE installation is a part.

The DES is responsible for the production of low-carbon energy, resource management, global system performance, the functioning of the energy system and, the main topic of CHICADE, which is nuclear decommissioning and dismantling (D&D), including project management for D&D and operation of nuclear service facilities, innovation and advanced R&D in support of this and waste management.

CHICADE (Cf. Fig. 2) is involved in R&D and technological development in the field of nuclear waste. It is part of the CEA Directorate of Energies and Directorate for Dismantling, Nuclear Service and Waste Management Projects which, overall, generate annually 25 000 $m^3$ of waste through its dismantling sites; this flow, therefore, requires support in terms of expertise and technology development, which is provided by CHICADE and made available to other producers.

## 2 Presentation of the CHICADE facility

CHICADE is a Nuclear Facility of more than 6000 $m^2$, including 4000 $m^2$ of hot surfaces, with a wide range of equipment from the bench to the fume cupboards (Cf. Fig. 4), to the glove box, and even to the shielded cells (Cf. Fig. 5) and measurement casemates (Cf. Fig. 3).

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**Fig. 1.** CEA Cadarache center.

**Fig. 2.** The CHICADE facility.

**Fig. 3.** A measurement casemates.

**Fig. 4.** Fume cupboards.

Thus, it allows the assessment of waste, ranging from mg to several tons, from mBq to TBq!

The fifty or so CHICADE employees contribute to the activities of the six laboratories, each with its own field of expertise: operation, characterisation, radiochemistry, imaging, gamma spectrometry and also the manufacture of fission chambers.

These skills, both technical and human, give CHICADE the opportunity to carry out research and technological development activities enabling us to supervise the research work of PhD students, conduct teaching activities and meet the needs of other waste producers such as ITER, ONDRAF/NIRAS, Orano, EdF, etc.

The LECD, i.e., the Laboratory of Expertise and Destructive Characterization, is set up in the BNF (Basic Nuclear Facility – N° 156) called "CHICADE" where heavy equipment is used.

The laboratory brings together both skills and means of characterization, using destructive methods on nuclear waste packages. It also carries out measurements on the whole waste package (gas release measurements, leaching tests) and is associated with other experimental laboratories within the framework of the R&D programs of the DES.

**Fig. 5.** The Cadecol shielded cell.

**Fig. 6.** Fission chamber.

**Fig. 7.** Logo of CHICADE.

It should also be noted that fission chambers are manufactured at CHICADE, in addition to the waste activities (Cf. Fig. 6).

The purpose of fission chambers is to measure the neutron flux in reactors. This measurement is important because it allows the heat flux to be regulated and the safety of reactor operation to be controlled.

## 3 Objectives of the assessments on nuclear wastes

The objectives of the assessments carried out at CHICADE (Cf. Fig. 7) are, therefore:

1. expertise in order to transport nuclear wastes to the appropriate waste stream,
2. development of waste conditioning methods,
3. sample controls of waste assigned to the existing waste stream.

CHICADE is, therefore, able to assess nuclear waste packages and answer certain questions, some of which are important for the safe storage of nuclear waste, such as:

- will the radionuclides contained in concrete waste packages remain in these packages after several hundred years and under severe conditions?
- Is the assessed waste assigned to the right waste outlet or is there a more suitable waste stream?
- Does the mechanical strength of the waste packaging comply with the storage requirements, in particular with regard to the stacking of waste packaging?
- For new waste, what are the methods for blocking the package to meet the storage requirements?
- …

**Fig. 8.** Preparing an inventory.

**Fig. 9.** Remote manipulators.

## 4 Presentation of expertise capacities of CHICADE

The means of expertise available on CHICADE enables the actions described in the following paragraphs to be carried out.

### 4.1 Inventory of the nuclear waste package content

This is the most basic investigation performed but not the easiest (Cf. Fig. 8). The objective of these investigations is to ensure the conformity of the content of technological waste packages to the acceptance criteria. According to the type of radiological risk involved, these operations are carried out using various types of equipment: vinyl tents, alpha cells, shielded cells and protective clothing adapted to the radiological exposure risks of the operators.

The inventory includes the identification of the type of waste, its activity, its conditioning state, and its weight distribution...

### 4.2 Destructive sampling

CHICADE is equipped to the core and/or cut waste materials up to several tons and to take samples suitable for the expertise to be performed. CHICADE is able to cut through drums under water spray and to drill dry axially or radially through shells. For this purpose, CHICADE owns suitably equipped shielded cells.

These equipments are the 'Alceste' (Cf. Fig. 10) and 'Cadecol' shielded cells which can handle waste packages up to 2 $m^3$, 16 tons and up to 11.1 TBq of activity.

For $\alpha$ or $\beta$-type waste packages with irradiated contents, all operations are carried out by a remote manipulator(Cf. Fig. 9) beginning with the opening by coring to the closing of the cored package by filling it up and subsequent removal of the samples and waste induced.

The coring process (Cf. Fig. 11) allows researchers to penetrate and sample envelopes of the waste package

**Fig. 10.** The Alceste shielded cell.

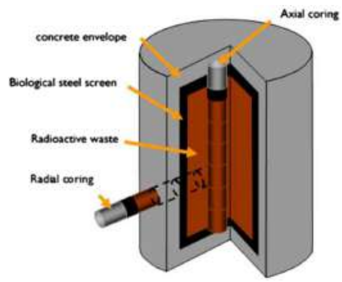


**Fig. 11.** Schematic diagram of core drilling.

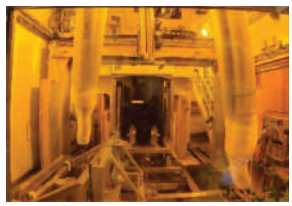

**Fig. 12.** Installation of an 870 l drum in CADECOL.

(mortar, concrete, possible biological steel screens and/or shielding) and to reach embedded waste in order to take samples.

Contrary to the wet process, the dry coring process, avoiding leaching of the samples, allows researchers to conduct leaching tests on samples (to measure the retention characteristics of radioelements in the matrix "waste").

These samples, obtained by dry coring of the waste package, are then prepared for the following analyses: permeability to gases, mechanical resistance, and radionuclide containment capacity... They can be evaluated by measurements taken on the whole waste package or on one of its components, concrete envelope, biological shielding steel screens or the waste itself.

In the latter case, those cores are then sliced into standardized sample shapes and sizes for experiments such as the determination of physical-chemical parameters (i.e., diffusion coefficients, leaching coefficients, compressive strength).

The cutting under water spray in CADECOL (Cf. Fig. 12) makes it possible to characterise and take samples. These assessments and characterisations aim to improve knowledge of the packages, optimise current and future characterisation methods and tools, and meet the storage requirements.

**Fig. 13.** Diffusion cells.

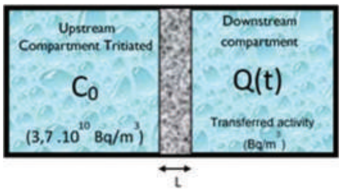


**Fig. 14.** Principle of measuring the diffusion coefficient.

**Fig. 15.** Permeability test.

### 4.3 Measurement of the diffusion coefficient

The capacity of the waste packages to contain the radionuclides in a saturated medium is an important characteristic for the safety of the storage.

The objective of the measurement of the diffusion coefficient is to answer the question: "Will the radionuclides contained in concrete waste packages remain in these packages after several hundred years and under severe conditions?"

This property is measured using a test of diffusion of tritiated water through a concrete sample (Cf. Fig. 13) that can have been cored in the envelope of the waste package (Cf. Fig. 14).

It is also possible to measure the diffusion coefficient of other materials, e.g., paints for containment purposes.

### 4.4 Permeability measurement

This expertise is to answer the question: "to which extent, a radioactive waste package is able to remove the gases produced by radiolysis (such as $H_2$, CO ...)".

CHICADE conducts a permeability test using nitrogen on samples cored in the envelope and the active part of the waste package (Cf. Fig. 15).

Special equipment is used to apply a gas pressure on the side of a sample in order to measure the flow through it. A permeability coefficient is thus deduced and must correspond to an expected characteristic.

**Fig. 16.** Mechanical resistance measurements.

**Fig. 17.** 870 L FI setup in airtight enclosure (middle) and closed airflow circuit for accumulation data acquisition (right).

### 4.5 Mechanical resistance measurements to compression

In storage, the mechanical resistance of the waste packages is also an important property.

The stacking of the waste packages requires preliminary tests or measurements in order to determine the mechanical resistance of the components in the waste packages to compression.

The cores of embedded waste or concrete from the envelope are sliced into standardized samples. These "test-samples" are then subjected to compression tests using a 50 or 100-Ton press and placed in a glove box or shielded cell according to their activity level. The pressure of the load is increased gradually until fracture. The measured value must be higher than the limit of acceptability (Cf. Fig. 16).

### 4.6 Gas measurements of waste package gas release

The storage of many waste packages requires knowledge of the nature and quantities of the gases released. In order to carry out these measurements, CHICADE has specifically designed equipment adapted to the various types of existing waste packages.

These gas analyses are carried out either on individual packages or in storage wells.

The technique used is either gas air flush measurements or gas accumulation measurements.

With regard to the accumulation technique, the basic tool is an airtight container in which the released gases are accumulated and then sampled for identification and measurement (Cf. Fig. 17).

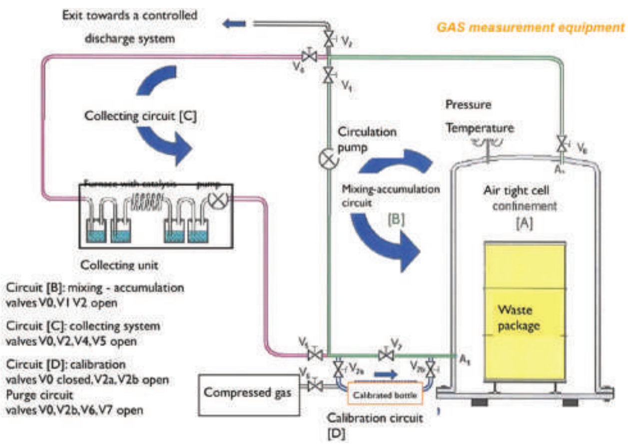


**Fig. 18.** Description of an accumulation measuring device.

**Fig. 19.** Leaching test.

Gas chromatography is then carried out using a sample of the released gas in order to quantify it. The radionuclides produced in gas forms are collected in order to be measured by a bêta liquid scintillation method (Cf. Fig. 18). This makes it possible to quantify gases such as tritium, and carbon-14...

### 4.7 Leaching test

The capacity of containment in a saturated medium of a block of waste and its coating is one of the important characteristics taken into consideration for storage.

A complete immersion of the waste is carried out on an entire waste package or a sample. This is the leaching test (Cf. Fig. 19) lead in the most unfavourable conditions (complete immersion vs. partial immersion).

The sampling of the leaching water during immersion is done according to a precise timetable. These water samples enable the rate of radionuclide release to be measured.

Over very long periods, such as those involved in storage conditions, radionuclide release can be calculated.

### 4.8 Development of solid waste conditioning methods

Another objective of CHICADE is the technological development of new waste conditioning methods this is to say to define and qualify new formulations (e.g., hydraulic binder) and/or new conditioning technologies, in line with downstream requirements.

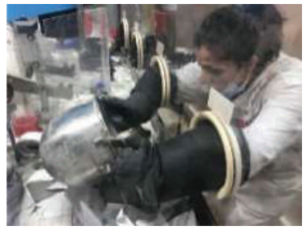

**Fig. 20.** Cementing of incinerator ash.

**Fig. 21.** Packaging of unused sealed sources.

These actions are carried out either in existing equipment (i.e., glove boxes) or in specific equipment designed and installed in CHICADE.

Two of our projects are presented below.

The first is the cementing of ashes originating from the incineration of radioactive wastes (Cf. Fig. 20). The formulation of the hydraulic binder was developed in cold conditions on dummy ashes and is currently being tested in hot conditions on the basis of aliquots of real ashes. The parameters studied are the incorporation rate and compliance with technical tests.

The second project under technological development is the packaging of unused sealed sources in 870-litre drums for the purpose of ILW-LL storage (Cf. Fig. 21). Once this process has been developed, it could be entrusted to an industrial company for packaging all the sources in the inventory.

### 4.9 Radiochemical analysis

The objective of the activities carried out in radiochemistry is to define and implement chemical and radiochemical analysis techniques, to develop analysis methods, to carry out expert assessments or characterisation and control operations, and to provide external support.

In the field of waste expertise, the challenges are to establish and update inventories, study the behaviour of radionuclides for storage, and characterisation of samples or structures.

### 4.10 Imagery

The objective of imaging is to obtain a non-destructive assessment of the waste. The associated challenge is to detect and interpret radiation on objects designed to reduce it to a minimum, for radiation protection purposes (Cf. Fig. 22).

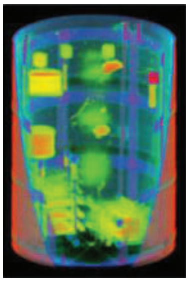

**Fig. 22.** Imagery of a nuclear waste.

Techniques developed and implemented at CHICADE are:

- physical characterization: X-rays and CT scans – HE.
- Radiological characterization: $\gamma$ spectrometries – Passive and Active Neutron Measurements.
- Chemical characterisation: $\gamma$ spectrometry after neutron/photon activation.

To do this, CHICADE has a number of facilities ranging from the bench to the fume cupboards, to the glove box, and even to the shielded cells and measurement casemates that allow the assessment of waste, ranging from mg to several tons, from mBq to TBq!

CHICADE has an organisation that highlights the six areas of expertise (operation, characterisation, radiochemistry, imaging, gamma spectrometry and also the manufacture of fission chambers) necessary for its mission.

Finally, CHICADE has the human resources to fulfil its missions of expertise on nuclear waste, research and technological development, to supervise the work of PhD students, to carry out teaching activities and to respond to requests from partners.

In conclusion, CHICADE is a nuclear facility with unique equipment, allowing exhaustive expertise to be carried out in a single location, benefiting from the cross and complementary methods.

## 5 Conclusion

In conclusion, CHICADE is therefore a strategic facility for nuclear waste management, allowing:

- to carry out the necessary expert assessments on existing waste to assign it to an open outlet or to define a new waste stream,
- technological development of waste conditioning processes, to send them to an existing or future waste stream,
- to record, by sampling, the conformity of waste streams sent to open outlets.

## Conflict of interests

The authors declare that they have no competing interests to report.

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## Data availability statement

This article has no associated data generated.

## Author contribution statement

All the authors have equally contributed to this article.

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# EURATOM PROJECTS & ENS YGN EVENTS

## EXHIBITION B2B

### Poster (60 per day, Euratom projects, MSc/PhD/R&D, 180 in total)

An opportunity to present your research results, within or related to the topics covered, at the conferences, to the Euratom and International Research Community. Euratom projects, PhD/MSc Students (under 35 years' old) are encouraged to submit abstracts related to the dedicated topics of the conferences, as well as R&D researchers from organisations not directly involved in projects co-funded by Euratom.

### Exhibition (20 per day, 20 in total)

Exhibition booths will be set up for almost 20 organisations to showcase advancements in various cross-cutting innovative, engineering, industrial and high-tech technologies relevant to nuclear and non-nuclear applications, radiation protection, radioactive waste management and geological repository development. Exhibition booths will remain open during all sessions and breaks and will give the opportunity for intensive B2B meetings.

### ENS-YGN events & B2B Matchmaking (estimated 200 in total)

ENS-YGN is a vibrant network connecting all Nuclear Young Generation Networks over Europe. These events, including Young Generation workshops, are a huge opportunity for Students, MSc/PhDs or young professionals to meet national / European / International leading managers, innovators and researchers from public and private research organisations.

Around 200 candidates will be selected after having submitted their CV. In depth 30 min face-to-face matchmaking interviews and networking opportunities will be organised for them with leading national / international managers, participating companies or even recruiters. This event will allow companies active in the nuclear industry, public and private research organisations or academia, to meet and interview students, graduates, engineers and experienced professionals to start or pursue their career within Europe and beyond. Institutions such as Nuclear Valley or GIFEN will take part in the event.

# ENS YGN WORKSHOPS

## ENS YGN WORKSHOPS

# Workshop 1: Are you ready for the international job market?

### Description of the event

Co-organised by Thomas Thor and ENEN

**Attendees** – young professionals with 1-10 years experience in the industry/research

**Workshop overview**

The session will be a joint insight of Thomas Thor Associates – recruitment consulting and young professionals who took a chance to start international careers in different sectors of nuclear science and industry.

The workshop will be enriched by the recent results of the global project measuring the attitude of young people towards nuclear jobs – the World Young Generation Nuclear Thermometer.

The aim of the workshop is to provide attendees with information and practical advice that they can use to understand and access the international job market.

Join us and ask everything you always wanted to know about a career in nuclear!

**Moderators:** Callum Thomas, Thomas Thor and Andrea Kozlowski, ENS-YGN

**Programme**

**Introduction with career testimonials of young professionals**

**Session 1 – Understanding your own motivations & priorities (30 minutes)**

Introduction, and then working in pairs to ask each other questions and create a picture of what each of you are looking for (example questions will be provided in the introduction)

**Session 2 – Mapping your motivations & priorities to opportunities in the international job market (30 minutes)**

Introduction, and then working in the same pairs again to create an outline of which countries, organisations and projects match each person’s capabilities, motivations and priorities

**Session 3 – Tools and techniques for successful international careers (30 minutes)**

- Information sources that can help you gather relevant information
- How to find and work with mentors and sponsors
- Network building
- Getting involved in areas of interest and building your personal brand

**Summary and Close – (10 minutes)**

A recap on what has been covered and suggestions of follow up and next steps

## Summary of the workshop

The workshop took place at the FISA 2022 & EURADWASTE '22 conference. It was led by Callum Thomas (CEO of Thomas Thor) and Andrea Kozlowski (ENS-YGN) and was attended mostly by young professionals with 1-10 years' experience in the industry.

The session included joint insights of Thomas Thor Associates, the international recruitment specialists, and young professionals who have started international careers in different sectors of nuclear science and industry.

The workshop was enriched by the recent results of the global project measuring the attitude of young people towards nuclear jobs – the World Young Generation Nuclear Thermometer.

The aim of the workshop was to provide attendees with information and practical advice that they can use to understand and access the international job market.

**The programme was structured as follows:**

### Session 1 – Understanding your own motivations & priorities

Working in pairs to ask each other questions and create a picture of what each of you are looking for (example questions were provided in the introduction)

### Session 2 – Mapping your motivations & priorities to opportunities in the international job market

Working in the same pairs again to create an outline of which countries, organisations and projects match each person's capabilities, motivations and priorities

### Session 3 – Tools and techniques for successful international careers

- Information sources that can help you gather relevant information
- How to find and work with mentors and sponsors
- Network building
- Getting involved in areas of interest and building your personal brand

### Participant Perspectives and Takeaways

There were some very interesting and valuable points raised during the discussion as well as takeaways from the workshop, including:

- There is often a high degree of uncertainty and ambiguity when career planning, due to the vast amount of options and directions available

- People who like certainty and are less comfortable with ambiguity, which characterises many people in the nuclear industry, find this type of planning difficult. We discussed how career changes could be seen as experimenting, looking for what works and what doesn’t and gathering evidence to inform decisions and steps

- Many participants realised things about themselves that they had not really fully acknowledged, so the exercise of speaking aloud about priorities and preferences acted as a catalyst to formalise their thinking and prepare for action

- Many participants had experience of mentoring, but not all were positive experiences. We discussed the importance of matching suitable mentors and mentees and in structuring the relationship.

# Workshop 2: Communicating science - Don’t waste it!

**Description of the event**

As scientists and nuclear professionals, we often have the opportunity to speak about nuclear and to share our passion for it. How do we best get this across? How can we communicate science?

Let’s take the example of nuclear waste. We are often confronted with questions about it. Don’t waste the opportunity and provide facts in an understandable way, using simple comparisons and handy references. Come and learn how to lead an engaging conversation!

**Moderators:** John C.H. Lindberg – author of a communications guide to conversations about nuclear.

Elsa Lemaitre, Chief Internal Auditor, CEA and Deputy Head of French YGN on Innovation

**On the agenda:** hands-on training on communications. We will all together develop a simple guide on communicating about nuclear waste.

What is important before you start

The magic of the first sentence

Facts about waste

Comparisons and visuals

Conclusion

## Summary of the workshop

### Goals:

The purpose of this workshop was to identify the challenges of communicating nuclear science, using the example of nuclear waste. Currently, several countries face the challenge of translating the language of scientists and nuclear professionals and their passion understandably. The presented communication method is explored into the depth, using participant exercises to enhance the discussion and target awareness.

### Summary:

The workshop focused on targeted communication and alternated between theory and practical parts. First, a group of young professionals showed several short plays, which dealt with realistic situations and typical mistakes made by the professionals whilst communicating. The target groups were society representatives, pupils, media, and policymakers. Elsa Lemaitre-Xavier presented the common fears appearing in public related to nuclear waste. During a short group session, each participant identified common fears in their professional area and country. Following, Stephanie Thornber presented a simple guide for successful communication, comprising five questions:

| | |
|---|---|
| • What is the message you want to convey? | Message |
| • Who is your audience? | Audience |
| • How to structure your content for your target audience? | Voice |
| • How are you going to deliver your message? | Channel |
| • What do you hope to achieve? | Outcome |

Examples have illustrated the method (e.g., HABOG building in the Netherlands) and applicable tips (Do’s and Don’ts) on successful communication regardless the audience have been shared. The focus on the workshop was to share and get practical experience. Therefore, small groups dealt with one of the exemplary audiences, identifying the challenges during communication and fear-overcoming information dissemination.

At the end of the workshop, the groups presented messages related to nuclear waste management, which are outstanding fact-based information. Overall, the participants gained skills in communication and increased their awareness of stepping out the professional bubble.

### Workshop participants:

Participants represented a variety of both domestic and international sectors, including federal governments, universities, private consulting firms, and NGOs.

**Workshop Organizer:**

**Elsa Lemaitre-Xavier**

Chief Internal Auditor

Commissariat à l’énergie atomique et aux énergies alternatives (CEA)

Deputy head of the French YGN on Innovation (SFEN)

Société française d'énergie nucléaire

**Stephanie Thornber**

Waste Management Specialist (SF&NM)

Nuclear Waste Services

# Workshop 3: Nuclear for Climate - Positive campaigning of nuclear topics”

## Description of the workshop

Imagine the enormous impact you, as a single individual, has in the climate change conversation. Your voice is powerful, and when directed in the right places, highly impactful. And now imagine what would happen if we compounded all our efforts, sharing the same message across the globe, to communicate to leaders and decision makers that 'enough is enough: we need action now'. It would be immense.

Global climate activism describes a growing movement of young people across the world taking action to halt the devastating effects of climate change. We are determined to reach net zero before 2050, and firmly believe that following the science and being technology inclusive is the best way to achieve this. Nuclear energy working alongside other clean energy technologies is essential to reaching this goal.

Using the ‘I, us, we’ principles of climate activism, this interactive, thought-provoking workshop will equip you with the necessary tools to communicate nuclear energy to friends, family, strangers, and everyone in between. This two-hour session will explore how trust, people and action lie at the heart of a successful climate campaign and how we can use the principles of compound interest to prepare for COP27. It will also give attendees the opportunity to explore their personal voice and contributions to the climate conversation, especially around discovering how to become bold, vocal climate champions.

We will draw on the experience and learnings of the hugely successful #NetZeroNeedsNuclear COP26 campaign, and workshop how we can build upon these achievements for November’s COP27 conference.

Join the Nuclear for Climate team as they guide you through this engaging, action-focused workshop. Open to all backgrounds, viewpoints, experiences. #Togetherisbetter

Moderator: Sophie Zienkiewicz

**Summary of the workshop**

"Imagine the enormous impact you, as a single individual, has in the climate change conversation. Your voice is powerful, and when directed in the right places, highly impactful."

This statement is what attendees to the Nuclear for Climate workshop were welcomed with at the beginning of the Wednesday afternoon session at the Euratom conference hosted in Lyon, June 2022. During the thought-provoking two-hour workshop, facilitated by Sophie Zienkiewicz, a Nuclear for Climate volunteer, the 30+ participants were challenged about their current perceptions of nuclear campaigning, and importantly, equipped with the tools to become a bold, confident nuclear advocate. It also created opportunities for delegates to reflect upon how people and action lie at the heart of a successful climate campaign and how we can draw upon the success of the Net Zero Needs Nuclear COP26 campaign, to effectively prepare for COP27.

A truly international group, the early career workshop delegates composed of industry individuals from across the globe, bringing a wealth of knowledge and experience to the session. But it was their enthusiasm and willingness to embrace a new way of approaching an old question - how do we become more efficient nuclear advocates? - that was really inspiring!

In groups of six, the workshop kicked off by asking: 'Why does nuclear energy need to be a part of the climate change conversation?'. A seemingly easy question that delegates instantly got to work answering. What was interesting though was how varied the responses were. Some teams discussed energy security, others debated the desire for battling climate change, whilst other teams talked about contributions to the UN Sustainable Development Goals and achieving social impact.

After ideating around the numerous merits of involving nuclear energy in the climate conversation, groups then took a step back to consider how nuclear energy fits into the wider context. The exercise gave teams the opportunity to analyse what other industries and existing successful climate campaigns all have in common. Key factors included emotional hooks, calls to action, and human-centric messaging.

So now that the delegates were equipped with the 'Why' and the 'What', it was time to consider 'How'. Being bold, creative and unforgettable is a huge factor in the success of a climate campaign. The Nuclear for Climate Team challenged the group to remove their own preconceptions about what a 'typical' nuclear campaign entails, and come up with the most innovative, unique ways of communicating the benefits of nuclear energy.

The suggestions were inspired! The ideas ranged from Eurovision songs, television series, children's books through to adverts at airports and train stations. It was rewarding to see was the creativity and confidence of the campaign suggestions!

However, equally as important to consider are the barriers and misconceptions nuclear energy faces. By identifying the hurdles advocates experience when communicating nuclear energy to different audiences, the group was able to devise tools and techniques about how to manage them. One of the greatest barriers the group discussed was around contextualising the positives of nuclear energy to the public. Workshop facilitator, Sophie, shared the example of how the COP26 team used gummy Bear sweets to explain the principle of uranium fuel pellet energy density. This concept of taking a complicated scientific principle and grounding it in everyday environments is key to effective communication of nuclear energy.

To close the workshop, the group was asked to reflect upon what attributes a successful nuclear activist has. Unsurprisingly, they realised that actually THEY had all the qualities and needed to effectively communicate nuclear in inspiring, novel ways.

**Personal reflection**

The greatest takeaway from the workshop experience was the sense that internationally, nuclear professionals are powerful climate advocates and are motivated to take action to halt the devastating effects of climate change.

We are determined to reach net zero before 2050, and firmly believe that following the science and being technology-inclusive is the best way to achieve this. COP27 is a golden opportunity to continue inspiring our nuclear colleagues and those outside of the industry to compounded all our extraordinary efforts, sharing the same ‘Net Nero Needs Nuclear’ message across the globe.

**Nuclear for Climate** is a grassroots initiative convening over 150 associations with the goal of educating policymakers and the public about the necessity of including nuclear energy among the carbon-free solutions to climate change. To find out more about our activities, visit our website here: https://www.euronuclear.org/nuclear-for-climate/

**Moderator:** The workshop was organised and moderated by Sophie Zienkiewicz, an accomplished public speaker and campaigner with excellent communication and leadership skills.

# ENEN PHD EVENT & PRIZE

**Description of the event**

Every year the ENEN PhD Event & Prize is organized to promote and support the work of young researchers in Europe (https://enen.eu/index.php/phd-events/).

**ENEN PhD Event & Prize** is an action of the European Nuclear Education Network to support the Research and Science in the Nuclear fields promoting the works of the young scientists and researchers who start their careers finishing their PhD. It takes place on a yearly basis in the framework of the international congress in the field of nuclear science.

**ENEN PhD Event** will consist of up to 12 PhD presentations nominated by ENEN Members and selected by the ENEN PhD Prize Jury. The event will be divided into several sessions according to the subjects. Participants will make a presentation of their research work for 25 minutes followed by 5 minutes of questions and discussion in a competitive but friendly environment.

All presentations will be judged by the Jury members taking into account the quality of the submitted paper as well as the quality of the presentation itself. Moreover, the participation in the discussion and the clarity in answering the questions received will also be taken into account in selecting the winners.

The **best three presentations** will be awarded the ENEN PhD Prize. And three awarded ENEN PhD Prizes related peer-reviewed papers should be published within the international Open Access Journal (EPJ-N) topical issue on FISA 2022 – EURADWASTE ’22 Awards and later within the conferences proceedings.

**Summary of the event**

*The 16th ENEN PhD Prize & Event took place in the framework of the 10th edition of the Euratom research and training conferences on fission safety of reactor systems (FISA 2022) and radioactive waste management (EURADWASTE '22), organised by the French Presidency of the Council of the EU and the European Commission, which was held on Monday 30 May – Friday 3 June 2022 in Lyon, France.*

https://enen.eu/index.php/phd-events/phd-ep-year-2022/

**The 3 Winners of the ENEN PhD Event & Prize 2021 are:**

- **Lubomír Bureš**, "Fundamental study on microlayer dynamics in nucleate boiling "
- **Chloé Cherpin**, "Measurement of the zeta potentials of corrosion products for their modelling in the primary circuit of PWRs in the OSCAR code"
- **Nicoló Abrate**, " An innovative eigenvalue formulation of the neutron transport problem for reactor design and control"

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 the conference.


FISA 2022
NEA


**The following Finalists were selected among all the received applications, to present their research works in the Event:**

- **Gabriel Pedroche**, “E-lite 360º neutronics model of the ITER tokamak”
- **Jaén Ocádiz Flores**, “Using the Quasi-chemical formalism beyond the phase diagram: density and viscosity models for molten salt fuel systems”
- **Andrea Di Ronco**,”Multiphysics simulation of next generation nuclear reactors: extension to fission product transport modelling”
- **Javier Alguacil**, “Propagation of statistical uncertainty in mesh-based R2S calculations”
- **Manon DELARUE**, “Photofission technique coupled to high-resolution gamma spectroscopy for the characterization of large concrete radioactive waste packages”
- **Alessio Magni**, “MOX-fuelled pins for fast reactor conditions: Modelling advancements and assessment”
- **Chengming SHANG**, “Implications of recently derived thermodynamic data for (Mg/Ca)nUO2(CO3)3(4-2n)- complexes on the predominance of the Mg-Ca-U(VI)-OH-CO3 systems, and application to natural waters.”
- **Simone Siriano**, “Numerical simulation of MHD flows in breeding blanket and plasma-facing components”
- **Norma Maria PEREIRA MACHADO**, “Rheological study of nuclear glass melts containing Platinum Group Metal aggregates”
- **Didier BATHELLIER**, “Properties of (U,Pu)O2 mixed-oxide fuels”

This year event was highly remarkable because of the friendly and competitive spirit of the participants where the questions between the fellow finalists raised the interest and admiration for each others' work.

With this activity, ENEN aims to promote the research work of PhD students. 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.

# SNETP ANNUAL FORUM

The SNETP Forum 2022 edition (https://snetp.eu/2022/02/28/save-the-date-for-the-snetp-forum-2022/) will be held on 2 June 2022 in Lyon, France, in conjunction with FISA 2022 (10th Euratom Conference on Reactor Safety) and EURADWASTE ’22 (10th Euratom Conference on Radioactive Waste Management).

The SNETP Forum 2022 will aim at discussing and analysing recent technological innovations in different fields selected by the SNETP Scientific Committee as to cover major topics of interest to the stakeholders of SNETP.

**Technical sessions**

**SMRs**

New innovative solutions are needed to ensure cost competitiveness with other power generation technologies, as well as speed of construction and implementation in local systems. In addition to the nuclear reactors in operation and those under construction, Europe needs to expand the range of reactors technologies available to meet national/local specificities. The development of different SMRs, based on most matured technologies or on other advanced technologies, offers the possibility to deploy flexible options for both power and non-power applications and contribute to decarbonisation of the economy. Research & Development & Innovation (R&D&I) should support the development of SMRs to make them safe and competitive with other means of production as part of a global deployment strategy over the coming decades.

**Nuclear codes and standards and supply chain**

Safety-related structures, systems and components (SSCs) of nuclear power plants are normally designed and produced according to stringent nuclear codes & standards (NC&S). Supplying such SSCs normally requires companies to establish and maintain costly nuclear quality-assurance (QA) programme. In response to growing supply chain challenges, European NPP operators started looking into greater deployment of high-quality non-nuclear industry standard components and equipment for safety-related SSCs of NPPs (i.e. commercial-grade dedication) and launched corresponding pilot projects with approval of their regulators. This is supported by European and international nuclear organisations like Foratom and the IAEA by providing guidance in this area. The further development of NC&S remains high on the agenda. Novel materials, manufacturing methods and technologies need to be included in NC&S before being allowed to be used for safety-related SCCs. This and also NC&S development for advanced reactors (SMRs, Gen IV) require significant R&D&I efforts. In this session, ongoing NC&S development activities and needs and supply chain related activities and challenges for the current reactor fleet and advanced reactors will be presented and discussed.

**Digital and robotics**

**Digital:** The digital transformation has become a cross-cutting trend to all industrial sectors and nuclear is no exception to this. The European Commission digital strategy aims to make this transformation work for people and businesses, while helping to achieve its target of a climate-neutral Europe by 2050. As such, it is essential for nuclear to be fit for the digital age, to achieve digital twins and a Digital Nuclear Reactor. Concerted R&D&I work is essential to make progress in terms of multi-physics modelling and simulation, high performance computing, data analysis and analytics, visualisation, virtual reality, advanced instrumentation (e.g. Internet Of things) and I&C.

**Robotics:** NPP operation combines a number of interlinked human, organisational and technical factors. A strong drive to opt for advanced robotics in nuclear industry appeared after the Three Mile Island incident and the development of engineering technologies. Improving nuclear power plant operation, health and safety of operators, managing safely their decommissioning are considered to be key, but also for further public acceptance of nuclear. If robots take over the human personnel in conducting risky operations, the latter will have a reduced exposure to radioactivity. Significant investments in artificial intelligence sustain this eventuality. Moreover, the ability to maintain the nuclear power infrastructure may depend on robots being able to carry out maintenance tasks that would otherwise be impossible, thus significantly extending the lifetime of reactors.

**R&D&I facilities**

Several R&D facilities have been shut down in the EU over the last decade. The loss of critical research infrastructures (i.e. facilities, capabilities and expertise) remains a concern to all EU policy makers, Member States and SNETP stakeholders as a whole. SNETP and some of its members took initiative to set up the “OFFERR” project in response to the Euratom Research and Training 2021-22 call for proposals. It aims to capitalise the Euratom R&D community’s operational and financial schemes facilitating open and inclusive trans-national access to infrastructures for R&D experts. The latest will be able to perform high-priority experiments within the best infrastructures available, with the benefit of co-funded grants (in-kind/in-cash) by Euratom, the consortia and/or Member States’ research infrastructure owners. The goal is to build a sustainable “User facility network (UFN)”. This session shall discuss the way this network of existing smaller networks shall be further managed, while providing the current status of research facilities available, which will also support the implementation of the SNETP Strategic Research and Innovation Agenda (2021), MS and Euratom Research and Training objectives, and beyond.

**Waste minimization and fuel cycle**

The current and projected fleet of plants consists largely of water-cooled, water-moderated reactors. These reactors have over time achieved a high degree of maturity in terms of economic performance and safety. To achieve major steps in terms of sustainability (by reducing high-level waste production, better use of resources and higher thermal efficiencies), new types of reactors based on other coolant technologies and high-temperature non-electrical applications, should be envisaged and combined with more advanced fuel cycles. The use of fast reactors in a closed fuel cycle approach will allow a large decrease in consumption of natural resource (uranium) and a significant reduction of high-level radioactive waste in terms of radiotoxicity and volume, which is one of the major concerns of society, towards a more sustainable implementation of nuclear energy. Advanced reprocessing and fuel manufacturing techniques, from a laboratory to an industrial scale of deployment, are needed to recycle for instance minor actinides. This session shall discuss how sustainability in terms of resource utilization and high level waste minimization can be gradually increased.

**The role of nuclear energy in mitigating climate change including non-electrical applications (hydrogen, heat, etc)**

With increased awareness of climate change in recent years, nuclear energy has received renewed attention. Nuclear energy can make a significant contribution to reducing greenhouse gas emissions (GHGs) worldwide, while at the same time meeting the increasing demand for energy of a growing world population and supporting global sustainable development. Nuclear energy has considerable potential to meet the challenge of climate change mitigation by providing a secured supply of electricity, district heating and high temperature heat for industrial processes while producing almost no GHGs. This session will focus on the different possible uses of nuclear to contribute to the EU 2050 decarbonisation strategy.

| SNETP FORUM TECHNICAL SESSIONS – 2 June 2022 | | | | |
|---|---|---|---|---|
| # | Room 1 | Room 2 | Room 3 | Room 4 |
| | **TS1: SMRs Moderators: Ferry Roelofs (NRG), Jozef Sobolewski (NCBJ)** | **TS4: R&D&I facilities Moderators: Pavel Kral (UJV), Petri Kinnunen (VTT)** | **TS2: Nuclear codes & standards & supply chain Moderators: Oliver Martin (JRC)** | **TS6: Nuclear to mitigate climate change including non-electricity applications Moderators: Ronald Schram (NRG), Michael Fütterer (JRC),** |
| 11:00 | **P1:** SMR-partnership, **DG-ENER** **P2:** Market analysis, **Bernard Dereeper** **P3:** Licensing harmonization, **ENSREG** | **P1**: OFFERR project, **Charles Toulemonde (EDF)** **P2**: Setting up the "European User Facility Network", **Jiri Zdarek (UJV)** **P3**: RJH, **Petri Kinnunen (VTT)** | **P1:** Comparison of pipe integrity concepts for LWRs, **Bruno Autrusson (nuclear consultant, formerly IRSN)** **P2:** Ongoing development activities on RCC-MRx and its enlargement to Gen IV reactor systems with coolants other than sodium, **Karl-Fredrik Nilsson (JRC)** **P3:** The NUCOBAM project – Incorporation of additive manufacturing into NC&S, **Oliver Martin (JRC)** | **P1**: N.N., NC2I: Introductory Scene Setter (new Euratom projects, NEA, GIF, IAEA) **P2**: **Andrei Goicea, Foratom**, EU: EU's energy sector integration and hydrogen strategies **P3**: **Agnieska Boettcher, NCBJ**, PL: Polish GOSPROSTRATEG project **P4**: **Jacek Jagielski, NCBJ**, PL: NOMATEN Centre of Excellence in Multifunctional Materials for Industrial and Medical Applications |
| 12:00 | **P4:** Supply Chain, **Roberto Adinolfi (Ansaldo)** **P5:** R&D&I - **Sylvain Takenouti** **P6:** Core and Fuel - **Eric Hanus (CEA)** **P11:** Non-electricity (power) applications, **Ville Tulkki (VTT)** | **P4**: NEA task Force on Nuclear Safety Research support facilities for existing and advanced reactors, **François Barré (IRSN)** **P5**: BR2, **Joris Van den Bosch (SCK.CEN)** **P6**: PKL/SACO, **Simon Schollenberger (Fra-G)** | **P4:** R&D challenges in improving civil structures design rules for sustainable nuclear energy technology, **Etienne Gallitre (nuclear consultant, formerly EDF)** **P5:** Qualification of electrical equipment according to RCC-E **Benedict-John Willey (EDF)** **P6:** European Commercial-grade Dedication Guidelines: **Andrei Goicea (Foratom)** **)** | **P5**: Integrated Energy Systems and the pathway to Net Zero by 2050 (a UK context), **Paul Newitt (NNL)** **P6**: **Michael Fütterer, JRC**, NL: GEMINI+ nuclear process heat applications, hydrogen, steel **P7**: **Andre Faaij, TNO**, NL: "Deployment of nuclear energy in deep decarbonization of the energy system." **P8**: **Geert-Jan de Haas, NRG**, NL: "Exploring the deployment of advanced reactor systems for decarbonization of future energy generation: research highlights of molten salt reactors and liquid metal cooled reactors." Wrap-up by **Ronald Schram, NRG**, NL: Wrap-up |
| 13:00 | **Lunch Break** | | | |
| | **TS1: SMRs Moderators: Ferry Roelofs (NRG), Jozef Sobolewski (NCBJ)** | **TS4: R&D&I facilities Moderators: Pavel Kral (UJV), Petri Kinnunen (VTT)** | **TS3: Digital & Robotics Moderators: Eero Vesaoja (FORTUM), Christophe Schneidesch (Tractebel), Elisabeth Guillaut (ORANO)** | **TS5: Waste minimization and fuel cycle Moderators: Erika Holt (VTT), Anthony Banford (NNL)** |
| 14:00 | **P7:** NSSS **Oliver Martin (JRC)** **P8:** Passive systems **F. Mascari** **P9:** Severe Accidents, **P. Dejardin** **P10:** Modularity, **M. Marconi (Ansaldo)** | **P7**: PASI-CWC, **Riikonen etc (LUT)** **(TBC)** **P8**: COSMOS-H, **Stefan Gabriel (KIT)** **P9**: HFR / Pallas, **Ronald Schram (NRG)** | **P1:** French Digital Reactor Initiative, **XXX – EDF** **P2:** Combination between Digital Twin and AI for anomaly detection for industrial processes, **Aurélien Schwartz - Métroscope, EDF group** **P3:** Data-sharing technologies, connectivity in the nuclear sector, **Vincent Champain – Framatome** | **P1:** Euratom introductory address, **Seif Ben Hadj Hassine (EC)** **P2:** Fuel Handling and Waste issues for Molten Salt Reactors, **Jiri Krepel (PSI)** **P3:** Plutonium management in GENIV reactors, **Francisco Alvarez Velarde (CIEMAT)** |
| 15:00 | **P12:** Energy Well – Czech molten salt SMR concept, **Marek Ruščák – CVR** **P13**: Conceptual design of EUHTER (Polish experimental HTGR), | **P10**: Czech research infrastructure for supporting the implementation of the SNETP strategic research | **P4:** AI in requirements engineering, **Santeri Myllynen – FORTUM** **P5:** Digital Solution Projects, **A. Duchêne – Tractebel** | **P4:** Waste minimization /recycle through whole fuel cycle, **Paul Nevitt (NNL)** **P5:** Recycling and circular economy of metallics– advanced reprocessing |

| | | | | |
|---|---|---|---|---|
| | **prof. Mariusz Dąbrowski** | agenda, **Marek Mikloš (CVR)**<br>**P11**: Open access of research infrastructures, **Rachel Eloirdi (JRC)** | | |
| 15:40 | **Coffee Break** | | | |
| | | **TS4: R&D&I facilities**<br>**Moderators: Pavel Kral (UJV), Petri Kinnunen (VTT)** | **TS3: Digital & Robotics**<br>**Moderators: Eero Vesaoja (FORTUM), Christophe Schneidesch (Tractebel), Elisabeth Guillaut (ORANO)** | **TS5: Waste minimization and fuel cycle**<br>**Moderators: Erika Holt (VTT), Anthony Banford (NNL)** |
| 16:00 | | **P12**: Education and training and facilities, **Leon Cizelj (IJS)** | **P6:** Modelling and simulation-assisted engineering of cyber-physical systems throughout their life cycle, **T. Ngugen – IAEA consultant**<br>**P7:** Robotics and drone program, **Anders Wik – Vattenfall**<br>**P8:** SHARK ROBOTICS, **Joseph PESME** | **P6:** Advanced Separation for the Optimum management of spent Fuel – portioning, fuel fabrication, secondary waste streams, **Christophe Bruggeman (SCK CEN)**<br>**P7:** Unique for SMR spent fuel and waste management, **Timothy Schatz (VTT)**<br>**P8:** SRA documentation development from projects SHARE and PREDIS, **Anthony Banford (NNL) and Erika Holt (VTT)** |
| 17:00 | | | **P9:** AERACCESS, **Jean-Luc AYRAL**<br>**P10:** Robotics in VVER SG inspection/cleaning, **Ville Lestinen - Fortum** | Guided Discussion: going forward topics and plan (future collaboration ideas) **– chairpersons** |
| 18:00 | **End** | | | |

# PROCEEDINGS SNETP

# SNETP REPORT

## SNETP FORUM 2022 - Proceedings

SNETP Association

c/o EDF

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The SNETP FORUM 2022 Proceedings report was prepared by the SNETP Association.

# Index

# Executive Summary

The SNETP FORUM 2022 was held on 2 June 2022 in Lyon, France. Over 300 participants from all European countries were actively involved in this 2022 edition.

The programme was designed with the help of the moderators of the SNETP FORUM:

- ✓ Abderrahim Al Mazouzi (EDF)
- ✓ Anthony Banford (NNL)
- ✓ Michael Fütterer (EC-JRC)
- ✓ Elisabeth Guillaut (ORANO)
- ✓ Erika Holt (VTT)
- ✓ Pavel Kral (UJV)
- ✓ Petri Kinnunen (VTT)
- ✓ Oliver Martin (JRC)
- ✓ Ferry Roelofs (NRG)
- ✓ Christophe Schneidesch (Tractebel)
- ✓ Ronald Schram (NRG)
- ✓ Eero Vesaoja (Fortum)
- ✓ Jozef Sobolewski (NCBJ)

And the organisation committee:

- ✓ Abderrahim Al Mazouzi (EDF)
- ✓ Gilles Quénéhervé (LGI)
- ✓ Clara Demange (LGI)

# 1. The challenges of nuclear energy in Europe

During the FISA 2022 & EURADWASTE'22 conferences, just before the SNETP Forum 2022, the SNETP president, **Bernard Salha**, delivered the following keynote speech featured here:

*SNETP[1] is an international association (AISBL) composed of around 120 members from 25 countries, gathering nuclear power plant operators, research centers, nuclear industry, and technical support organizations. The association has been supporting the creation and the implementation of R&D programmes since 2007.*

*European Technology Platforms (ETPs), such as SNETP, are industry-led stakeholder fora recognised by the European Commission as key players in driving innovation, knowledge transfer and European competitiveness in support of the SET Plan Implementation. Among their numerous activities, they develop research and innovation agendas supported by private and public funding for an implementation at the EU but also at national levels.*

*SNETP members believe that continuous technological innovation is fundamental to maintaining a high level of safety and competitiveness and requires the establishment of a coordinated R&D&I programme at European level in close collaboration with international partners to continuously make the European nuclear sector more competitive and safer, in a context of climate change and global competition within which nuclear energy can play a significant role in meeting climate objectives as a near zero-greenhouse gas emissions source.*

*During the Covid pandemic, our sector has demonstrated a high-level of resilience thanks to the highly skilled competences available in Europe[2]. Today, we are facing an unprecedentedly complicated situation in the energy sector with the need to ensure a smooth and affordable transition to a decarbonised economy in 2050. All low-carbon technologies will be needed, and many member states have confirmed that nuclear will be an essential part of their energy mix.*

*Recently, the European Commission has approved the complementary delegated act (CDA) on the taxonomy regulation and nuclear technology has been included, even though with drastic limitations[3]. Nuclear can indeed help the EU tackle the current energy challenges, providing a positive contribution to the security of supply, the stability of power prices and the achievement of the decarbonisation goals. Therefore, there is a growing relevance of R&D&I to reduce the EU dependence on unreliable sources and to provide more diversified and affordable energy.*

*New innovative solutions are needed to ensure competitive costs compared with other production technologies and short time construction and implementation in the local systems. It is also important to cover the needs of industry and transport with very low-carbon supply of industrial heat and hydrogen at large scale. In addition to the operating nuclear power reactors and those that are under construction or ready to be launched, Europe needs to broaden the available reactor offer to meet national/local specificities. The development of various* ***SMRs, based either on LWR technology or others*** *offers the possibility to deploy flexible options for electricity and non-electricity applications. R&D&I must support the*

[1] http://www.snetp.eu/

[2] https://op.europa.eu/en/publication-detail/-/publication/08f1e63d-a8cf-11ec-83e1-01aa75ed71a1/language-en?pk_campaign=ENER%20Newsletter%20APRIL%202022

[3] https://snetp.eu/2022/01/24/snetp-reacts-to-the-draft-of-the-complementary-delegated-act-of-the-eu-taxonomy-regulation/

*development of SMRs to make them **safe and competitive** with other production means within a global strategy of deployment within next decades.*

*In this context, SNETP, thanks to its members, has been working hard to **streamline and foster collaboration in the technological sectors** that are critical for our field based on the updated **SNETP SRIA** and on the visions of its pillars (**NUGENIA vision**, **ESNII vision**, **NC2I vision**). Moreover, SNETP has taken a leading role on the co-creation of the **EU SMR partnership preparation**, together with other institutions (FORATOM renamed recently "**NUCLEAREUROPE**", the European Commission and ENSREG) and stakeholders, gathering our best efforts to make Europe play its part in the development of this very promising technology for power generation and non-electric applications.*

*It has become increasingly clear – and widely documented – that achieving the 2°C target and complete carbon-neutrality by 2050 cannot be achieved without nuclear power. Thus, large light water reactors and SMRs based on various technologies are complementary with renewables to meet this objective. This is also related to the expected massive electrification of buildings, transport and industry in the future:*

- ***Growing demand of electricity and capacity to supply it at a stable price through nuclear power***

*Several recent studies from the European Commission[4], the IPCC[5] and various stakeholders[6] have explored the potential for increased ambition for the decarbonisation of the power sector: These studies suggest a growing role of electricity, from circa 20% of the European final energy consumption in 2015 to more than 40% to 50% by 2050 through electrification of transport, heating and cooling and industrial processes.*

*Nuclear energy also contributes to improving the dimension of energy security (i.e., to ensure that energy, including electricity, is available to all when needed) since:*

- *fuel and operating costs are relatively low and stable: about 15% of the Kwh produced by a nuclear power plan (the remaining 85% are related to the construction and dismantling);*
- *it can generate electricity continuously for extended periods; and*
- *it can make a positive contribution to the stable functioning of electricity systems*

*Thus, nuclear, together with renewables, can play an important role in reducing the dependence on fossil fuel energy imports in Europe and produce industrially a large quantity of decarbonised electricity at affordable and stable price.*

- ***Decarbonization of energy intensive industry at a stable price through nuclear energy***

*Demand for non-electric forms of energy is also growing and will be decisive for the success of re-industrialization in the EU and for the security of supply. This concerns mainly process heat and the production of hydrogen or its derivatives, for instance syngas, synthetic hydrocarbon fuels or ammonia. These are not only used as energy carriers but as feedstock for many industrial products. Because they can be easily stored, they can also facilitate the interfacing of nuclear with variable renewables.*

- ***Industrial autonomy and security of supply of the EU thanks to nuclear energy***

*The European nuclear industry is robust and experienced, it can ensure the independence and the autonomy of the EU covering the entire life cycle from design to construction and safe exploitation of nuclear power plants:*

[4] 2030 Impact assessment (2020), 2050 EU Energy roadmap (2018), EU Reference scenario 2013, 2016, PINC

[5] IPCC: Global Warming of 1.5C, October 2018 (3)

[6] World Energy Outlook (IEA, 2020)

- *In 2019, the nuclear industry sustains more than 1.1 million jobs throughout the European Union, out of which more than half a million are staffed with highly skilled professionals, among them 15000 researchers[7].*
- *Today, 104 reactors are in operation across the union, still several industrial units are operating for the fabrication and the recycling of fuels (France, Germany, Netherlands) including Uranium chemical treatment and enrichment*
- *The EU has developed over decades, a consistent and well qualified supply chain starting from the beginning of the process cycle, these are raw material suppliers, fabricators, sub-component suppliers, original equipment manufacturers, system integrators and technology vendors, including within the member states that have decided the phase-out (Italy, Germany)*
- *The nuclear research in Europe encompasses multiple layers of local and centralized initiatives and programs (including Euratom) using high quality research infrastructures (even though scarce and ageing) that allows the strengthening and the maintenance of the EU leadership;*
- *Important capacities, although ageing, for the production and the recycling of fuel quasi-exclusively for light water reactor technology*
- *The EU has the most advanced legally binding and enforceable regional framework for nuclear safety in the world and, despite diverging views among Member States on nuclear generated electricity, there is a shared recognition of the need to ensure the highest possible standards for the safe and responsible use of nuclear power and to protect citizens and environment from radiation.*
- *Disposal facilities for high level radioactive waste are under construction in Finland, Sweden and France and many other facilities for intermediate storage are being operated across almost the entire Union.*

- ***Strategic approach for value and growth***

*To keep the pace and to take stoke of the experience gained, the challenges of the European nuclear industry should be addressed along two paths:*

- *Contribute to achieving carbon neutrality in Europe by 2050: to ensure this objective only the technology of industrially mature water reactors grants a sufficient capacity by this horizon to contribute significantly. The means to achieve this are:*
    - *To maintain a high level of safety for existing and future reactors - Operate existing reactors in the long term up to their technical limit, extend the lifetime beyond 60 years whenever aging analyzes permit it, avoid premature closures (case of Belgium that decided to maintain 2 reactors, the case of Germany that decided to close the last 3 running reactors).*
    - *To build new large-scale reactors (EPR2 in France, call for tenders in the Czech Republic, announcements from the British PM) where the sites and the electrical transmission network allow it. They will be based on existing technologies (no development of new large models in the Western world today), either French (EPR2), American (AP1000) or Korean (APR1400) by maximizing the European local share in these last two cases.*
    - *To develop and build SMR/AMR in Europe (see European Partnership on SMR). These will be new models because this technology is not currently deployed on an industrial scale. Water-based SMR technology is the most promising to rapidly play a significant role*

[7] FORATOM | Economic and Social Impact Report, 2019

*alongside large reactors as they are based on proven technology. SMR/AMR could also foster the use of nuclear energy for other application than electricity (e.g., industrial high temperature heat, hydrogen production…) contributing to the net zero objective.*

  - *To sustain by modernizing and adapting them to the needs of the production, operation and recycling of fuel for light water reactors*

- *Ensure the sustainability of nuclear power in the long term by reducing the volume of long-lived waste products, in particular actinides, and limiting the dependence on natural uranium through closed fuel cycle. To this end, it is necessary to:*

  - *Develop Generation IV reactors, specifically Advanced Modular Reactors (AMR), with first demonstrators operating by 2035 at the soonest to support a fully established commercial deployment by 2050.*
  - *Develop associated fuel industrial offer (including recycling) based on existing know-how on light water reactor technology;*
  - *Take advantage of the European approach of the SMR partnership to produce these developments at the European level and pool efforts on reactors that still are not industrially mature;*
  - *Bring together players working on similar technologies (sodium, lead, molten salts, high temperature) to build critical mass of skills and competences with the needed infrastructures.*

- ***SMR-partnership initiative***

*The above-described strategic approach is well aligned with the initiative "SMR-partnership" launched in June 2021 under the auspice of the European commission. It is an opportunity to develop cross-sectorial synergies and to deploy modern and innovative technologies in the nuclear sector. It is also an opportunity to strengthen EU research and industrial nuclear capabilities on SMR/AMR which may lag behind a number of other countries.*

*Key attributes of the SMR partnership can be synthetized as follows*

- *SMRs are small-scale reactors, factory constructed in series, whose deployment must be based on the same model produced identically in several countries to maximize the series effect. The European partnership is therefore a necessity to ensure the economic and industrial viability of these reactors.*
- *Supported by the European Commission, Foratom (European association of nuclear industry), SNETP (European nuclear research platform), ENSREG (association of European nuclear regulators), it brings together all the European players in the sector.*
- *It is based on five streams and working groups:*

  1. *Exploration of market conditions and in particular the use of SMR for the production of electricity but also of hydrogen or high temperature heat;*
  2. *Harmonisation of safety rules to limit regulatory changes for reactors built in different European countries and thus maximize the series effect;*
  3. *Adoption of favourable financing and support mechanisms;*
  4. *Mobilization of the European industrial supply chain to become the backbone of the industrial deployment of SMRs from manufacturing to maintenance of the needed equipment of these reactors;*

5 *Mobilization of the European research network and its experimental facilities to validate the innovative concepts of these reactors and train new engineers.*

*The SMR partnership should lead to the selection of 3 to 5 future SMR reactor designs (for LWR) or reactor technologies (for AMR) on which the above working groups will focus. These models will be selected based on the support they receive from member states and European utilities and the principles of autonomy and independence of the European Union concerning the manufacturing capabilities and intellectual property rights.*

*Most of these will be water reactors, but also of generation IV design. Several models with a strong European content will thus emerge, facilitating the deployment of SMRs in Europe on mid-long term scales. Furthermore, this will allow the identification of the appropriate fuel management systems for generation IV type designs.*

- ***Conditions for success***

*The success of this industrial approach requires a favorable regulatory context and financing mechanisms reconciling revenue visibility and stable costs for customers:*

- *The European nuclear taxonomy is being finalized: the European Supplementary Delegated Act should be voted on in parliament at the beginning of July and come into force at the beginning of 2023 if it is approved.*
- *Nuclear power plants (and recycling facilities) are long-term investments (from launch to construction, followed by an operating period of ~60 years). Their financing requires mechanisms to give investors visibility on revenues beyond short-term energy prices. In return, customers must benefit from stable and competitive energy prices over a long period of time*

- ***Additional Cross sectorial benefits***

*Nuclear is a cutting-edge R&D&I.*

- *Nuclear R&D&I develops cutting-edge knowledge that may be beneficial to several other sectors, such as health, aerospace, digital, …*
- *Vice-versa other cutting-edge technologies such as artificial intelligence for example could be used in nuclear technology, for example for design and maintenance of nuclear facilities.*
- *SNETP intends to promote those cross-sectorial benefits in its R&D&I programme.*
- *Cross-sectorial industrial cooperation between electricity, heat, hydrogen generation and energy intensive sectors will be a key element to drive success*

# 2. SNETP Forum programme

| SNETP FORUM TECHNICAL SESSIONS – 2 June 2022 | | | | |
|---|---|---|---|---|
| **#** | **Room 1** | **Room 2** | **Room 3** | **Room 4** |
| | **TS1: SMRs**<br>**Moderators: Ferry Roelofs (NRG), Jozef Sobolewski (NCBJ)** | **TS4: R&D&I facilities**<br>**Moderators: Pavel Kral (UJV), Petri Kinnunen (VTT)** | **TS2: Nuclear codes & standards & supply chain**<br>**Moderators: Oliver Martin (JRC)** | **TS6: Nuclear to mitigate climate change including non-electricity applications**<br>**Moderators: Ronald Schram (NRG), Michael Fütterer (JRC)** |
| 11:00 | **P1:** SMR-partnership, **Yves Desbazeille (Foratom)**<br>**P2:** Market analysis, **Bernard Dereeper**<br>**P3:** Supply Chain, **Roberto Adinolfi (Ansaldo)** | **P1**: OFFERR project, **Charles Toulemonde (EDF)**<br>**P2**: Setting up the "European User Facility Network", **Jiri Zdarek (UJV)**<br>**P3**: RJH, **Petri Kinnunen (VTT)** | **P1:** Comparison of component integrity concepts for LWRs and activities of CEN Workshop 64 Prospective Group 1, **Bruno Autrusson (nuclear consultant), Manuela Triay (Framatome)**<br>**P2:** Ongoing development activities on RCC-MRx and its enlargement to different Gen IV systems, **Karl-Fredrik Nilsson (JRC), Cecile Petesch (CEA)**<br>**P3:** The NUCOBAM project – Incorporation of additive manufacturing into nuclear codes & standards, **Oliver Martin (JRC)** | **P1**: EU's energy sector integration and hydrogen strategies, **Andrei Goicea (Foratom)**<br>**P2**: Introductory Scene Setter (new Euratom projects, NEA, GIF, IAEA), **Michael Fütterer (JRC)**<br>**P3**: The European chemical industry on the path to climate neutrality, **Nicola Rega (CEFIC)**<br>**P4**: Deployment of nuclear energy in deep decarbonization of the energy system, **Andre Faaij (TNO)**<br>**P5**: Integrated Energy Systems and the pathway to Net Zero by 2050 (a UK context), **Paul Newitt (NNL, 10min video)** |
| 12:00 | **P4:** R&D&I - **Sylvain Takenouti**<br>**P5:** Core and Fuel - **Eric Hanus (CEA)**<br>**P6:** Non-electricity (power) applications, **Ville Tulkki (VTT)** | **P4**: NEA task Force on Nuclear Safety Research support facilities for existing and advanced reactors, **François Barré (IRSN)**<br>**P5**: Possibilities of the BR2 reactor as a support facility to materials and fuels R&D, **Joris Van den Bosch (SCK.CEN)**<br>**P6**: PKL/SACO, **Simon Schollenberger (Fra-G)** | **P4:** R&D challenges in improving civil structures design rules for sustainable nuclear energy technology, **Etienne Gallitre (nuclear consultant), Pekka Valikangas (STUK), Tadeusz Szczesiak (ENSI), Alexis Courtois (EDF)**<br>**P5:** Qualification of electrical equipment according to RCC-E **Benedict-John Willey (AFCEN)**<br>**P6:** High-quality European industrial grade items guidelines: **Andrei Goicea (Foratom), Natalia Amosova (Apollo+)** | **P6**: Summary of the Polish national project: GOSPOSTRATEG-HTR, **Agnieska Boettcher (NCBJ)**<br>**P7**: NOMATEN Centre of Excellence in Multifunctional Materials for Industrial and Medical Applications, **Jacek Jagielski (NCBJ)**<br>**P8**: Exploring the deployment of advanced reactor systems for decarbonization of future energy generation: **Geert-Jan de Haas (NRG)**<br>Wrap-up by **Ronald Schram (NRG)** |
| 13:00 | **Lunch Break** | | | |
| | **TS1: SMRs**<br>**Moderators: Ferry Roelofs (NRG), Jozef Sobolewski (NCBJ)** | **TS4: R&D&I facilities**<br>**Moderators: Pavel Kral (UJV), Petri Kinnunen (VTT)** | **TS3: Digital & Robotics**<br>**Moderators: Eero Vesaoja (FORTUM), Christophe Schneidesch (Tractebel), Elisabeth Guillaut (ORANO)** | **TS5: Waste minimization and fuel cycle**<br>**Moderators: Erika Holt (VTT), Anthony Banford (NNL)** |
| 14:00 | **P7:** NSSS **Oliver Martin (JRC)**<br>**P8:** Passive systems **F. Mascari**<br>**P9:** Severe Accidents, **P. Dejardin**<br>**P10:** Modularity, **M. Marconi (Ansaldo)** | **P7** : Source Term Experimental Research - IPRESCA and OECD/NEA THEMIS Projects, **Sanjeev Gupta (Becker Technologies GmbH)**<br>**P8**: COSMOS-H, **Stephan Gabriel (KIT)**<br>**P9**: HFR / Pallas, **Ronald Schram (NRG)** | **P1:** The Nuclear Digital Nuclear Initiative, **Benoît Levesque/Chai Koren – EDF**<br>**P2:** Combination between Digital Twin and AI for anomaly detection for industrial processes, **Aurélien Schwartz - Métroscope, EDF group**<br>**P3:** Data based solutions & performance in the nuclear sector, **Vincent Champain – Framatome** | **P1:** Euratom introductory address, **Seif Ben Hadj Hassine (EC)**<br>**P2**: Fuel Handling and Waste issues for Molten Salt Reactors, **Jiri Krepel (PSI)**<br>**P3**: Plutonium management in GENIV reactors, **Francisco Alvarez Velarde (CIEMAT)** |
| 15:00 | **P11:** Energy Well – Czech molten salt SMR concept, **David Harut – CVR**<br>**P12**: Conceptual design of EUHTER (Polish experimental HTGR), **prof. Mariusz Dąbrowski** | **P10**: Czech research infrastructure for supporting the implementation of the SNETP strategic research agenda, **Marek Mikloš (CVR)**<br>**P11**: Open access of research infrastructures, **Rachel Eloirdi (JRC)** | **P4:** Utilization of artificial intelligence in the analysis of nuclear power plant requirements, **Santeri Myllynen – FORTUM**<br>**P5:** Digital Solution Projects, **A. Duchêne – Tractebel** | **P4:** Waste minimization /recycle through whole fuel cycle, **Luke O'Brien (NNL)** |
| 15:40 | **Coffee Break** | | | |
| | | **TS4: R&D&I facilities**<br>**Moderators: Pavel Kral (UJV), Petri Kinnunen (VTT)** | **TS3: Digital & Robotics**<br>**Moderators: Eero Vesaoja (FORTUM), Christophe Schneidesch (Tractebel), Elisabeth Guillaut (ORANO)** | **TS5: Waste minimization and fuel cycle**<br>**Moderators: Erika Holt (VTT), Anthony Banford (NNL)** |
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| 17:00 | | | **P9:** Robotics in VVER SG inspection/cleaning, **Ville Lestinen - Fortum** | Guided Discussion: going forward topics and plan (future collaboration ideas) **– chairpersons** |

# 3. Technical session #1 – Small Modular Reactors (SMR)

This technical session was moderated by J. Sobolewski (NCBJ) and F. Roelofs (NRG). A zip file containing the presentations is available for download here.

## 3.1 Scope

New innovative solutions are needed to ensure cost competitiveness with other power generation technologies, as well as speed of construction and implementation in local systems. In addition to the nuclear reactors in operation and those under construction, Europe needs to expand the range of reactors technologies available to meet national/local specificities. The development of different SMRs, based on most matured technologies or on other advanced technologies, offers the possibility to deploy flexible options for both power and non-power applications and contribute to decarbonization. R&D&I should support the development of SMRs to make them safe and competitive with other means of production as part of a global deployment strategy over the coming decades.

## 3.2 Summary

**EU SMR-partnership, Yves Desbazeille (Foratom)**

A short introduction was provided on the preparations of an EU SMR partnership. The preparations are divided in 5 workstreams, some of which were presented in follow-up presentations. Since SNETP is responsible for work stream 5 on R&D and Innovation, this work stream was explained by the various topics in subsequent presentations.

**Work Stream 1 - Market Analysis, Andrea Goicea (Foratom)**

Work stream 1 focuses on the market analysis for SMR deployment in Europe. Future needs in Europe are being identified with respect to the various product streams, i.e., electric power, heat, and hydrogen production through literature review and surveys. After that the technical/economical capabilities of SMRs and the market potential for SMR deployment will be analyzed. The analysis should be ready by the end of 2022.

**Work Stream 5 – R&D and Innovation, Sylvain Takenouti (EDF)**

The objective of work stream 5 is to define a roadmap for SMR R&D&I consistent with market needs and licensing requirements. The work stream is divided in 7 technical topics: Core/fuel (1), NSSS Integrated vessel and its internals (2), Passive systems (3), Severe Accidents (4), Modularity (5), Human Factors and autonomy (6), Uses beyond electricity (7). All technical topics consider and distinguish where needed between small modular light water reactors (SMRs) as well as advanced modular reactors (AMRs).

**Work Stream 5 Topic 1 - Reactor Core and Fuel, Eric Hanus (CEA)**

Main directions identified for SMRs are the design of smaller cores with high neutron leakage, design with non-soluble boron, adaptability to ATF and HA-LEU, thermal-hydraulic aspects, fuel limits for cogeneration modes, core instrumentation and monitoring, and multi-scale / multi-physics modelling tools to reduce conservatisms and costs. For AMRs, the main directions are fuel characterization, fuel qualification, fuel manufacturing, fuel reprocessing techniques, quality control techniques, fission product behavior, validation of analysis tools, passive shutdown systems, and multi-scale / multi-physics modelling tools for analysis of AMR cores.

**R&D Needs for Non-power Uses of Nuclear Energy, Ville Tulkki (VTT)**

Specific R&D gaps include the coupling between a nuclear heat source and a heat use facility, the analysis of the requirements for electric power, heat, and hydrogen production, the operability, maneuverability, and flexibility of SMRs and AMRs and their economic, impact, public acceptance and safety analysis, and the development of tools.

**Work Stream 5 Topic 2 - R&D Needs & Technical Issues of the Nuclear Steam Supply Systems, Oliver Martin (JRC)**

The R&D&I gaps for the nuclear steam supply systems can be found in the regulatory framework (varying levels of harmonization), applicability of nuclear codes & standards, reactor internal hydraulics (incl. vibrations), reactor structural materials and coolant chemistry control (especially for LFRs), specific reactor components (e.g., compact and/or high temperature component designs like pumps or heat exchangers), advanced manufacturing, and in-service inspection.

**Work Stream 5 Topic 3 - Passive Systems, Fulvio Mascari (ENEA)**

The main needs for development and implementation of passive systems are summarized as the further development of an experimental assessment database, modelling approaches and numerical tools, system reliability, and system designs and engineering process.

**Work Stream 5 Topic 4 - Severe Accidents, Philippe. Dejardin (Tractebel ENGIE)**

SMRs and AMRs should include inherent safety features to drastically reduce the likelihood of severe accidents. Two high level needs are identified: the identification of potential and postulated severe accident scenarios, and the associated needs with respect to vessel and containment integrity and emergency planning zones. For SMRs, the main direction is to investigate the possibility of crediting applicability of large reactor knowledge. For AMRs, a prerequisite is to determine the definition of a severe accident and subsequently to investigate the scenarios.

**Energy Well Project, Mathieu Reungoat (CVR)**

The Energy Well project was presented. Energy well is a micro-SMR with a power of about 20 MWth (8 MWe) for local production of electricity and/or heat based on a molten salt cooled technology and using TRISO fuel. Currently, work is ongoing to realise a non-nuclear demonstrator by 2024.

**Conceptual Design of EUHTER (Polish Experimental HTGR), Mariusz Dąbrowski (NCBJ)**

The current plans for deployment of HTR technology for cogeneration of electricity and heat in Poland are explained. A prototype is planned in the early 30's, while commercialization is aimed at in the 40's. A pre-conceptual design for a 40 MWth prototype under the name TeResa was completed within the Polish national program. A strategic partnership has been established with JAEA in Japan for the transfer of knowledge, experience and support.

Some important questions were raised during the many discussions that took place. The first one was whether the EU SMR partnership should aim at the deployment of an SMR in Europe or at the development of a European SMR design. The steering group of the partnership should discuss this and take a position. Related to this, a question was raised about the market for SMR/AMR deployment in Europe. And another question raised during the discussions was the focus of the partnership on light water reactor designs and/or AMRs and especially the involvement of the AMR experts in the various work streams and technical topics.

# 4. Technical session #2 – Nuclear codes & standards & supply chain

This session was moderated by Oliver Martin (JRC). A zip file containing the presentations is available for download here.

## 4.1 Scope

Safety-related structures, systems and components (SSCs) of nuclear power plants are normally designed and produced according to stringent nuclear codes & standards (NC&S). Supplying such SSCs normally requires companies to establish and maintain a quite costly nuclear quality-assurance (QA) programme. In response to growing supply chain challenges, European NPP operators started looking into greater deployment of high-quality non-nuclear industry standard components and equipment for safety-related SSCs of NPPs (i.e., commercial-grade dedication) and launched corresponding pilot projects with approval of their regulators. This is supported by European and international nuclear organisations like Foratom and the IAEA by providing guidance in this area. The further development of NC&S remains high on the agenda. Novel materials, manufacturing methods and technologies need to be included in NC&S before being allowed to be used for safety-related SCCs. This and also NC&S development for advanced reactors (SMRs, Gen IV) require significant R&D&I efforts. In this session ongoing NC&S development activities and needs and supply chain related activities and challenges for the current reactor fleet and advanced reactors will be presented and discussed.

## 4.2 Summary of the technical session

Technical session 2 “Nuclear codes & Standards and Supply Chain” of the SNETP Forum 2022 covered six presentations, with four of them on the ongoing project CEN Workshop 64 on the further evolution of the AFCEN codes (= French nuclear codes & standards (NC&S)), one on the ongoing Euratom project NUCOBAM and the remaining one on the recently published European commercial-grade dedication guidelines by Foratom.

**P1**: ***Component Integrity Concepts for LWRs and Activities of CEN Workshop 64 Prospective Group 1*****, Bruno Autrusson (nuclear consultant), Manuela Triay (Framatome), Oliver Martin (EC-JRC)**

P1 was a summary of recent activities of CEN WS64 PG1 whose scope are the AFCEN codes RCC-M design rules for mechanical components of LWRs and RSE-M rules for maintenance and in-service inspection of LWRs. In Phase 2 of the CEN WS64 (2014-2018) PG1 performed a qualitative study to investigate to what extent known degradation mechanisms of mechanical components of LWRs and their possible effects are accounted for in these codes. In Phase 3 (2019 – 2022) PG1 looked into pipe integrity concepts and defect assessment procedures and approaches.

**P2*****: Ongoing Development Activities for RCC-MRx and its Enlargement to Different Gen IV Systems*****, Karl-Fredrik Nilsson (EC-JRC), Cecile Petesch (CEA)**

P2 was a summary of recent activities of the CEN WS64 PG2 whose scope is the AFCEN code RCC-MRx design and construction rules for mechanical components of high-temperature reactors. Being initially introduced to provide design & construction rules for mechanical components of SFRs, PG2 made considerable efforts to enlarge RCC-MRx to LFRs, which have peculiar degradation mechanisms like liquid metal embrittlement and erosion. Thus, there has been and still is a strong interaction with the European LFR community and associated Euratom project consortia (e.g., Matter, Gemma). Introduction of novel materials mechanical characterization tests (e.g., small punch test) and additive manufacturing in RCC-MRx are also high on PG2's agenda.

**P3**: ***The NUCOBAM Project – Incorporation of Additive Manufacturing into Nuclear Codes & Standards*, Oliver Martin (EC-JRC)**

P3 was on the ongoing Euratom project NUCOBAM on additive manufacturing of reactor components. The main aim of the project is the development of a methodology to qualify additive manufactured components for use in safety-classified structures and components, essentially to ensure that they meet the requirements of NC&S. The main focus of the presentation was the qualification methodology, which is already available in draft form.

**P4**: ***R&D Challenges in Improving Civil Structures Design Rules for Sustainable Nuclear Energy Technology*, Etienne Gallitre (nuclear consultant), Pekka Valikangas (STUK)**

The focus of P4 was on the technical challenges and R&D needs of the further evolution of RCC-CW, the AFCEN design rules for containments and civil structures of NPPs, which is the scope of PG3 of the CEN WS64. The technical challenges and R&D needs identified by PG3 are liners for both NPP containments and spent nuclear fuel pools, robustness of civil NPP structures against events for which they have not been explicitly designed, impact of aircraft crashes into containments and computational analyses of such processes, shear in reinforced concrete structures and ageing management of concrete structures.

**P5**: ***Qualification of Electrical Equipment According to RCC-E*, Benedict-John Willey (AFCEN)**

P5 was an introduction into RCC-E, the AFCEN codes for electrical and I&C equipment and systems of nuclear islands, which is the scope of PG4 of the CEN WS64. Besides a few general words on RCC-E, the focus of the presentation was on the qualification of electrical and I&C equipment and maintaining such qualifications over time, e.g., in view of LTO. The presentation was intended for non-experts on the field.

**P6**: ***Quality Assurance Guidelines for Procuring High-quality Industrial-grade Items Aimed at Supporting Safety Functions in Nuclear Facilities*, Andrei Goicea (Foratom)**

P6 was dedicated to the quality assurance guidelines for procuring high-quality non-nuclear industry grade items (often referred to as commercial-grade items) for safety-related SSCs in nuclear facilities recently published by Foratom. Increased use of such items in safety-related SSC of nuclear facilities is a way to solve supply chain challenges currently facing European utilities, such as SSC obsolescence and difficulty of finding new suppliers. The available guidance on using such items in safety related SSCs of nuclear facilities originates from the U.S. and as a consequence is primarily tailored to U.S. nuclear industry needs and regulation. The Foratom guidelines are targeting mainly European utilities that are more versatile to cope with different nuclear regulations of EU MS or European countries in general. The publication of the Foratom guidelines is a milestone and use of high-quality non-nuclear industry grade items for safety related SSCs in nuclear facilities is becoming more widespread in Europe.

Overall TS2 contained interesting presentations and there were fruitful discussions after each presentation despite the limited attendance of the session overall due to the sessions on SMRs and research infrastructures running in parallel. TS2 emphasised the need of NC&S development, to turn R&D results into design and construction rules for SSCs, so that they can be used by end-users, mainly vendors and suppliers and utilities. All PGs of the CEN WS64 are currently completing Phase 3 and preparing Phase4, whose main focus will most likely be SMRs. In this sense, having a similar session like TS2 in a SNETP Forum in couple of years, would be highly beneficial. NUCOBAM paves the way to allow production of reactor components via additive manufacturing. Similar R&D projects for other advanced manufacturing techniques (e.g., electron beam welding) are required. The publication of the Foratom guidelines enables more widespread use of high-quality non-nuclear industry grade items for safety related SSCs in nuclear facilities. Although primarily intended for currently operating NPPs, the guidelines are also relevant for new-build and advanced reactors / SMRs and offer the possibility to organize supply chains of safety-related SSCs of such reactors differently straight from the beginning and thus avoid to some extent the supply chain challenges of the current fleet.

# 5. Technical session #3 – Digital & Robotics

This session was moderated by Elisabeth Guillaut (ORANO), Eero Vesaoja (FORTUM), Christophe Schneidesch (TRACTEBEL). A zip file containing the presentations is available for download here.

## 5.1 Scope

Digital and robotics technologies are innovative tools developed for a safe and optimal plant management, while improving the security of workers. As part of the SNETP annual forum, two consecutive sessions were dedicated several innovations developed on those topics. The digital transformation and the use of robotics have become cross-cutting trends to all industrial sectors and nuclear is no exception to this: the European Commission considers that the climate transition should be coupled with a digital transition. Therefore, it is essential to build a European digital integration bench to achieve digital twins such as a Digital Nuclear Reactor. Moreover, robots limit exposure to radioactivity and support maintenance tasks that would otherwise be impossible, thus significantly extending the lifetime of reactors.

The presentations cover a wide range of IR&D developments already supporting practical applications with a clear benefit to nuclear activities and operational processes efficiency.

## 5.2 Summary of the technical session

### Digital

- **The Nuclear Digital Nuclear Initiative, Cécile Clarenc-Mace -EDF**
  - Project developed with 8 partners over 4 years starting in 2020, to provide Operators as well as Engineering Design Offices with two products based on a continuum of models in reactor physics. The outcome will be digital twins of a nuclear reactor comprising a platform to perform advanced studies relying on Multi-Physics / Multi-Scale couplings and a full scale training simulator, the two supported by visualization tools and all services accessible by a single web portal. Current results match the objectives on practical test cases and demonstrate the operability of the two products. Work is on-going to optimize or include missing peripheral functionalities.
- **Combination between Digital Twin and AI for Anomaly Detection for Industrial Processes, Aurélien Schwartz - Métroscope, EDF group**
  - To monitor and diagnostic plants through confronting deviations from the measured plant data and from the expected behavior of a digital twin. The software is used to capture and understand root causes for abnormal behaviors of the installation. 300 active users worldwide (whole nuclear EDF fleet is equipped). Used at site, engineering, corporate levels. A practical example illustrates the analysis performed for a PWR in operation and highlights the benefit of the software for a plant Operator, which from the diagnostic, was capable to optimize maintenance activities and recover missing power.
- **Data Based Solutions & Performance in the Nuclear Sector, Vincent Champain – Framatome**

  - The Nuclear sector is characterized by a huge amount of data and limited value creation from it. Framatome is investing to valorize those data with the deployment of a wide portfolio of specific data acquisition technologies, covering e.g. inspection/ND testing, measurement/capture, monitoring/analysis, remote inspection, product certification/quality and product integrity. Each value creation was illustrated by typical examples of dedicated software application, e.g. forecast how manufacturing can help to avoid problems (Graphsight using NLP to extract references to make engineers safe). However, if the Nuclear sector can benefit from advances from the non-nuclear industry, it still faces some inherent challenges and barriers to be tackled well before taking full advantage of the various innovative solutions in development.

- **Utilization of Artificial Intelligence in the Analysis of Nuclear Power Plant Requirements, Santeri Myllynen – FORTUM**
  - The requirement text is filled in into a language model and converted into a feature vector. AI can clearly be utilized in requirement engineering, can save time and money. The current tools show that it reduces manual errors in rather monotonic and time-consuming processes, but important work still remains in developing further dedicated algorithms may be further developed for, e.g., recognizing and potentially combining similar requirements or assessing the fulfillment of requirements.
- **Digital Solution Projects, Arnaud Duchêne – Tractebel**
  - Tractebel implementation of digital twin functionalities for dismantling activities. The developments cover BIM (virtual reality / Augmented reality/ system engineering) complemented by digital models for simulations and asset management. Dismantling digital twins are used either for design of new waste management facilities or modification of existing installations. They bring together digital capabilities to predict the waste quantities, perform simulation for the characterization. The interoperability and integration of data, models as well as functionalities between the different components of the application are illustrated by practical applications. The platform however calls for further improvements in its functionalities.
- **Modelling and Simulation-assisted Engineering of Cyber-physical Systems Throughout their Life Cycle, T. Nguyen – IAEA consultant (ex EDF)**
  - Developed a method called BASAALT (behavioral simulation) helping maintenance of the engineering and safety knowledge. The issue is that too many requirements are poorly engineered and inadequate, mainly because of a lack of understanding the full picture and wrong assumptions; from there a need to have tool to support the engineering: BASAALT was developed with as main characteristics: modularity, tracking progress, enabling coordination.

## Robotics

- **Robotics and Drone Program, Anders Wik – Vattenfall**
  - Drone inspection in BWR NPP 2021 (esp. in radioprotection area) – developed internally Birdflapper and mini solar boat for autonomous inspections. Many floor/air/water robots (generally commercially available) are used with different type of sensors. They are deployed for example in inspection of the dome liner. Future applications cover creation of radiations maps, regular inspection tours in NPP, surveillance of work progress, which could be combined with AI for image recognition. A strong validation process is required for nuclear sector applications. Security of the information transmission is a major issue.

- **Foldable Oranef UAV for High Radiation Zone Inspection in Nuclear Plants, Jean-Luc Ayral – AERACCESS**
  - Programme developed with Orano, under the European RIMA programme and the French recovery plan (Factories of tomorrow project) to improve navigation and compensation of the drifts (acoustic ranging and use of elevation). The Oranef UAV has a unique architecture embarking 4K camera for vision and peripheral sensors on 3-axis and capable to carry payloads such as ultrasonic (NDT) or dosimetric sensors SLAM (simultaneous localization and mapping) navigation based on stereoscopic vision is foreseen to address different types of requirements (mapping of HRZ cells, fusion of the 3D mapping and control of the trajectory according to obstacles).
- **Robotics in VVER SG Inspection/Cleaning, Ville Lestinen**
  - Project started in 2019 for and inspection and cleaning robot of steam generators of Lovissa as part of the regulatory requirement to clean every 4 year the steam generator. The work presents high radiation doses and other occupational health and safety risks. A first version of a robot was tested in outage of Loviisa NPP in September 2020 and its feedback led to consider a second robot version focusing on more flexible inspection capacities. The testings proved how present and future robots can operate in hazardous and dangerous places. First business cases could be around inspection of pools, containers and all other waterways

Concerted RD&I work is essential to make progress in terms of multi-physics modelling and simulation, High Performance Computing, data analysis and analytics, visualization, Virtual Reality, advanced instrumentation (e.g., Internet Of things) and I&C.

# 6. Technical session #4 – R&D&I facilities

This session was moderated by Pavel Kral (UJV) and Petri Kinnunen (VTT). A zip file containing the presentations is available for download here.

## 6.1 Scope

Several R&D facilities have been shut down in the EU over the last decade. Therefore, loss of critical research infrastructure (i.e., facilities, capabilities and expertise) remains a concern to all SNETP stakeholders and the nuclear community as a whole. SNETP and some of its members decided to set up the "OFFERR" project that aims to support the European nuclear R&D community, and to establish an operational scheme facilitating access for R&D experts to key nuclear science through the channeling of financial grants provided by the Euratom programme. The goal is to construct a sustainable "User facility network (UFN)".

This session discussed the way this network should be built and provided the current status of research facilities that support the implementation of the SNETP Strategic Research Agenda (2021) and beyond.

## 6.2 Summary of the technical session

The following presentations were given in the meeting:

- **Charles Toulemonde: The OFFERR Project**
- **Jiri Zdarek: Setting up the European User Facility Network (presented by C. Toulemonde)**
- **Leon Cizelj: Education Training and Research Facilities**
- **P. Kinnunen: JHR**

- **F. Barre: NEA Task Force on Nuclear Safety Research Support Facilities for Existing and Advanced Reactors**
- **J. Van den Bosch: Possibilities of the BR2 Reactor as a Support Facility to Materials and Fuels R&D**
- **Sanjeev Gupta: Source Term Experimental Research - IPRESCA and OECD/NEA THEMIS Projects**
- **Ronald Schram: HFR and Pallas**
- **Marek Miklos: Czech Research Infrastructure for Supporting the Implementation of the SNETP SRA**
- **Rachel Eloirdi: JRC Open Access of Research Infrastructures**

The meeting started with the two presentations related to the OFFERR project. The aim of this project is to create a European user facility network - list and synergies with 17 partners and a budget of 9 M€ of which 7 M€ to R&D facilities. OECD NEA is the latest member. In OFFERR there will be different tracks available for obtaining the funding and the network will be increased during the course of the project. Two other presentations were connected to the OFFERR presentation: J. Zdarek's and L. Cizelj's which both reflected the willingness to focus the European efforts on research and competence creation. This OFFERR "entity" raised many discussions as the audience commended quite widely the plans and the use of budget. It was concluded to be a little bit disappointing that the OFFER can give in maximum 300 k€ support as that amount does not help too much with the expensive irradiation tests. In addition, several listeners asked how will the OFFERR try to benefit of the existing roadmaps and infra listings etc.

L. Cizelj presented good statistics on the ENEN+ project outcome. In the future ENEN+ project will aim at moving 1000 persons (i.e. ~100 person years) as it has been observed that this kind of scientist mobility is of great value. Zdarek's presentation focused mainly on the first contact with PNNl & EPRI (USA) initial collaboration involving information exchange.

F. Barre described in his presentation (“NEA task force on nuclear safety research support facilities for existing and advanced reactors”) the structure of OECD/NEA and relevant activities, mostly organized in CSNI and WGAMA. Objectives of the cooperation with partner-countries through joint safety research projects are as follows: maintain key experimental facilities and key competencies and support the operating agents, address a wide range of high priority safety issues, facilitate cooperation between countries, anticipate needs for future technologies, preserve and disseminate high quality data. The contribution of Senior Expert Group on Safety Research (SESAR) was also discussed. In the end, the short term and long-term recommendations related to preservation of experimental infrastructures for nuclear safety were summarized.

In the topic “Source term experimental research - IPRESCA and OECD/NEA THEMIS projects” given by Sanjeev Gupta. SNETP/NUGENIA IPRESCA is an in-kind project and aims to promote integration of international research activities related to pool scrubbing by providing support in experimental research and modelling work. OECD/NEA THEMIS project focuses on combustible gases and source term issues to support analysis and further improvement of Severe Accident Management measures. Both projects are cross-cutting between Nugenia TA1 and TA2.

The group of existing and future reactor capacities handled presentations of BR" 8 in Belgium), LVR-15 (Czech) and JHR (France), HFR and PALLAS (Netherlands) as well as a description of the JRC open access to the research infra. The reactor presentation was very interesting giving the views from the history up today and described thoroughly what kind of irradiation capabilities and laboratories are available in the current fleet of research reactors and in the future reactors (JHR, Pallas). It is obvious that the current fleet will be needed still for many years and the reactors have been renewed to answer the current and foreseen challenges in the near future. BR2 is the most versatile available reactor at the moment, LVR-15 has excellent laboratories for many purposes and is an important tool among others for future technologies, HFR is a multipurpose reactor - old reactor but working well. The JHR is delayed and the plans for Pallas are such that it should start in the early 2030's like the JHR.

JRC open access of research infrastructures is the key tool for the EC to optimise the use of the existing JRC facilities. Altogether JRC has a total 56 research infrastructures of which 20 are for nuclear. JRC open access has granted more than 40 accesses but the covid has delayed the use of them.

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*In addition to these presentations, one presentation was sent as a video (S. Schollenberger: Experimental programs at the PKL test facility). Unfortunately, we did not have time to watch it during the meeting as there were many discussions on other presentations.*

*The last presentation from the original Programme – the presentation of Stephan Gabriel on COSMOS-H thermohydraulic test facility – was cancelled as the presenter asked for withdrawal of his contribution due to his illness.*

# 7. Technical session #5 – Waste minimisation and fuel cycle

This session was moderated by Erika Holt (VTT) and Anthony Banford (NNL). A zip file containing the presentations is available for download here.

## 7.1 Scope

The current and projected fleet of plants consists largely of water-cooled, water-moderated reactors. These reactors have over time achieved a high degree of maturity in terms of economic performance and safety. To achieve major steps in terms of sustainability (reduced high-level waste production, better use of resources and higher thermal efficiencies) and to open the way for high-temperature non-electricity applications, new types of reactors based on other coolant technologies should be envisaged combined with more advanced fuel cycles. The use of fast reactors in a closed fuel cycle approach will allow a large decrease in natural resource (uranium) consumption, allowing therefore a more sustainable implementation of nuclear energy. One of the major concerns of society regarding the implementation of nuclear energy is also the high-level nuclear waste. Fast spectrum reactors with closed fuel cycles will allow a significant reduction in high-level nuclear waste radiotoxicity and volume. Advanced reprocessing and fuel manufacturing techniques are needed to recycle the minor actinides. This session discusses how sustainability in terms of resource utilisation and high-level waste minimisation can be gradually increased.

## 7.2 Summary of the technical session

This technical session was developed to bring together thinking on future reactor concepts, fuel cycles and waste management, in the interest of developing a lifecycle approach to minimise waste and enhance system sustainability. The discussions will feed into the Strategic Research Agendas (SRAs) currently under development. *The session was attended by over 40 delegates from a range of countries and the IAEA.*

**Seif Ben Hadj Hassine (EC)** opened the session with an **Introduction to EC Programmes on Radioactive Waste Management and the Linkages with the Complimentary Decommissioning Projects**. The presentation stressed the importance of adopting a whole cycle approach, from reactors and fuel through to pre-disposal waste processing and final disposal.

**Jiri Krepel (PSI)** presented on **Fuel Handling and Waste Issues for Molten Salt Reactors**, including indications of impacts of solid and liquid fuel in these salt systems, and the impacts on operation, safeguards, criticality safety, and waste management. The ongoing benchmark work for burn up and design issues within the European SAMOFAR project (http://samofar.eu/ ) is to be published soon.

**Francisco Alvarez Velarde (CIEMAT)** – highlighted work on **Plutonium Management in GENIV Reactors** (PUMMA project, https://pumma-h2020.eu/ ), with particular respect to the importance of assessing the impacts on to whole cycle including fuel recycle and plutonium management.

**Luke O'Brien (NNL)** described how a range of innovative tools have been applied in the **UK Advanced Fuel Cycle Programme to Apply the Waste Hierarchy during the Development of Future Fuel Cycles**. The project outputs have demonstrated the potential benefits of applying these techniques to optimise concept flow sheets at the earliest opportunity.

**Christophe Bruggeman (SCK CEN)** moved the discussions onto **Advanced Separation for the Optimum Management of Spent Fuel (ASOF)**. The ASOF project is linked to the MYRRHA demonstrator transmutation facility, and includes evaluating the contribution of actinides and fission product impact on the radiotoxicity of the final waste and their impact on disposability.

**Timothy Schatz (VTT)** presented on **SMR Spent Fuel and Waste Management**, setting the scene using Finland as an example of the demand and prospects for SMR deployment and showed results with case studies for spent fuel, waste management (including interim storage, ownership responsibility) and disposal.

**Reka Szoke (IFE)** **introduced the new HARPERS project** which will focus on opportunities for harmonised practices, regulations and standards in waste management and decommissioning. The coordinators encouraged SNETP members and delegates to get involved in the stakeholder discussions and feedback to help prioritise activities.

**Anthony Banford (NNL)** gave an overview of the **SHARE project** highlighting the development of the decommissioning Strategic Research Agenda and Roadmap of R&D needs, and also the **ongoing PREDIS project** that is updating the future R&D needs in pre-disposal radwaste management. The objective of sharing this was to encourage discussion and identification of priority areas for future R&D (needs) within the SNETP community and member states. Further information on the SRAs is available https://share-h2020.eu/ and https://predis-h2020.eu/

## Discussion

The questions and discussion in the session all reinforced the importance of adopting a holistic lifecycle approach to fuel cycle optimisation, and waste minimisation in both legacy and future systems. Specific examples raised for potential collaboration include,

- Legacy waste optimisation with the goal of waste minimisation, which is common to SNETP objectives and to the PREDIS and EURAD SRAs.
- Future reactor system (SMR, AMR & Gen IV) and associated fuel cycle waste management.
- Challenges and linkage (cross-border solutions for treatment, disposal, techniques).
- Treatment options for problematic waste streams without existing treatment routes
- Social acceptability of waste systems.

# 8. Technical session #6 – Nuclear to mitigate climate change including non-electricity applications

This session was moderated by Ronald Schram (NRG) and M. Fütterer (JRC). A zip file containing the presentations is available for download here.

## 8.1 Scope

With increased awareness of climate change in recent years, nuclear energy has received renewed attention. Nuclear energy can make a significant contribution to reducing greenhouse gas emissions (GHGs) worldwide, while at the same time meeting the increasing demand for energy of a growing world population and supporting global sustainable development. Nuclear energy has considerable potential to meet the challenge of climate change mitigation by providing a secured supply of electricity, district heating and high temperature heat for industrial processes while producing almost no GHGs.

This session will focus on the different possible uses of nuclear to contribute to the EU decarbonisation strategy.

## 8.2 Summary of the technical session

In this session, moderated by Ronald Schram (NRG) and Michael Fütterer (JRC), a broader view of nuclear was provided, from different angles: Industry's perspective, energy-mix perspective, and R&D perspective.

**Scene Setter**

Michael Fütterer (JRC) provided a short introduction and recalled that successful decarbonization and energy security require not only large new capacity of low-carbon electricity generation, but also the replacement of fossil hydrocarbons for industrial process heat and, importantly, as feedstock and reactants in the chemical and steel industry. Several new projects from Euratom, OECD/NEA, the Generation IV International Forum and at the IAEA are addressing this challenge.

**Industry**

Andrei Goicea (FORATOM) spoke about **EU’s Energy Sector Integration and Hydrogen Strategies**. FORATOM promotes the capabilities of nuclear beyond electricity considering hydrogen as one of the main vectors of the energy sector because of its versatility for storage and use. The hydrogen position paper states i.a. that from 2025 to 2030, hydrogen needs to become an intrinsic part of our integrated energy system. The current plan at EU level is to build by then at least 40 GWe of renewable hydrogen electrolyser capacity and the production of up to 10 million tonnes of renewable hydrogen in the EU, which is equivalent to the current annual consumption. In this context, nuclear energy can help achieve these goals more easily than with renewables alone.

Nicola Rega (European Chemical Industry Council - CEFIC) provided a talk on **the European Chemical Industry on the Path to Climate Neutrality**. CEFIC launched the iC2050 project: a model representing the EU27 chemical industry to identify potential pathways to climate neutrality. The model identifies four different scenarios to achieve neutrality for the chemical industry. All simulations run so far assume a strong electrification of processes and thus confirm a substantial increase in electricity consumption. The question is to what extent the nuclear industry can support the electrification of the chemical industry, including through the delivery of process heat, for instance in the form of steam.

**Energy mix**

Andre Faaij (Utrecht University, The Netherlands) provided **a pre-recorded presentation on Deployment of Nuclear Energy in Deep Decarbonization of the Energy System**. Recent analyses on global, European and national level were presented with specific attention for the situation in the Netherlands, on how nuclear energy may or may not fit in reaching the GHG emission reduction targets set by the Paris Agreement. Very recent system and scenario analyses shed light on the interaction of nuclear energy units in an energy system with a rapidly increasing role for solar and wind energy, with detailed attention for overall system costs, flexibility (also to use nuclear energy for generation of heat and hydrogen) and cost projections for different technologies.

Paul Nevitt (National Nuclear Laboratory, UK) provided a pre-recorded presentation on **Integrated Energy Systems and the Pathway to Net Zero by 2050 (a UK Context).** (This presentation was too long for the available time but will be provided to the participants of the session). The UK Government has committed to net zero greenhouse gas emissions by 2050, demanding an integrated approach to ensuring an optimum low-cost, low carbon energy system. As part of its recent Energy Security Strategy, it also set out a clear role for nuclear, committing to up to 24 GW of new nuclear by 2050; supporting development of large, small, and advanced nuclear across all sectors, not just electricity. Nuclear, for example, is included in the 'Industrial Decarbonisation' and 'Hydrogen' strategies recently published. To understand better future scenarios and the role of nuclear, NNL published a groundbreaking new modelling report demonstrating the role nuclear can play in delivering the UK's net zero goals.

**R&D**

Agnieska Boettcher (National Centre for Nuclear Research, Poland) presented a **Summary of the Polish National Project: gospostrateg-htr**.

GOSPOSTRATEG-HTR is a national project under the strategic Polish program of scientific research and development for the preparation of legal, organizational and technical instruments for HTR demonstration and deployment in Poland. The GOSPOSTRATEG-HTR project was divided into two phases. The first phase of the project includes research work, the second phase included the implementation of the developed procedures and strategies. The key objectives were presented: Preparation to the licensing process, Material tests, and the legal, societal, economic and industrial aspects of the project.

Jacek Jagielski (National Centre for Nuclear Research, Poland) presented **the Nomaten Centre of Excellence in Multifunctional Materials for Industrial and Medical Applications**. One of the main goals of the newly created NOMATEN Center of Excellence is to conduct research on materials for extreme applications, defined as high temperature, radiation and corrosion. As such, the project supports the Polish HTR demonstration and deployment efforts. NOMATEN should be regarded as a tool for initiation of a broad cooperation network on materials for harsh environments.

Geert-Jan de Haas (NRG, The Netherlands) spoke about **Exploring the Deployment of Advanced Reactor Systems for Decarbonization of Future Energy Generation**. The view of the Dutch nuclear stakeholders on current and future nuclear energy generation was outlined. Their nuclear development roadmap was presented and explained. In addition, it was demonstrated how the Dutch PIONEER R&D program has been tailored towards this roadmap with emphasis on the support for the advancement of molten salt, gas and liquid metal cooled reactor technology towards demonstration and deployment.

# Appendix 1: Photos




FISA 2022
EURADWASTE'22


FISA 2022
EURADWASTE'22


FISA 2022


L'ASSEMBLÉE
HÉMICYCLE GEORGES POMPIDOU
HÉMICYCLE


FISA 2022
EURADWASTE'22


FISA 2022
EURADWASTE'22
10TH EDITION
May 30 to June 3, 2022 | Lyon, France

SNETP
Sustainable Nuclear Energy Technology Platform

## ABOUT SNETP

The Sustainable Nuclear Energy Technology Platform (SNETP) was established in September 2007 as a R&D&I platform **to support technological development for enhancing safe and competitive nuclear fission in a climate-neutral and sustainable energy mix.** Since May 2019, SNETP has been operating as an international non-profit association (INPA) under the Belgian law pursuing a networking and scientific goals. It is recognised as a European Technology and Innovation Platform (ETIP) by the European Commission.

The international membership base of the platform includes industrial actors, research and development organisations, academia, technical and safety organisations, SMEs as well as non-governmental bodies.

secretariat@snetp.eu    www.snetp.eu    SNETP    SNE_TP

9 782919 313334


FISA 2022
EURADWASTE'22

# Workshop
# on the European Joint Programme
# on Radioactive Waste Management (EURAD)
# Monday, 30 May 2022
# Hôtel de Région Auvergne-Rhône-Alpes, Lyon, France

## INVITATION

A workshop dedicated to the evaluation of the European Joint Programme on Radioactive Waste Management (EJP EURAD[1]) and the preparation of the next European Partnership EURAD-2 will be held on, Monday 30 May 2022, the first day of the EURADWASTE'22 conference[2]a workshop in Lyon (France).

The workshop will be an invitation-only, in-person event at the Hôtel de Région Auvergne-Rhône-Alpes, Lyon, France. Interested participants are encouraged to pre-register.

**Participants**

- EC RTD representatives: Seif Ben Hadj Hassine, Roger Garbil, Elena Righi-Steele, Domenico Rossetti di Valdalbero
- EC ENER representatives: Zuzana Monika Petrovicova, Gianfranco Brunetti
- Mandated experts for EURAD mid-term review: Hans Forsstrom, Merle Lust, Gérald Ouzounian, Bo Strömberg
- EURAD Coordinators: Stéphan Schumacher and Louise Théodon
- EURAD Programme Management Office: Tara Beattie, Paul Carbol, Michelle Cowley, Bernd Grambow and Elisabeth Salat
- EURAD Bureau :
  - WMO: Astrid Göbel and Lukáš Vondrovic
  - TSO: Valéry Detilleux, Christophe Debayle and Ioannis Kaissas
  - RE: Christophe Bruggeman, Dirk Bosbach and Crina Bucur
- EURAD Chief Scientific Officer: Piet Zuidema
- EURAD WP leaders : Diederik Jacques, Marcus Altmaier, Francis Claret, Sergey Churakov, Xavier Sillen, Séverine Levasseur, Markus Olin, Anders Sjöland, Petra Christensen, François Marsal, Daniela Diaconu, Alexandru Tatomir, Tobias Knuuti, Jiri Faltejsek, Balint Nos, Michelle Coeck, Niels Belmans, Nikitas Diomidis, Alexandre Dauzères and Johan Bertrand

[1] EURAD homepage https://www.ejp-eurad.eu/ and CORDIS https://cordis.europa.eu/project/id/847593
[2] FISA 2022 & EURAWASTE '22 conferences https://new.sfen.org/evenement/fisa-2022-euradwaste-22/

- EURAD External Advisory Board: Pierre Toulhoat, Hans Wanner, Philippe Lalieux and Saida Engström
- The PREDIS[3] project coordination team: Maria Oksa, Erika Holt
- The Euratom Programme Committee
- Invited observers form the IAEA: Stefan Meyer, Rebecca Robbins
- Invited observer from the NEA/OECD: Rebecca Tadesse
- Invited observers from associated countries in EURAD: Rob Arnold (UK BEIS), Robert Winsley (UK NWS) Lucien von Gunten (Switzerland)

**Foreword**

The first EJP EURAD was launched in June 2019 for five years with a EUR 32.5 million EU/Euratom contribution and a total budget of EUR 59.9 million. Fifty-one beneficiary organisations and 62 affiliated entities or third parties from 23 European countries (20 Member States and 3 associated countries) have been working together over the three past years.

EURAD's work programme is steered by the three categories of representatives of the key players in radioactive waste management: Waste Management Organisations (WMOs), Technical Support Organisations (TSOs) and the Research Entities (REs). The work programme aims at improving and developing science and technology for radioactive waste management and consolidating knowledge in support of the national programmes and in line with the requirements of the Nuclear Waste Directive[4]. One important focus of the work programme is knowledge management, ensuring that information and competences are retained over time and promoting knowledge transfer between Member States with advanced research programmes and those at an early-stage.

The EJP has delivered exceptional results over its first two years and a half. Its five years' period will come to an end in May 2024. In order to capitalise and to guarantee a smooth transition from EURAD-1 to a potential second EJP EURAD-2, the Commission intends to propose a specific action in the 2023-2024 Euratom Work Programme. The lessons learnt from EURAD-1, its achievements according to the vision, the Strategic Research Agenda and Roadmap[5] and challenges and opportunities will be taken into account.

The consensual dialogue based on key strategic documentation and R&I activities e.g. The Implementing Geological Disposal of radioactive waste Technology Platform (IGD-TP)[6], the Sustainable network for Independent Technical EXpertise on radioactive waste management[7], or EURADScience network is also expected to be a useful resource.

For that purpose, the preparatory work for EURAD-2 will build on the external, mid-term review of EURAD launched in December 2021 with four external experts. These same experts were involved in a

[3] PREDIS homepage https://predis-h2020.eu/ and CORDIS https://cordis.europa.eu/project/id/945098
[4] Council Directive 2011/70/Euratom https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32011L0070
[5] EURAD Roadmap https://www.ejp-eurad.eu/roadmap
[6] IGTP https://igdtp.eu/
[7] SITEX https://www.sitex.network/

review after the first year of EURAD and have good knowledge of the Programme. In December, they were provided with the second EURAD annual report, the deliverables that were completed and supporting documentation. By the end of January they conducted virtual individual interviews with all 17 EURAD Work Package leaders to discuss the work accomplished so far. The experts will draft their assessment report by April and, with feedback from the consortium, will present their conclusions at the workshop.

The objectives of the workshop are:

- To present the conclusions and recommendations of the experts performing EURAD's mid-term review.
- To present an overview of EURAD achievements by Programme Management Office and Chief Scientific Officer and the views of the Colleges (via the Bureau members).
- To present the feedback of the EURAD External Advisory Board on the progress and way forward
- To present an overview of the PREDIS project's achievements by the project team.
- EURAD and PREDIS together will give their first recommendations for a potential second EJP format and way forward.
- For European Commission representatives to provide input on the challenges in radioactive waste management research and the opportunity of a follow-up through EURAD-2.
- For Member State representatives to share their views on a future European Joint Programme on radioactive waste management.

Ultimately, the open exchanges chaired by the European Commission, between the participants, stakeholders and Member States' Fission Programme Committee are expected to further refine all recommendations for a future EJP EURAD-2.

| **AGENDA**<br>**Workshop on the achievements of EURAD-1 and the preparation of EURAD-2**<br>**On Monday 30 May 2022**<br>At **Hôtel de Région, 1, Esplanade François Mitterrand, Lyon, France** | |
|---|---|
| **10:00 – 10:10** | Welcome (European Commission) and Objectives of the meeting |
| **10:10 – 10:20** | State of play at EU level (European Commission representative) |
| **10:20 – 10:40** | EURAD (PMO, CSOff, 20 min) |
| **10.40 – 10.55** | EURAD Bureau (views of the Colleges, 15 min) |
| **10:55 – 11:05** | EURAD (EAB, 10 min) |
| **11.05-11.25** | Questions on EURAD presentations |
| **11:25 – 11:50** | PREDIS (PMO, 15 min + 10 min questions) |
| **11:50 – 12:30** | Experts (30 minutes + 10 min questions) |
| ***12:30 – 14:00*** | *Lunch* |
| **14:00 – 15:00** | State of play at national level (Member State representative, Programme Committee) |
| **15:00 – 16:00** | EURAD-PREDIS first recommendations for a second EJP<br>Discussion and exchange of views<br>Agreement on the recommendations for the second EJP and the preliminary steps for the preparation of the proposal. |
| **16:00 – 16:30** | *Conclusions* |


FISA 2022
EURADWASTE'22

**Organisation of the European Research Community on Nuclear Materials**

A Coordination and Support Action in Preparation of a Co-Funded European Partnership on Nuclear Materials

This project has received funding from the Euratom research and training programme 2019/2020 under grant agreement No. 899997

# ORIENT-NM 2nd Workshop

## FISA 2022 – Hôtel de Région Auvergne-Rhône-Alpes - Lyon, France

**Tuesday 31st May 2022 – 14:00-18:00**

# Concept Note and Preliminary Agenda

# Context and Concept

ORIENT-NM (http://www.eera-jpnm.eu/orient-nm/) is a **Euratom-funded coordination and support action** coordinated by CIEMAT (Spain), **with the objective of exploring consensus on a co-funded European partnership (CEP) on nuclear materials**, by establishing the relevant Strategic Research Agenda (SRA), the governing structure and implementation guidelines, and the means for interaction with external stakeholders.

The ORIENT-NM consortium is formed by 15 organisations: **11 among the major nuclear materials and energy research centres in Europe**, correspondingly representing 11 Member States; **SNETP** (Sustainable Nuclear Energy Technology Platform) and **EERA** (the European Energy Research Alliance) as associations; the European Commission through the **Joint Research Centre**; and **one industry** (EDF).

The ORIENT-NM consortium shares the consideration that **research to understand materials behaviour in operation, and to improve materials performance, plays a crucial role to enhance the safety, efficiency and economy of nuclear energy**. These materials cover a wide spectrum: from metallic structural alloys to polymers and concrete, and from nuclear fuel to substances for neutron control. The accurate **health monitoring of these materials and relevant components** while operating is also crucial.

To enable enhanced safety, efficiency and economy of nuclear energy, the development, manufacturing and qualification of innovative nuclear materials must be accelerated, thus reducing their time to market. This implies a **shift from the traditional "observe and qualify" to the modern "design and control" materials science approach,** which is enabled by advanced digital techniques and suitable models.

This paradigm shift in nuclear materials science is at reach **for Europe, provided that an integrated nuclear materials research programme, i.e., a partnership, is set up to make coordinated use of assets that are spread across Member States and Associated Countries**. The partnership will need and feed, and thus complement, available schemes and roadmaps for access to, and use of, infrastructures. These include those designed in the parallel coordination and support actions JHOP2040, for utilising Euratom access rights in the Jules Horowitz Reactor, and OFFERR, which sets up a mobility scheme to access nuclear infrastructures in Europe, or established in the framework of international organisations (e.g., OECD/NEA's FIDES framework).

Such an integrated nuclear materials research programme, in full consistency with the activities foreseen in the SET-plan implementation plan on nuclear safety, will pivot around **five research lines that are transversal to all classes of nuclear materials**, namely: (1) nuclear materials test-beds, (2) nuclear materials acceleration platforms, (3) combined physics-based and data-driven models, (4) advanced health monitoring of materials and components and (5) European nuclear materials FAIR[1] database. Such a cross-cutting programme is expected to leverage substantial national and industrial support. Because of its multidisciplinary approach, **it will maintain and build competences and will equally serve all the various nuclear energy national**

[1] Findable, Accessible, Interoperable, Reusable

**strategies, supporting nuclear industry competitiveness and a robust supply chain**, with benefits for fusion and non-nuclear energy as well.

# Objectives of the workshop

- To present the ORIENT-NM vision and work, sketching the content of the SRA, presenting the first draft of the governance and structure, and listing the possible interactions of the future CEP with external stakeholders.
- To provide the opportunity for European Commission and Member States' representatives to express comments and recommendations, in connection with a possible CEP on nuclear materials, in a dialogue with the ORIENT-NM community.
- To agree about the opportunity of launching a CEP on nuclear materials as part of the Euratom work-programme 2023-24, to guide the operation of the ORIENT-NM CSA in the remaining months of coordinated work.

# Expected participants

- EC RTD representatives
- Euratom Fission Programme Committee members in representation of the Members States
- Representatives of Associated Countries
- ORIENT-NM coordination group and governing board members
- Any interested stakeholder

# Preliminary Agenda

| Time | Title |
|---|---|
| 14:00 – 15:30 | **ORIENT-NM Context**<br>Lorenzo Malerba, CIEMAT, ORIENT-NM Coordinator<br><br>**ORIENT-NM Vision and Strategic Research Agenda**<br>Marjorie Bertolus, CEA<br><br>**Partnership structure, governance and analysis of resources**<br>Lorenzo Malerba, CIEMAT, on behalf of Petri Kinnunen, VTT<br><br>**Partnership interaction with stakeholders and use of infrastructures**<br>Angelika Bohnstedt, KIT |
| 15:30 – 16:00 | **Coffee Break** |
| 16:00 – 17:00 | **Member State Representatives' comments and recommendations**<br>C. Ducu (RO), M. Ripani (IT), P. Seltborg (SE), T. Tadić (HR), S. Grandjean and F. Legendre (FR) |
| 17:00 – 18:00 | **Q&A, discussion and conclusions**<br>All |
| 18:00 | **Workshop closure** |

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This project has received funding from the Euratom research and training programme 2019/2020 under grant agreement No. 899997

# ORIENT-NM - Organisation of the European Research Community on Nuclear Materials

ORIENT Organisation of the European Research Community on Nuclear Materials

## ORIENT-NM Context

L. Malerba, CIEMAT, ORIENT-NM and EERA JPNM coordinator, lorenzo.malerba@ciemat.es

This project has received funding from the Euratom research and training programme 2019/2020 under grant agreement No. 899997

## Outline:

- What is ORIENT-NM
- How is ORIENT-NM working
- What has ORIENT-NM produced
- Analysis of national plans
- Mission of the nuclear materials science community
- Timing of ORIENT-NM

# What is ORIENT Nuclear Materials?


A Coordination and Support Action partially funded by Euratom, WP 2019-20, NFRP-08

Goals as from the call:

- Consolidate the domain of nuclear materials in Europe
- Avoid duplication, improve complementarity
- Involve EERA (JPNM) and SNETP (NUGENIA)

In practice:

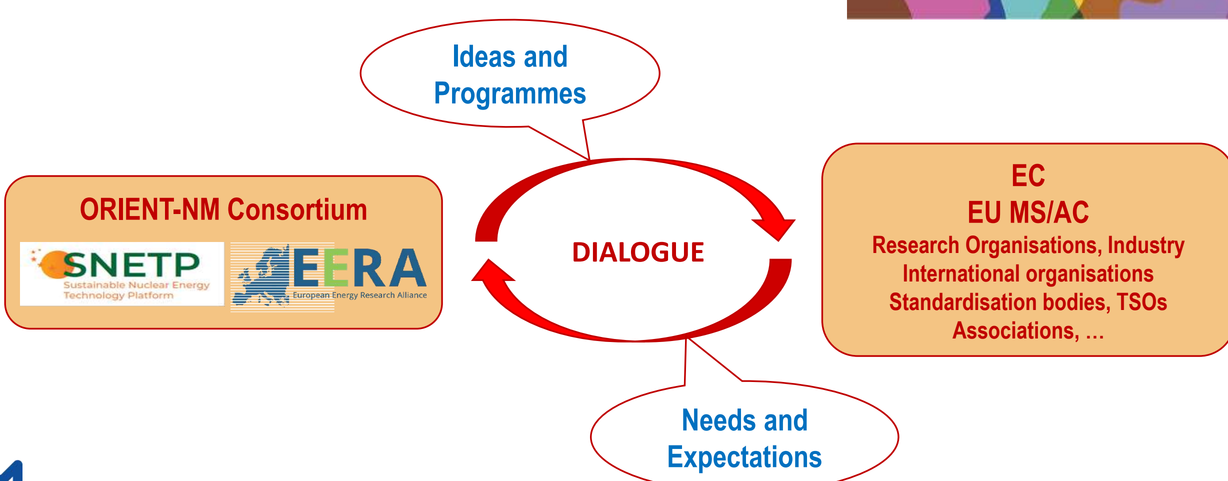
- Explore the ground for a European Partnership* on nuclear materials

**ORIENT-NM Budget:**
**Total: 1.6 M€**
**Euratom part: 1.1 M€**

**European Partnerships in HEU replace among others H2020 European Joint Programmes, EJP*

# How is ORIENT-NM working?

**Dialogue & Inclusiveness**



# What is ORIENT-NM producing?

1 Single Vision Strategic Reasearch Agenda on Nuclear Materials <u>for the benefit of ALL reactor generations</u> until 2040

2 Most suitable governance, structure and implementation design for the European Partnership

3 Plan of interaction of the European Partnership with all interested stake-holders

Following Presentations

ORIENT NM

# What is ORIENT-NM producing?

**Documents that can be found on the website*:**

- Analysis of MS/AC programmes concerning nuclear energy until 2040 and beyond
- Vision Paper: context and identification of Grand Goals
- First version of SRA – peer-reviewed article*
- Materials ID cards – technical document to which the SRA will refer
- First analysis of governance structures
- First analysis of legal issues
- First drafts of interaction of the partnership with international organisations
- First analysis of commonalities with non-nuclear energy

**Coming up:**

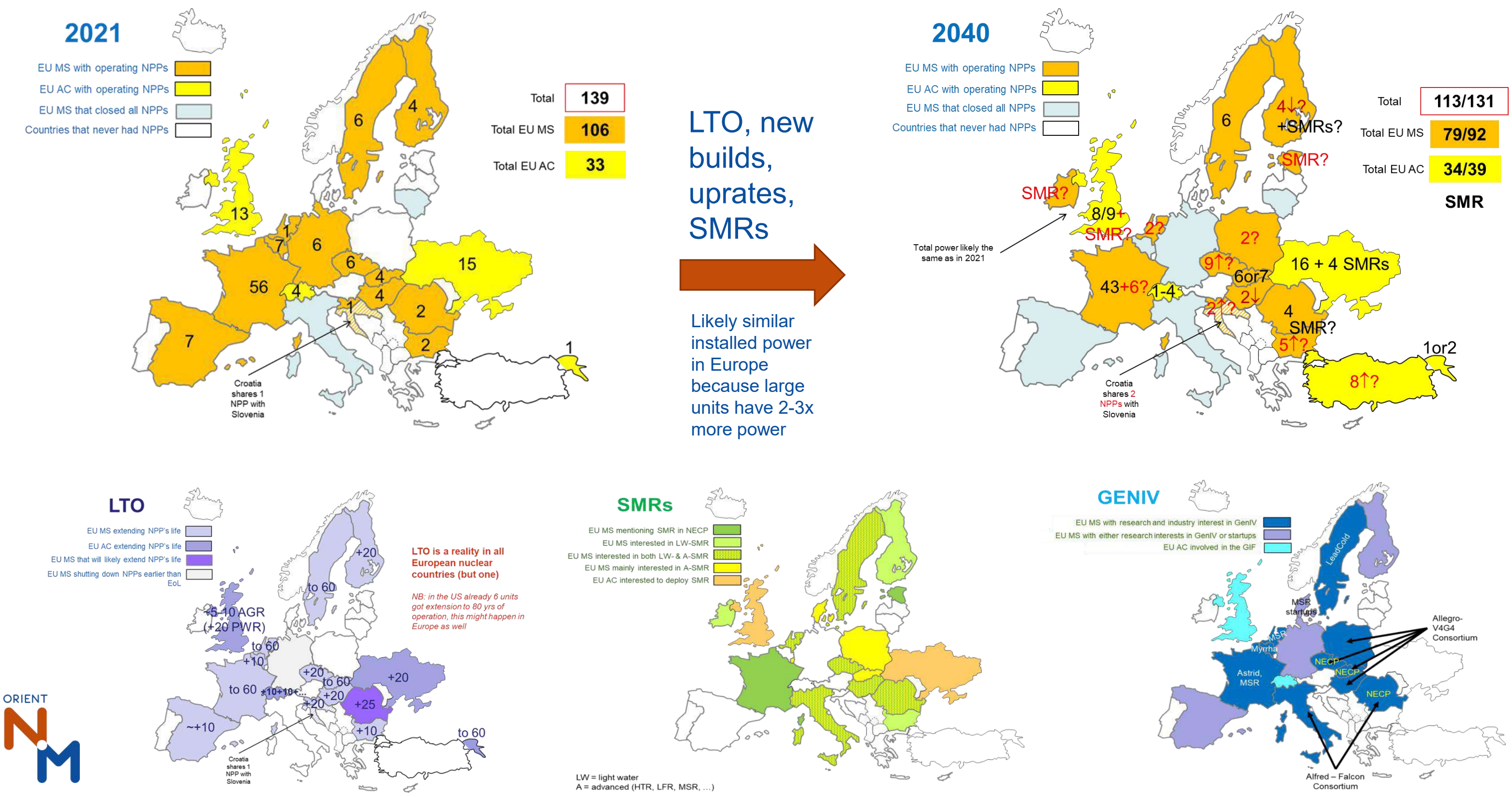
- First draft of training and education activities
- First draft of implementation and quality plan
- First drafts of interaction of the partnership with various stakeholding bodies
- First analysis of commonalities with fusion energy
- First analysis of available and future infrastructures, with emphasis on MTRs/ESFRII facilities
- Critical assessment of the added value of a European partnership on nuclear materials

*http://www.eera-jpnm.eu/orient-nm/

*https://doi.org/10.3390/en15051845

ORIENT NM

# Analysis of nuclear energy national plans




# Mission of the nuclear materials science community

In this context <u>the research activities of a European partnership dedicated to nuclear materials should **support**</u>:

⇒ Safe and affordable LTO of current generation reactors

⇒ Increasingly safe design, licensing and construction of Gen III+ new builds

⇒ Deployment of light water SMRs within the next decade

⇒ Reduction of time and costs for the design, licensing and construction of competitive next generation (GenIV) nuclear reactors, including advanced SMRs, within the time horizon of 2040

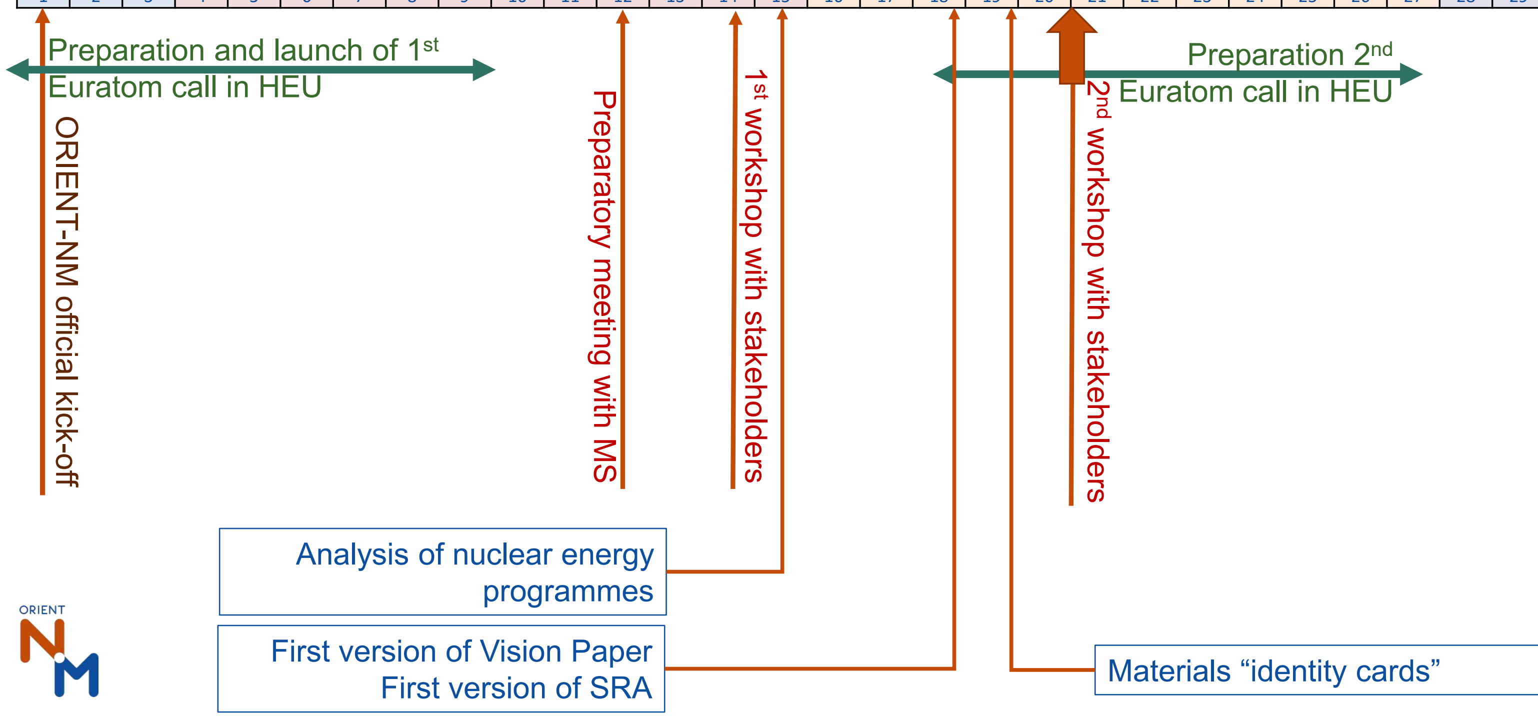
**Keywords**:

- Predictive methodologies, continuous monitoring, supply chain and advanced manufacturing
- Accelerated development & qualification capabilities
- Advanced digital technologies

Euradwaste'22

# Timing of ORIENT-NM

| 2020 | | | 2021 | | | | | | | | | | | | 2022 | | | | | | | | | | | | 2023 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Jan | Feb | Mar |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 |






ORIENT NM

**Thank you!**

www.eera-jpnm.eu/orient-nm

**ORIENT-NM - Organisation of the European Research Community on Nuclear Materials**

ORIENT
Organisation of the European Research Community on Nuclear Materials

## ORIENT-NM Vision and Strategic Research Agenda

M. Bertolus, CEA, marjorie.bertolus@cea.fr

This project has received funding from the Euratom research and training programme 2019/2020 under grant agreement No. 899997

**Outline:**

- Which systems
- Which materials: identity cards
- ORIENT-NM Vision
- Research lines and grand goals
- Perimeter of activities
- Timing and Planning
- Link with national programmes and other initiatives

# What is ORIENT-NM producing?

1. Single Vision Strategic Reasearch Agenda on Nuclear Materials <u>for the benefit of ALL reactor generations</u> until 2040
2. Most suitable governance, structure and implementation design for the European Partnership
3. Plan of interaction of the European Partnership with all interested stake-holders

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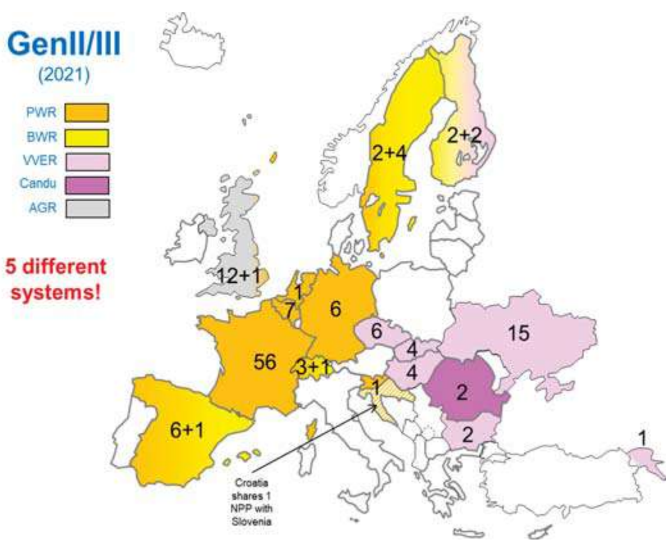
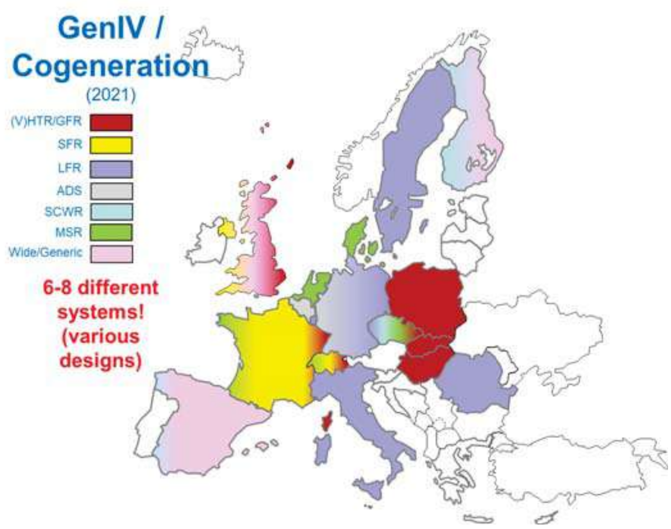
# Which nuclear systems? Europe is united in diversity

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4

## Which materials? 7 classes for both current and future NPPs with significant impact on safety and efficiency

| | Concrete | Metallic alloys for structural components | Refractory materials for structural components | Polymers for cables and structural applications | Fuel cladding materials | Nuclear fuel materials (fissile and fertile) | Materials for neutron control: absorbers, moderators, reflectors |
|---|---|---|---|---|---|---|---|
| Safety | External containment, last barrier to release of radioactive material, protection of reactor core from external agents | Vessel: main barrier to release of radioactive material | Maintain integrity at high temperature in both operating or accidental conditions | Efficient transmission of energy or signals | Barrier to radioactive material release into coolant | Inherent barrier to fission product release<br>Heat production even after shutdown | Control of reaction |
| Efficiency | | Piping and supports define inlet/outlet temperature | Higher temperature brings higher efficiency | | Define possibility of high burnup | There is no reactor without fuel!<br>Defines neutron spectrum, burnup, etc. | Define neutron spectrum and criticality |

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5

## Which materials? 7 classes for both current and future NPPs with significant impact on safety and efficiency

| Concrete | Metallic alloys for structural components | Refractory materials for structural components | Polymers for cables and structural applications | Fuel cladding materials | Nuclear fuel materials (fissile and fertile) | Materials for neutron control: absorbers, moderators, reflectors |
|---|---|---|---|---|---|---|

**MATERIALS IDENTITY CARDS DEFINE THE ISSUES TO BE ADDRESSED FOR EACH SPECIFIC MATERIAL BELONGING TO THESE CLASSES**

**CARDS WERE PRODUCED ONLY FOR 4 CLASSES OUT OF 7, DENOTING THE NEED TO DEVELOP EUROPEAN RESEARCH COMMUNITIES FOR SOME OF THE MATERIALS CLASSES**

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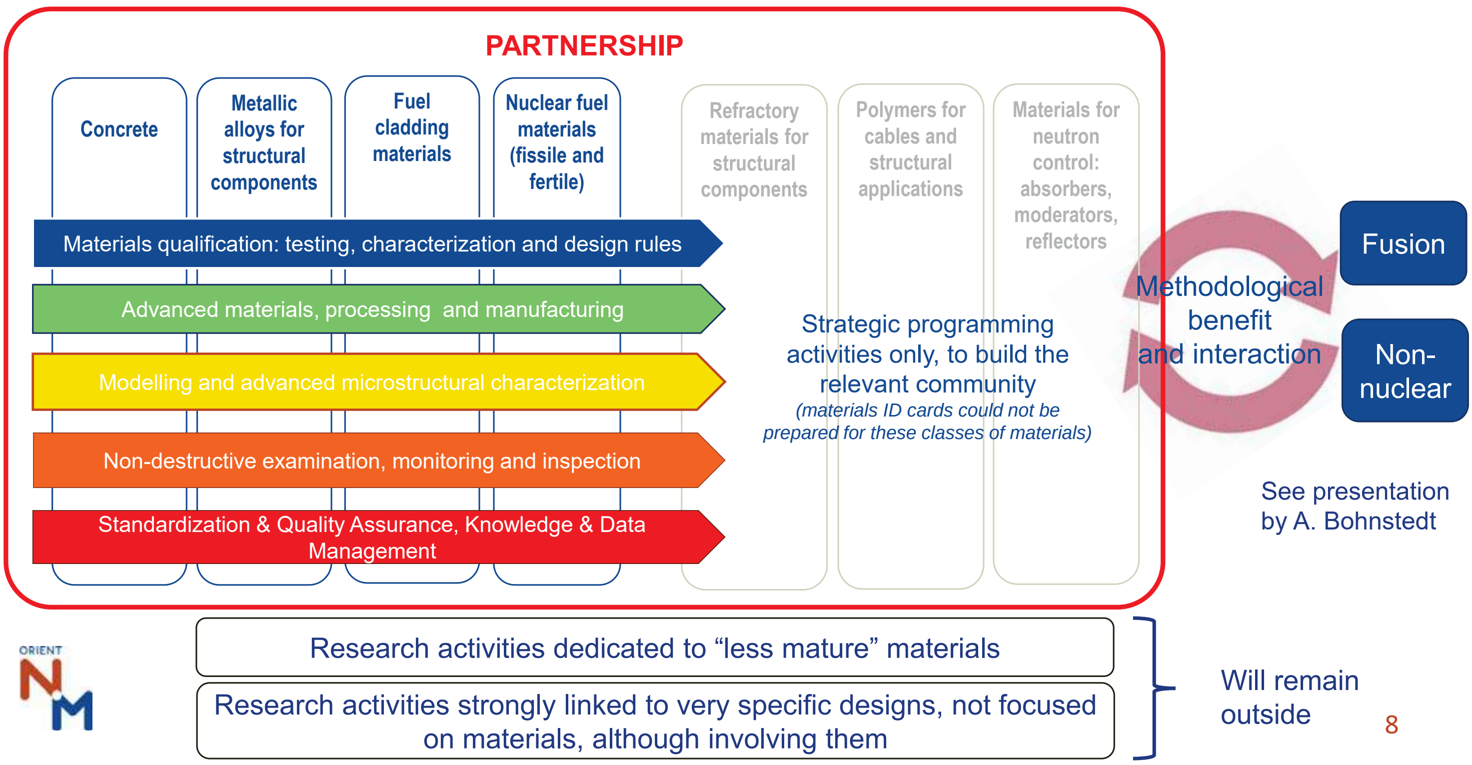
6

## ORIENT-NM Vision

- **Nuclear power will be maintained in Europe through LTO, power uprates and new builds** to 2040 and beyond
- **Small modular reactors and advanced designs** are game-changers throughout the continent
- **Research to understand and monitor materials behaviour in operation, and improve materials performances, has a crucial role** to continuously enhance the safety, efficiency and economy of nuclear energy
- **Research needs to be boosted to accelerate** the development, manufacturing and qualification of innovative nuclear materials, and so **reduce their time to market**
  - shift from the **traditional "observe and qualify"** to the **modern "design and control"** materials science approach, enabled by advanced digital techniques and suitable models
- **An integrated nuclear materials research programme, i.e. a partnership, needs to be set up** to make coordinated use of assets spread across MS & AC, to give continuity to the pursued research lines
- **To produce fruitful results for all, including non-nuclear countries, research lines are transversal to all classes of nuclear materials**:
  - inherent **multidisciplinary approach**
  - maintains and **builds competences**
  - **cross-cutting nature** to equally serve all nuclear energy national strategies
  - benefits for **fusion and non-nuclear energy**

7

## Perimeter of activities

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## Timing: the first 5 years

**Methodological developments applied to selected materials**

**Identification of needs for instrumented neutron irradiation campaigns**

Concrete

Metallic alloys for structural components

Fuel cladding materials

Nuclear fuel materials (fissile and fertile)

Materials qualification: testing, characterization and design rules

Advanced materials, processing and manufacturing

Modelling and advanced microstructural characterization

Non-destructive examination, monitoring and inspection

Standardization & Quality Assurance, Knowledge & Data Management

New materials
New methodologies
Integrated characterization
Populated databases

**Emphasis on innovation for the benefit of any reactor generation**

Infrastructures

See presentation by A. Bohnstedt

9

## Timing: 10 year horizon

**Wider application of methodological developments**

**Contribution to preparation / realization of major neutron irradiation campaigns of relevance**

Concrete

Metallic alloys for structural components

Fuel cladding materials

Nuclear fuel materials

Refractory materials for structural components

Polymers for cables and structural applications

Materials for neutron control

Materials qualification: testing, characterization and design rules

Advanced materials, processing and manufacturing

Modelling and advanced microstructural characterization

Non-destructive examination, monitoring and inspection

Standardization & Quality Assurance, Knowledge & Data Management

Nuclear-oriented test-beds
Nuclear materials acceleration platforms
Advanced predictive methodologies
Advanced materials health monitoring
Nuclear materials database

Infrastructures

**Grand goals** will be reached on **case studies** with sufficiently ample validity

Criterion of success: **extensibility of methodology** rather than specific application

10

## Link with national programmes and other European initiatives

- Materials 2030 Manifesto, Feb. 2022, impulsed by European industry [1]
  - The vision of this document is completely consistent with the approaches pursued in the planned partnership
- French project DIADEM: DIscovery Acceleration for the Deployment of Emerging Materials [2]
  - "2- to 5-fold acceleration of materials discovery from about 20 years to between 4 to 10 years"
- German initiatives FAIR-DI, FAIR-Mat, NOMAD [3]
  - FAIR-DI: FAIR Data Infrastructure for Physics, Chemistry, Materials Science, and Astronomy e.V. (non-profit association based in Germany, includes BE and NL participants)
  - FAIR-Mat: FAIR Data Infrastructure for Condensed-Matter Physics and the Chemical Physics of Solids
  - NOMAD (Novel Materials Discovery): Laboratory - enables FAIR sharing and use of materials science data; CoE - Bringing computational materials science to exascale
- German-Canadian Mission Innovation partnership
  - Development of a "Corrosion" Materials Acceleration Platform
- NOMATEN Centre of Excellence in Multifunctional Materials for Industrial and Medical Applications (NCBJ, CEA, VTT) [4]
  - Novel high-temperature, corrosion and radiation resistant materials for industrial applications

[1] https://ec.europa.eu/info/sites/default/files/research_and_innovation/research_by_area/documents/advanced-materials-2030-manifesto.pdf
[2] https://simap.grenoble-inp.fr/en/about-simap/diadem
[3] https://www.fair-di.eu/
[4] http://nomaten.ncbj.gov.pl/

Consistent with SET-plan Implementation Plan 10

## Thank you!

www.eera-jpnm.eu/orient-nm

## ORIENT-NM - Organisation of the European Research Community on Nuclear Materials

### Partnership structure, governance and analysis of resources

P. Kinnunen, VTT, petri.kinnunen@vtt.fi, presented by L. Malerba, CIEMAT

This project has received funding from the Euratom research and training programme 2019/2020 under grant agreement No. 899997

## Outline:

- Work done on governance and structure
- Type of partnership
- Co-funding details
- Type of structure
- Effects of allocated resources on planning
- Analysis of expenditures for materials in H2020
- Open issues

# What is ORIENT-NM producing?

1. Single Vision Strategic Reasearch Agenda on Nuclear Materials for the benefit of ALL reactor generations until 2040
2. Most suitable governance, structure and implementation design for the European Partnership
3. Plan of interaction of the European Partnership with all interested stake-holders

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# Work done in ORIENT-NM for structure and governance

- The partnership needs to be planned in all of its aspects.
- This includes:
  - Governance and structure
  - Legal issues
  - Resourcing
  - Implementation and quality management
  - Data and knowledge management
  - Education and training

Focus here at the moment

ORIENT NM

# Type of Partnership

- Existing partnerships have been investigated (EURAD, CONCERT, EUROFusion,…*) and the differences in structures and ways of working have been mapped.
- The basic features of different partnership types (**co-funded, co-programmed and institutionalised**) have been collected and compared, resulting in the following **conclusion**:
  - **The selection for the nuclear materials partnership would be the co-funded type**
    - *Co-funded European Partnership - **CEP***
    - *Resembles current EU projects and is most probably the easiest to build and manage*

*https://www.ejp-eurad.eu/ ; https://www.concert-h2020.eu/ ; https://www.euro-fusion.org/

## Co-funding details and caveats

- Expected EU funding rate: **55%** **(**Current EJPs above this)
- Complementary funding rate: **45%**

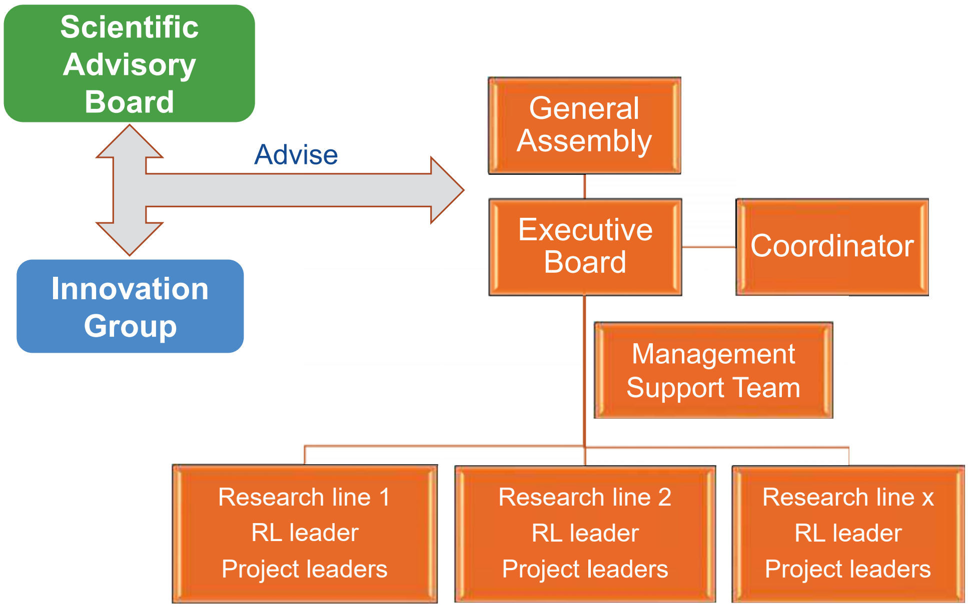
- **Co-funding scheme**
- The CEP agreement is signed by **Programme owners** (ministries, funding agencies...) and/or **Programme Managers** (usually large national research institutes), which receive a **clear mandate** from the Programme Owners
  - This has not been successful in other CEP´s: not strong enough mandate was given to programme managers to decide about the complementary funding
- **Complementary funding agreements must be binding** (for both partners and affiliated parties)
  - National legislation and research programme structures need to be taken into account carefully
  - Can complementary funding be in-kind?
    - E.g. in the EURAMET partnership (metrology) co-funding is fully covered by the in kind work/investments

- Points of attention:
  - CEP legal structure vs. national legislation: are there contradictions?
  - May participation fees be considered to partly cover the fixed costs of the programme?

## Standard structure, but with emphasis on innovation

**“Standard” advisory body: experts in charge for the assessment of the activities with scientific and technical background, emanation of R&D environments**

**Experts in leading business, supporting entrepreneurship and commercializing technology, in connection with materials development and/or nuclear energy, emanation of industrial and innovation environments**




## Ambition and scope, but also functioning scenarios, depend on allocated resources

**Financing for CEP = functioning costs + costs of projects performed within the CEP**

Expected advantage: no need for complex internal structures of projects, one single GA and one single management support team operate for all → **more resources for research**

However, there is a minimum funding (to be calculated) below which this advantage is not clearly seen

**Crucial decision to be made: macroproject or internal calls?**

Macroproject model: implies either sufficient resources to cover all research lines for all materials and applications (unlikely), or consensual pre-selection of case-studies (pre-defined selected projects)

**advantage:** work can start immediately

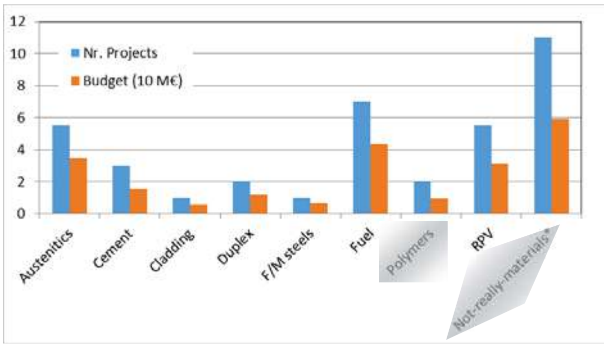
**disadvantage:** it may prove very difficult to agree on case-studies

Internal call model: only choice when resources are limited

**advantage**: proposed projects are the result of spontaneous wide convergence, introduces a competitive dimension and selects the best proposal based on defined criteria

**disadvantage**: calls need to be managed and research work cannot start immediately when the partnership starts

## Resources: Analysis of materials expenditure in Euratom in H2020 (over 7 years)

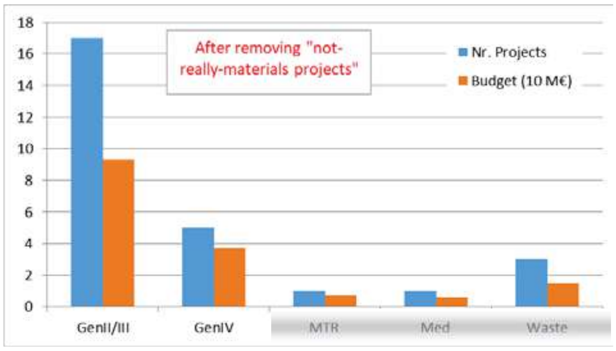



**38 PROJECTS**
**217.5 M€**

perimeter

**25 PROJECTS**
**148.8 M€**

*Materials are part of the research, but embedded in design, safety or strategic aspects – out of partnership's perimeter




**27 PROJECTS**
**158.0 M€**

perimeter

**22 PROJECTS**
**130.0 M€**

**The H2020 5 year expenditure for materials within the perimeter of the partnership is about 93 M€ (55% → ~51 M€)**

## Issues that remain to be addressed

- Ensure the most transparent management possible while enabling sufficient flexibility, e.g. by giving the coordinator and the ExBo sufficient autonomy of action on behalf of the consortium
- Define as clearly as possible the participation and financing rules for the various types of possible partners (in addition to signatories, affiliated partners, industry, associations, ...)
- Applicability of in-kind complementary funding
- Close analysis of the legal EC clauses versus applicability in different MS

In addition:

- Education and Training scheme is being drafted
- Implementation plan (quality, knowledge, data, ...) needs to be elaborated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Thank you!
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# ORIENT-NM - Organisation of the European Research Community on Nuclear Materials

## Partnership interaction with stakeholders and use of infrastructures

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This project has received funding from the Euratom research and training programme 2019/2020 under grant agreement No. 899997

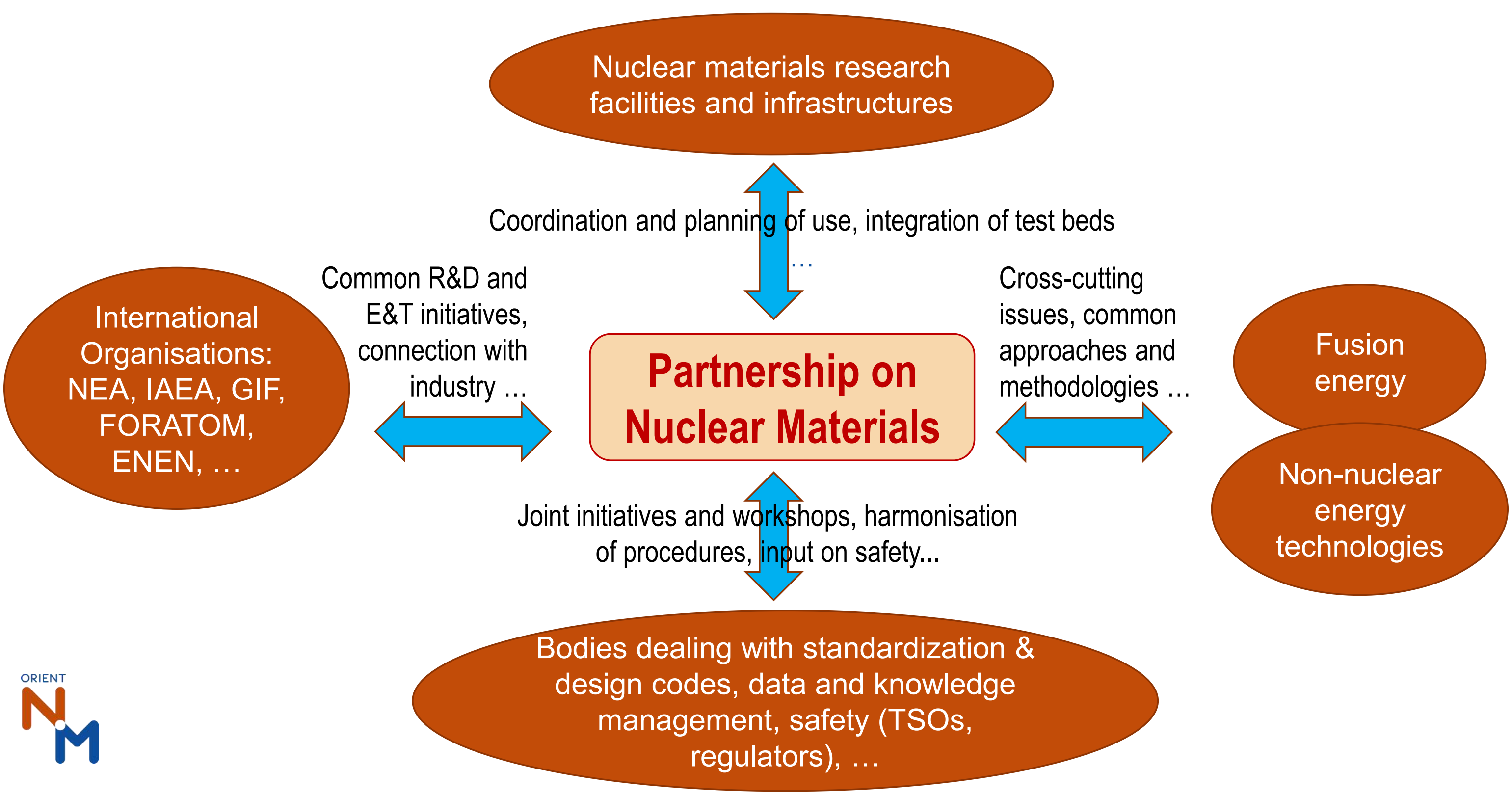
**Outline**

- Partnership expected interactions
- Relationship with international organisations
- Relationship with stake holding bodies
- Relationship with fusion
- Interaction with non-nuclear energy technologies
- Interaction with research infrastructures and facilities: feed and need connection

# What is ORIENT-NM producing?

1. Single Vision Strategic Reasearch Agenda on Nuclear Materials for the benefit of ALL reactor generations until 2040
2. Most suitable governance, structure and implementation design for the European Partnership
3. Plan of interaction of the European Partnership with all interested stake-holders

## Partnership's expected interactions



## Relationship with international organisations

**outcome stakeholder workshop June 2021**

NEA observer in CEP; CEP nominees in NEA bodies. Several WP have activities that overlap with CEP and can be steered to overlap more. NEST and **FIDES**.

NEA
NUCLEAR ENERGY AGENCY

**Partnership on Nuclear Materials**

**Legal agreements generally not possible, but several opportunities for collaboration exist, including exchange of experts and mutual membership in specific bodies**

Possibility of agreeing on launching CRPs connected with CEP activities. Several sections potentially interested.

IAEA

Collaboration through CEP experts participating in technical meetings of system steering committees.

GEN IV International Forum
Expertise | Collaboration | Excellence

FORATOM can act as springboard and amplifier of CEP activities towards industry. Networking events.

FORATOM

ENEN may offer contact with students and universities. Collaboration through use of mobility programme and coordinated E&T initiatives on materials.

enen

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## Relationship with stake holding bodies

**Partnership on Nuclear Materials**

**Mainly stakeholders on 'Codes & Standards and Data Management' were contacted**

AFCEN, EMCC, CORDEL, EPERC, ETSON and EMMC:

Stakeholder workshop January 2022

- Benefits of a CEP: Collaboration on guidelines for new test standardization, harmonization of (new) materials qualification
- Reach critical mass, sharing of R&D facilities
- Use of artificial intelligence for data analysis, data format and ontologies
- Collaboration outside the nuclear sector
- Collaboration also outside Europe

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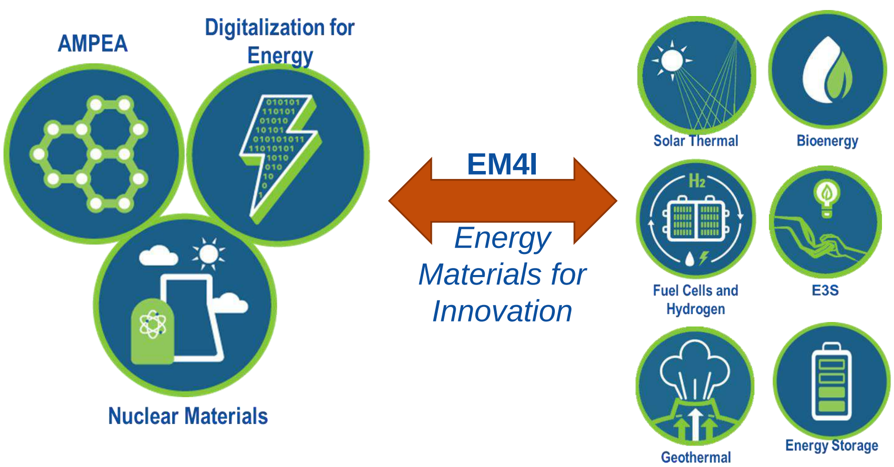
## Relationship with fusion

Outcome of the discussion during the 1st workshop: ***"The partnership should interact with the fusion community, by organising joint actions in which a structured dialogue for cross-fertilisation should be established between the two communities"***

Two aspects addressed:

- Identification of cross-cutting issues: plenty of them have been identified in the case of materials, also by participating in IAEA initiative dedicated precisely to this goal (technical meeting October 2021, March 2022, next 6-10 June 2022)
- Benefit of CEP on nuclear materials for fusion: no overlap or interference with EUROfusion's activities dedicated to qualification of EU-DEMO materials, but the approaches pursued and developed within the partnership can be eventually applied to the benefit of fusion, as well, thus the fusion community has interest in being involved

## Interaction with non-nuclear energy technologies within EERA and outside





**Link was established with Materials Manifesto community**

**5 online workshops on cross-cutting issues (~50-60 attendants):**

1/7/21 "Materials Discovery and Development"
4-6/10/21 "From Lab to Engineering"
21/12/21 "Approaches for the implementation of Digital Twins"
25/2/2022 "Sustainability Assessment of materials and technologies for a clean energy transition"
7-8/4/2022 "Energy Materials for Harsh Operating Conditions"

**Provided complete snapshot of modern materials science trends exploiting advanced digital tools, as well as materials cross-cutting issues**


**Final EM4I Strategic Meeting planned to be held close to SETplan conference (8 Nov. 2022), in Prague**

Interaction is expected to be similar as in the case of fusion

## Interaction of the CEP with infrastructures and facilities

**The partnership will naturally need & feed current and future irradiation facilities and relevant schemes of coordination of use**

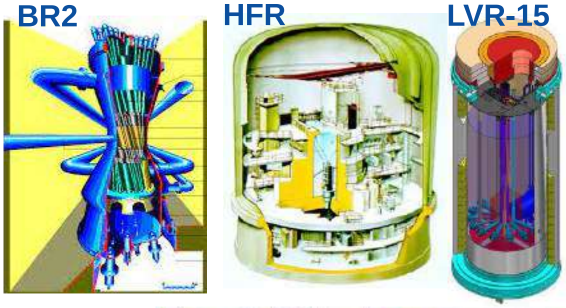
Nuclear-oriented materials qualification test-beds (n-test-beds)

Nuclear materials acceleration platforms (n-MAPs)

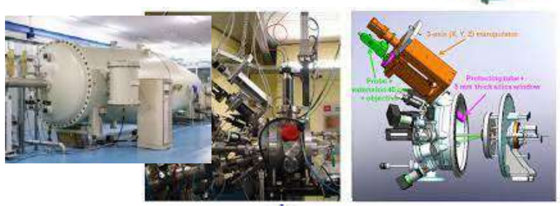
JHOP2040, OFFERR

FIDES (NEA-OECD)

BR2 HFR LVR-15

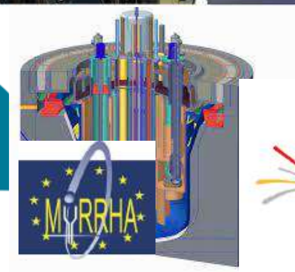


**Neutrons in operation**



**Ions**


JHR Jules Horowitz Reactor




IFMIF DONES GRANADA

**Future neutrons (> 2030)**

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# Thank you!

[www.eera-jpnm.eu/orient-nm](www.eera-jpnm.eu/orient-nm)

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EURADWASTE '22, the 10th European Commission (EC) conference on the management of radioactive waste and geological disposal was held under the auspices of the French Presidency of the Council of the European Union (EU) in Lyon, on 31 May - 3 June 2022. It was co-organised together with the CEA and concurrently with the 10th FISA 2022 conference on the Safety of Reactor Systems.
EURADWASTE'22 structure and its sessions' objectives aim at taking stock of what kind of research the Commission has funded during Horizon 2020 and open-up exchange and discussions on future collaborative research of EU added-value. Speakers from international organisations such as the IAEA and the OECD/NEA were invited as well to present an overview of their recent activities on radioactive waste management. Each one of the three sessions was introduced by a keynote lecture given on behalf of one of the three colleges of EURAD, followed by a series of presentations from the different on-going projects and work packages and closed by a round-table discussion between the speakers. The proceedings include written contributions from invited presentations and posters, session summaries and panel reports

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