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FISA 2022

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

enen

ENS

FORATOM THE VOICE OF THE EUROPEAN NUCLEAR INDUSTRY

igd-tp

SITEX

FISA 2022 – 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

FISA 2022

Conference Proceedings

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

2024

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.

FISA 2022 and EURADWASTE '22 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.

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

FISA 2022 technical sessions covered progress of the research carried out through 60 projects on: safety of existing nuclear installations; severe accidents prevention and mitigation including emergency management; advanced nuclear systems and fuel cycles for increased safety and sustainability, numerical simulation and digitalisation, innovative materials, low dose radiation protection, decommissioning, research infrastructures, education & training and mobility of researchers, as well as cross-cutting actions such as International Cooperation.

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!

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 Nuclear Valley's competitiveness cluster.

All material presented at these International Conferences are gathered within these FISA 2022 Proceedings (in parallel to those for EURADWASTE '22, each including keynote speeches, PPTs presentations and posters, sessions and workshops' summaries, introduction and conclusion).

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 10th 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,

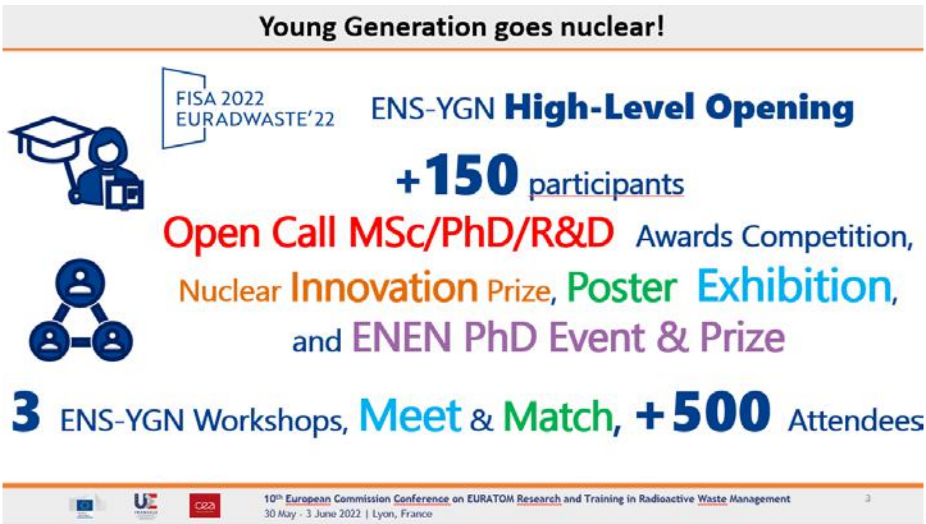
On behalf of the Organising and Programme Committee

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


A global audience
550+ Participants, 49 Nationalities
51
Companies
35
Universities
29
Gov. Organisations
28
Research Centres
13
NGOs
FISA 2022
EURADWASTE'22
Euratom4U iOS Android App. & desktop version
10th European Commission Conference on EURATOM Research and Training in Radioactive Waste Management
30 May - 3 June 2022 | Lyon, France


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

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FISA 2022
EURADWASTE'22

PROGRAMME OVERVIEW

Tuesday 31 May 22	
Day 1 AM	**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)
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 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 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 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 Keynote: IAEA Research and Innovation for safe, secure and safeguarded nuclear for every citizen, in support of the UN Sustainable Development Goals

09:45 (15')	**William D. MAGWOOD IV** (OECD/NEA), Director-General of OECD Nuclear Energy Agency 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 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 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 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 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 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

	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 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 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 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** Co-chair: Myriam CALACICCO (FR, NUCLEAR VALLEY) Co-chair: Stefano MONTI (IAEA) Rapporteur: Ferry ROELOFS (NL, Expert)
14:00 (20')	**Bernard SALHA** (EDF, FR) *SNETP* 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) *ENTENTE – ATLASplus – NOMAD – STRUMAT-LTO* Euratom projects supporting Long Term Operation of primary circuit components, including RPV
14:40 (20')	**Tomasz BRYNK** (SCK-CEN, BE) *FRACTESUS – MEACTOS – INCEFA-SCALE*

	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) *sCO2-4-NPP – APAL –* CAMIVVER 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) *TEAM-CABLES – EL-PEACETOLERO* Methodologies for efficient and reliable NPP polymer ageing management
	Advanced numerical simulation and modelling for reactor safety
15:40 (20')	**Christophe DEMAZIERE** (CHALMERS, SE) *CORTEX – McSAFER – METIS* 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) *ELSMOR – PASTELS – NUCOBAM* Ensuring safety with passive systems
16:50 (20')	**Jared WIGHT** (SCK-CEN, BE) *EU-QUALIFY – LEU-FOREvER* 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) *MUSA – PIACE – AMHYCO* Towards an optimized management of accidents

	Probabilistic Safety Assessment for internal and external events on nuclear power plants and on mitigation strategies
17:30 (20’)	Atte HELMINEN (VTT, FI) *BESEP – NARSIS – R2CA* 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** Co-chair: Daniela DIACONU (RO, RATEN ICN) Co-chair: Seif BEN HADJ HASSINE (EC, DG RTD) Rapporteur: Marie-Anne BRUNEAUX (FR, Expert)
14:00 (30’)	Tiina JALONEN (POSIVA, FI) *IGD-TP* Keynote: IGD-TP – Towards operating and optimization.
14:30 (25’)	Erica FRANCHINI (CAEN, IT) on behalf of Massimo MORICHI (CAEN, IT) *MICADO – CHANCE – PREDIS* Radioactive Waste Characterization
14:55 (25’)	Erika HOLT (VTT, FI) *PREDIS – THERAMIN* Predisposal conditioning, treatment, and performance assessment of radioactive waste streams
15:20 (25’)	Johan BERTRAND (ANDRA, FR) *CORI – CONCORD – FUTURE – MODATS* 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) *ACED – DONUT – MAGIC – BEACON*

	Modelling of the long term evolution and performance of engineered barrier systems
Coffee Break (20')	
16:30 (25')	**Séverine LEVASSEUR** (ONDRAF/NIRAS, BE) *GAS – HITEC* Mechanistic understanding of gas and heat transport in clay-based materials for radioactive waste geological disposal
16:55 (25')	**Anders SJÖLAND** (SKB, SE) *SFC – DISCO* 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

Day 2 AM	**FISA 2022 – Session 2: Advanced nuclear systems and fuel cycles** Co-chair: Hamid AIT ABDERRAHIM (BE, SCK-CEN) Co-chair: Jan PANEK (EC, DG ENER) Rapporteur: Teodora RETEGAN-VOLLMER (RO, Expert)
08:45 (15’)	**Welcome**
09:00 (20’)	**Stefano MONTI** (IAEA), Head of section Nuclear Power Technology Development 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) *ESFR-SMART – SafeG – ECC-SMART – ACES – SAMOSAFER* R&D in support to safety assessment, design and licensing of ESNII/Gen-IV
09:45 (25’)	**Nathalie CHAUVIN** (CEA, FR) *PUMMA* Plutonium management in the whole fuel cycle
10:10 (25’)	**Paul SCHUURMANS** (SCK-CEN, BE) *PATRICIA - PASCAL* Partitioning and Transmutation, contribution to an EU strategy for HLW management
Coffee Break (25’)	
11:00 (25’)	**Lorenzo MALERBA** (CIEMAT, ES) *ORIENT-NM – GEMMA – M4F* 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) *GEMINI-PLUS* Nuclear Cogeneration with High Temperature Reactors

11:45 (15’)	**Carola FRANZEN** (HZDR, DE) *ARIEL – SANDA* 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** Co-chair: Irina GAUS (NAGRA, CH) Co-chair: Zuzana Monika PETROVICOVA (EC, DG ENER) Rapporteur: Piet ZUIDEMA (CH, Expert)
08:45 (15’)	**Welcome**
09:00 (30’)	**Valéry DETILLEUX** (Bel-V, BE) *SITEX Network* Keynote: SITEX Network: key activities, lessons learned and upcoming challenges
09:30 (25’)	**Daniela DIACONU** (RATEN ICN, RO) *UMAN* UMAN – A pluralistic view of uncertainties management
09:55 (20’)	**Marja VUORIO** (COVRA, NL) *ERDO* ERDO – a road to sharing radioactive waste management solutions
10:15 (20’)	**Zuzana Monika PETROVICOVA** (DG ENER, EC) Radioactive Waste Management in the European Union - State of play and strategic prospects
Coffee Break (25’)	
11:00 (25’)	**Liz Harvey** (Galson Science, UK) *ROUTES*

	ROUTES - Identified key issues and open questions about waste management routes in Europe, from cradle to grave
11:25 (20’)	**Rebecca ROBBINS** (IAEA) *IAEA* Different Missions – Common Goals: the IAEA, PREDIS and EURAD Working Together to Strengthen Radioactive Waste Management World-wide
11:45 (45’)	**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.**
Lunch (90’)	
Day 2 PM	**FISA 2022 – Session 3: Education and training, research infrastructures, low dose radiation protection, decommissioning and international cooperation** Co-chair: Tatiana IVANOVA (FR, OECD/NEA) Co-chair: Roger Garbil (EC, DG RTD) Rapporteur: Said ABOUSAHL (FR, Expert)
14:00 (20’)	**Marco UTILI** (ENEA, IT) Keynote: Synergies between Fission and Fusion R&D towards demonstration plants
14:20 (30’)	**Joerg STARFLINGER** (ENEN, DE) *ENENplus – GREaT-PIONEeR – ENEEP – PIKNUS – A-CINCH* 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) *MEDIRAD – HARMONIC – SINFONIA – EURAMED rocc-n-roll*

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

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** Co-chair: Rebecca ROBBINS (IAEA) Co-chair: Manuel MARTIN RAMOS (EC, DG JRC) Rapporteur: Christophe BRUGGEMAN (BE, Expert)
14:00 (50’)	**Christophe BRUGGEMAN** (SCK-CEN, BE) and **Paul CARBOL** (JRC, EC) Keynote: EURADSCIENCE, Knowledge Management aspects in the EJP EURAD and the PREDIS project
14:50 (25’)	**Alexandru TATOMIR** (BGE, DE) *SoK (EURAD)* Capturing the state of knowledge in EURAD knowledge management
Coffee Break (30’)	
15:50 (25’)	**Jiri FALTEJSEK** (SURAO, CZ) *Guidance (EURAD) - PREDIS* Development of guidance documents in EC projects EURAD and PREDIS
16:15 (25’)	**Niels BELMANS** (SCK-CEN, BE) *Training & Mobility (EURAD) - PREDIS* Training and mobility in EU projects EURAD and PREDIS
16:40 (20’)	**Rebecca TADESSE** (NEA/OECD) *NEA/OECD* NEA Activities on information , data and knowledge management

17:00 (20’)	**Stefan MAYER** (IAEA) *IAEA* 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

Day 3 AM	**Joint conclusion FISA 2022 / EURADWASTE ’22** Co-chair: Philippe STOHR (FR, CEA) Co-chair: Bernard MAGENHANN (EC, DG JRC) 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 Keynote: JRC’s role in Euratom Research and Training and Horizon Europe
08:50 (20’)	**Hans FORSSTROM** (SE, Expert), General Rapporteur EURADWASTE ’22 - Key messages and future perspectives
09:10 (20’)	**Henri PAILLERE** (FR, Expert), General Rapporteur 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

09:50 (20')	Keynote: Région Auvergne-Rhône-Alpes, promoting Innovation Ecosystems and Strategic Clusters
10:10 (20')	**Philippe FRANTZ** (FR, NUCLEAR VALLEY), President of Nuclear Valley 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)
Coffee Break (30')	**Philippe STOHR** (FR, CEA) and **Bernard MAGENHANN** (EC, DG JRC) Closing remarks from the French Presidency and the European Commission
Day 3 AM-PM	**SNETP Forum 2022**
11:00 (1h30) 14:00 (4h)	SNETP annual FORUM in 2022 workshops to launch new project ideas: • SMRs • Nuclear codes and standards and supply chain • Digital and robotics • R&D&I facilities • Waste minimization and fuel cycle • 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)

-
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

Day 1 PM 14:00 (2h)	A fun ice breaker connecting and encouraging ENS YGN team bonding!
Day 2 AM-PM 09:30 (2h)	**1. Kick-off of B2B sessions - Are you ready for the international job market?** 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!** 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 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. Join the Nuclear for Climate team as they guide you through this engaging, action-focused workshop. Open to all backgrounds, viewpoints, experiences. #Togetherisbetter

Tuesday 30 May 22	**SIDE EVENT**
Day 1 PM **16:30 (2h)**	**AWARD and PRIZE pitches** OPEN CALL – POSTER COMPETITION ➔ 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

Friday
3 June 22

Day 4
AM-PM

Technical visits

JACOMEX
https://www.jacomex.com/
-
SILEANE
https://www.sileane.com/en/
-
VELAN
https://www.velan.com/
-
CEA Marcoule
https://www.cea.fr/Pages/le-cea/les-centres-cea/marcoule.aspx
-
ANDRA – Cigéo (cancelled)
https://international.andra.fr/


FISA 2022
EURADWASTE'22

CONFERENCE SUMMARY

SUMMARY REPORT OF THE FISA 2022 CONFERENCE

Henri PAILLERE, France, Expert, General Rapporteur

FISA 2022 was the 10th edition of the European Commission Conference on Euratom Research and Training (R&T) in fission safety of the reactor systems organised jointly with EURADWASTE'22, the Euratom Conference on Radioactive Waste Management. The joint conferences were attended by more than 500 participants from almost 50 countries. It was reassuring to see that more than 150 participants came from the young generation, at a time when more than one third of the present nuclear workforce is over 55 years' old. Parallel workshops were organised for the young participants and networking events with established researchers. A tribute was also given to Bernard Bigot, a recognised high-level scientist and true promoter of both nuclear fission and fusion research.

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 following Russia's invasion of Ukraine. The present geopolitical and energy crisis calls for a reconsideration of energy and climate policies. IPCC pathways reflect on average the need for global nuclear capacity to triple by 2050. 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 centre stage. The window to act is short and there is an urgency to act now e.g. more and more EU countries looking at nuclear, RepowerEU, the EC plan for an affordable, secure and sustainable Energy in Europe, explicitly mentions nuclear energy for its contribution to strengthening security of energy supply, competitiveness of European industry and as a potential source of low carbon hydrogen.

In particular, the recent increasing interest in new Small Modular Reactors (SMRs) was much discussed and played an important role 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. The joint organisation of FISA and EURADWASTE provided an opportunity for cross contacts between those who produce most of the radioactive waste (reactor developers and operators) and those who will take care of and dispose of waste (the waste management organisations). At this meeting the contacts were only starting, but it was recognised that this will be of utmost importance for the future work, as new challenges will arise from new and innovative reactors including SMRs, and it will be very important to ensure a close cooperation between them.

High-level speakers at the opening session re-stated that despite different energy policies in EU Member States, Europe produces about 25% of its electricity through the operation of 106 reactors in 27 Member States. It represents about 50% of the European clean electricity production. Moreover, in a number of EU Member States, nuclear energy plays a significant role and as a component of low carbon electricity supply to address, in particular, the obligations under the Paris Agreement on climate change, highlighted in the latest 2050 roadmap for carbon-neutral economy.

All the EU Member States, including those with no NPPs, have a primary interest to ensuring nuclear safety throughout the EU. Maintaining a high level of safety and competitiveness is a major challenge and requires the establishment of a coordinated and well focused R&D programme at European level, grounded on the corresponding national efforts and interconnected at international level, in particular with the International Atomic Energy Agency and the Nuclear Energy Agency of the OECD.

The Euratom treaty is 65 years' old and Europe can be proud of its achievements, and how it build up competence in the nuclear energy sector, from fission to fusion. The EU regulatory framework for nuclear safety and radioactive waste management are well implemented by Member States. The European Commission also wants to exploit synergies across sectors and financial instruments, and Marie Skłodowska-Curie actions (25 years' old) are now opened to nuclear research.

This conference was an opportunity to learn and to share knowledge through the outcomes of Euratom research programmes, to hear recommendations from the research community, and to better inform policy-makers about the future potential of nuclear energy but also challenges to be addressed such as an ageing workforce. All projects totalising EUR 300 million Euratom contribution for a total budget of around EUR 500 million during the last 4 years.

Most European countries operating NPPs are now considering prolonging the lifetime of their reactors from an originally foreseen 40 years' operation to 60 years. In order to safely extend the lifetime of these reactors, the nuclear sector – in particular both operators and regulators - needs to have, in addition to a skilled and well-trained workforce, reliable tools to assess the ageing and degradation processes of components, materials and structures, as well as methods and guidelines for their validation and safe management. Reactor performance, system reliability, accident tolerant fuels, advanced numerical simulation and modelling for reactor safety, are also equally important to maintain the current European NPPs fleet safe and competitive with the other carbon-free energy sources. The contribution from the Euratom R&D programme to this top priority must continue and be focused on the expressed needs of the European Member States and their industry.

After a forthcoming period of stagnation, also characterized by the definitive shutdown of the most aged NPPs and by a limited number of new NPP realisation, all the medium-, long-term energy scenario studies forecast a new and increasing deployment of nuclear energy after 2050. This is coherent with the maturity of Generation III+ reactors like EPR or AP1000, as well as with the industrial scale deployment of so-called Generation IV nuclear energy systems expected in Europe around the middle of the current century. As a consequence, a European contribution, above all to safety, sustainability, non-proliferation resistance, physical protection and competitiveness aspects of these innovative systems, is key and already clearly recognized at the international level, in particular within the Generation-IV international Forum (GIF). JRC remains the implement agent of Euratom in GIF, whilst specific indirect actions should aim at coordinating the contribution from interested Member States, also with the goal to proceed in the next two decades to the realization of GEN-IV experimental and demonstration plants.

In view of these first realisations, after a first broad-spectrum investigation of all the possible technology options which has characterized the last 20 years of R&D, there is an increasing consensus in the European nuclear community on the need to focus on the most promising innovative nuclear energy systems and associated fuels and fuel cycles. Multi-recycling and closing the fuel cycle for Europe e.g. through Partitioning and Transmutation. Research to understand materials behaviour in operation, and to improve materials performance, also plays a crucial role to enhance the safety, efficiency and economy of nuclear energy. Concentration of effort, critical mass and synergies between national and European programmes seem to be seem to be necessary conditions for success.

However, Europe should also broaden the available offer to meet national specificities. To this purpose, there is the need to maintain flexibility within current and future Euratom programmes to consider, at appropriate time, other emerging nuclear technologies, including those given high priority in other regions of the world, like for instance Small Modular Reactors, micro-reactors, hybrid energy systems integrating NPPs, renewables, energy storage and non-electric applications. The establishment of a shared R&D programme at European level could lead to a detailed European SMR design – to be integrated with increasing new renewables and based on harmonized European safety standards - by 2025

Hydrogen production, district heating, several industrial applications, desalination, etc. are of increasing interest in many regions of the world including some EU Member States. The imperative to ensure an extended industrial deployment with a decarbonisation of the energy sector, offers to nuclear power a unique opportunity to finally penetrate the non-electric energy market. Synergies and integration with the chemical industry should be developed and pursued as soon as possible, and related R&D in Europe should be focused on near-term deployment while maintaining a correct balance with the very high temperature applications expected in the second half of the century

Despite the planned life extension of aging NPPs, a number of NPPs in Europe are expected to be shut down in coming years. Decommissioning and dismantling industrial-oriented R&D activities and roadmaps have to be appropriately supported by forthcoming Euratom programmes

Many efforts have been devoted during the last decades to develop advanced physical models and computer simulation codes of high fidelity, including in the very challenging area of severe accident Modelling and Simulation. However new technologies such as artificial intelligence, on-line monitoring, deep learning, etc. are rapidly being introduced in many advanced technology sectors. Forthcoming Euratom programmes should take into account these new trends and foster the early involvement of European industry and TSOs which represent the final users.

Nuclear applications and technologies, and related competence and expertise, in the fields of medicine, radiation protection (for European patients, population and the environment) and in general non-power applications are recognized of great value for a modern society in all the EU Member States. As a consequence, Euratom programme should be seen as an integral part of the broader Horizon Europe proposal able to capitalise on synergies over a much wider range of research areas. Joint projects between Euratom and Horizon Europe programmes should be pursued whenever possible.

Research and technology development must be accompanied by appropriate actions to further develop and to strengthen education and training, infrastructures, cooperation throughout EU and at international level. To this end:

- Ensuring a top-level education & training, involving basic academic education as well as continuous professional development and capacity building, is of paramount importance to create a new generation of nuclear researchers and experts able to maintain high levels of safety in all the fields, as well as address the challenges posed by advanced nuclear power and non-power technologies of European interest.
- It is more and more urgent to assure adequate maintenance and strengthen a robust, enduring and efficient infrastructure base across the EU to underpin all aspects of research and innovation throughout the sector.
- It is highly advisable to capitalise on the European Technology Platforms SNETP- NUGENIA, -ESNII, -NC2I as well as ENEN for E&T, MEENAS for radiation protection or IGDTP for Waste Management Organisations. ETPs have proved to be very effective in fostering and strengthening collaboration between research/academic institutes and industry. This successful mechanism of collaboration should be enhanced and further implemented.
- Euratom is highly recognised as a framework benefitting from a high European added value fostering increased cooperation, joint programming activities and partnerships (e.g. EURAD, PIANOFORTE, EUROfusion, future on Nuclear Materials capitalising achievements of the European Energy Research Alliance Joint Programme on Nuclear Materials) between EU and Member States, Public and Private investments involving industry, research centres, academia and technical safety organisations capitalising international partnerships and any use of key infrastructures;
- There are significant cross-cutting benefits and synergies that can be realised between fission and fusion energy research programmes, as the latter evolves from activities focused on basic plasma physics to ones focused more on technology and safety, security and safeguards-related aspects.
- International cooperation and synergies with initiatives launched by other international agencies like NI2050 (Nuclear Innovation 2050), FIDES (Framework for Irradiation Experiments) and NEST (Nuclear Education, Skills and Technology Framework) by OECD-NEA, ICERR (International Centre based on Research Reactors), Collaborating Centres and E&T networks by IAEA, GIF Gen-IV task forces on infrastructure and E&T have to be encouraged and intensified.

All EU stakeholders, from policymakers to academia, research organisations, regulators, and industry are unanimous in stating that 'a common pan European approach is the way forward'. There is an urgency to act now as more and more EU countries looking at nuclear with the present geopolitical and energy crisis. Horizon Europe (2021–2027) excellent science, industrial leadership, and societal challenges, one of the latter being the secure, clean, and competitive energy challenge for Europe in the context of the Energy Union, can only be significantly reinforced with the complementing Euratom Research and Training programmes.


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 10th 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:

- o une mise en commun préalable de moyens au sein de six plateformes expérimentales européennes,
- o 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 effected.

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’s 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�do 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 more 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 impact 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. So, 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.

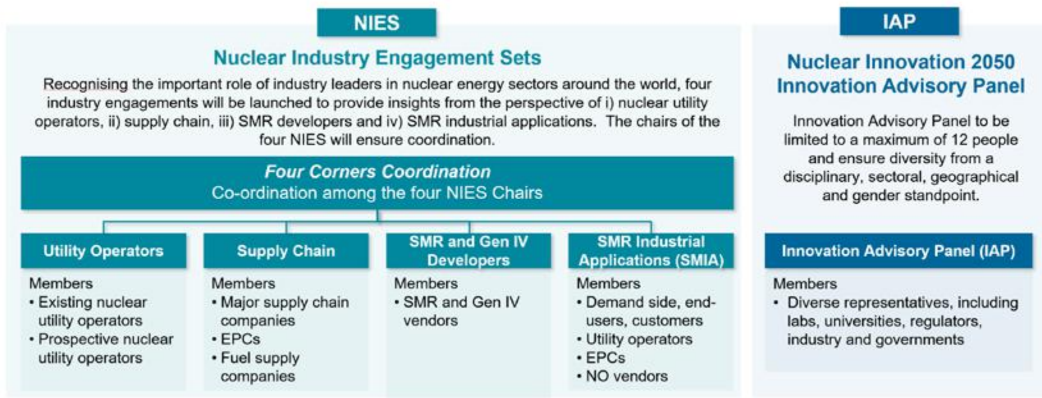
- In this context, the NEA launched a multinational framework for in-pile fuels and material testing: The Framework for Irradiation Experiments (FIDES). The main objective of FIDES is to strengthen our collective nuclear fuel and material experimental expertise and capabilities. Most of the countries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

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

Focus on Deep Geological Repositories

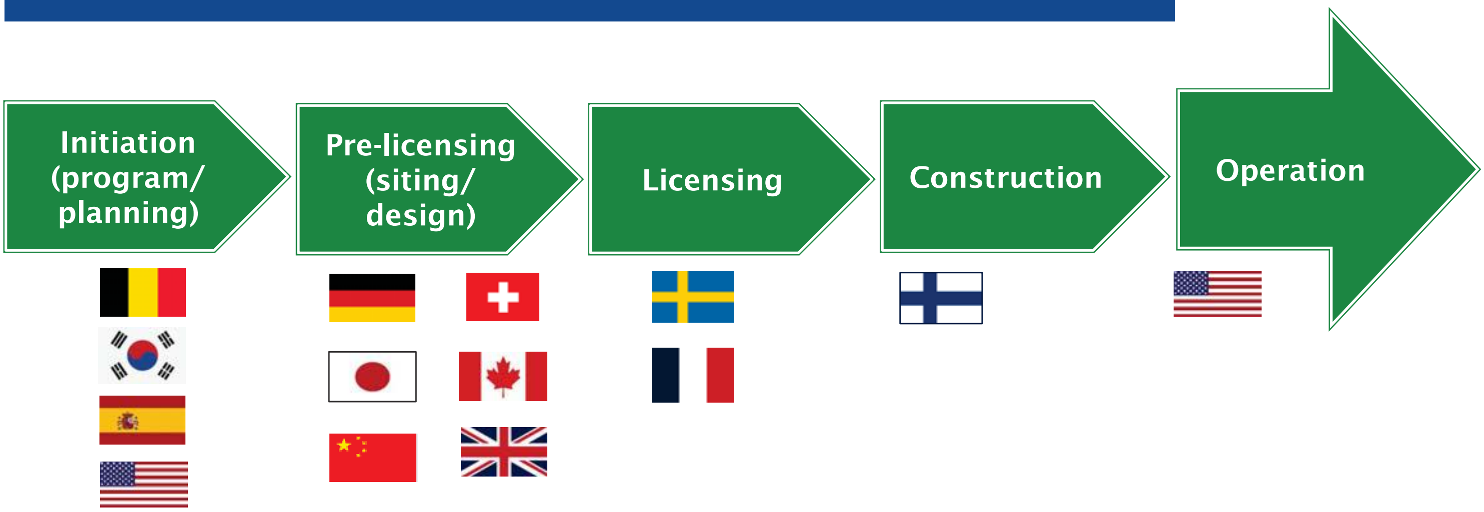
DDP/RI/22-0043

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, …

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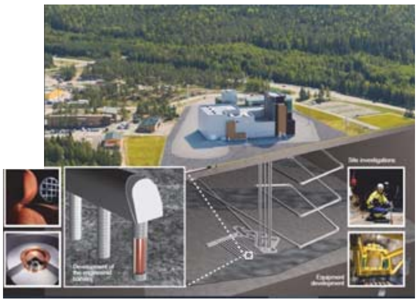
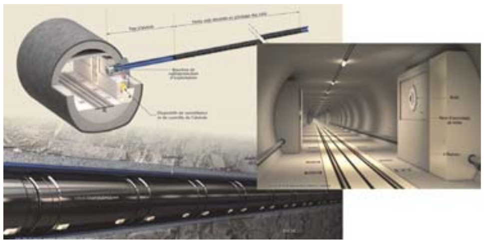
Focus on some projects…

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)

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

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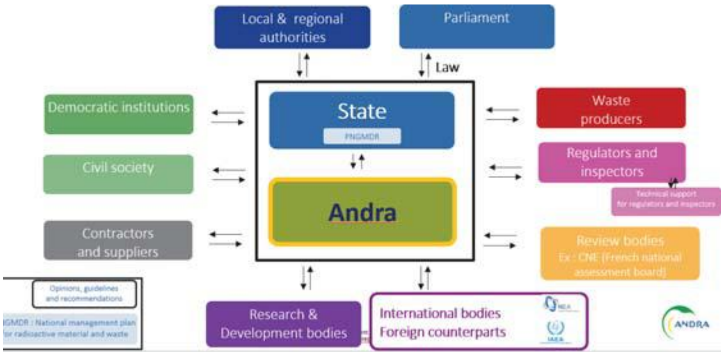
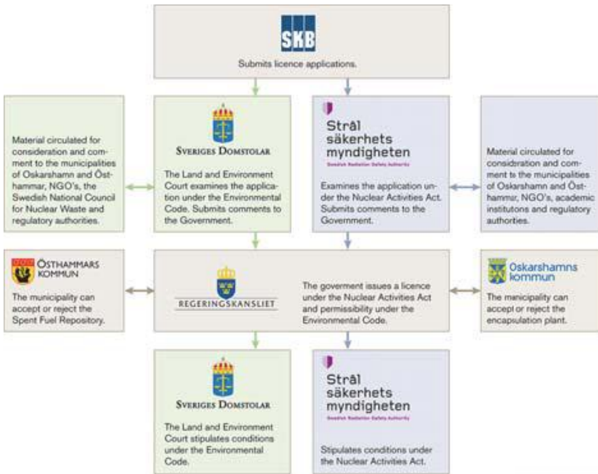
Key success factors

Governance and interactions between stakeholders

Example of France and Sweden





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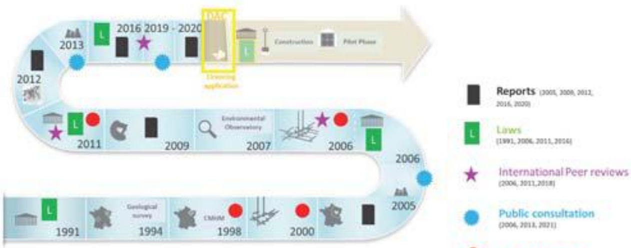
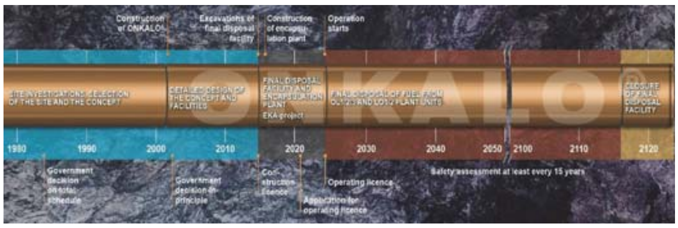
Key success factors

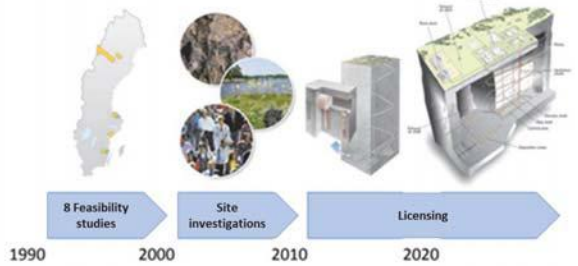
Roadmap and milestones



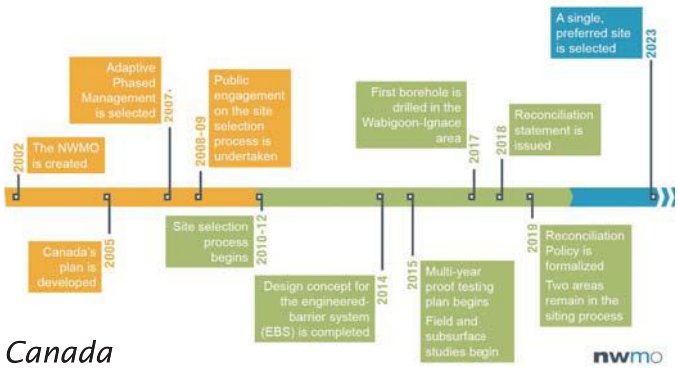
France



Finland



Sweden

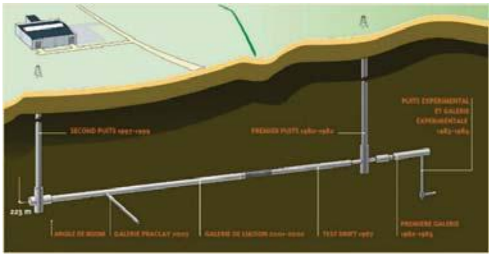


Canada

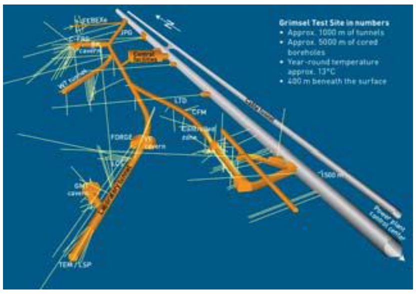
Key success factors

R&D programme — Underground research laboratory, research, technical innovation…

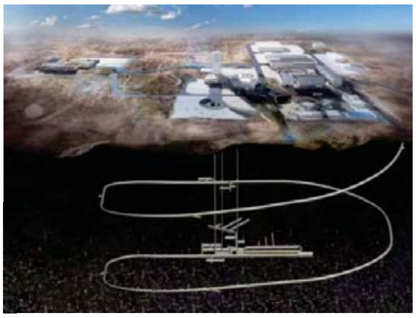
Andra URL (France)



HADES laboratory (Belgium)



Grimsel laboratory (Switzerland)



Beishan URL (China)

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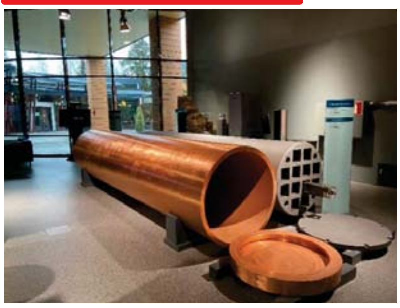
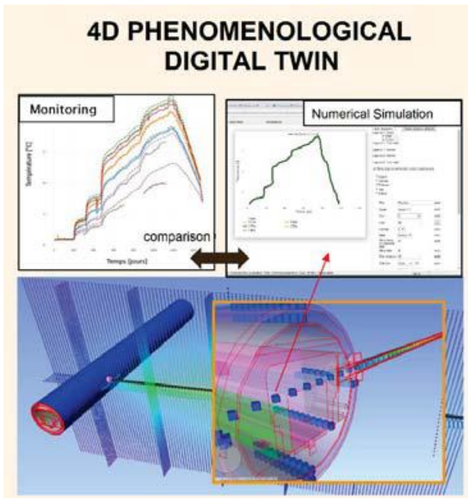
Key success factors

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)

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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

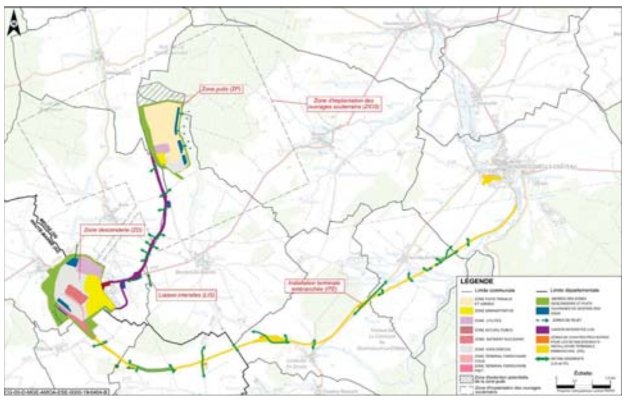
Licencing and construction of DGR

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)…

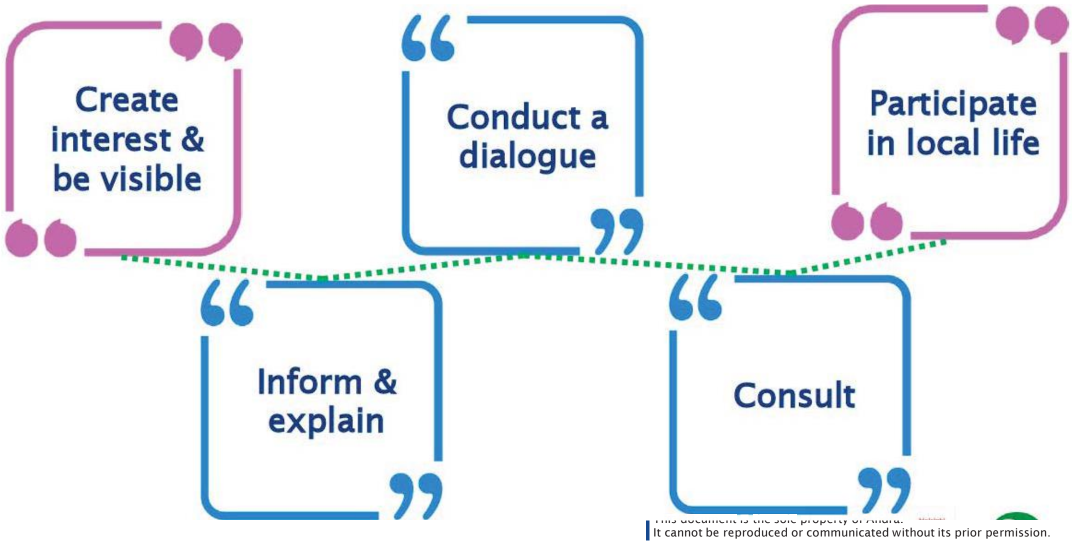
➔ Long licensing procedures / challenging longlife project management



Ex : France, railway connection to Cigéo

Challenges : Dialogue & stakeholder involvement

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



Challenges : Young generation

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

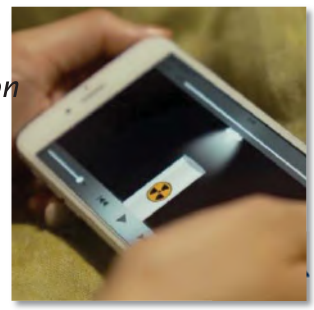
Cartoon characters UK

Street art France

Escape Game Spain

Conference Belgium

video production contest Japan



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International Cooperation : EURAD

eurad
European Joint Programme on Radioactive Waste Management

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)

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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

ANDRA

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

1.1 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.

1.2 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

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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 DÉFIS D'UNE SOCIÉTÉ DURABLE ET DÉCARBONÉE

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.

- 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!

TEN SECTION

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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.

[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

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 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

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

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, 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: SAFETY OF NUCLEAR INSTALLATIONS

Co-chair: Myriam CALACICCO (FR, NUCLEAR VALLEY)

Co-chair: Stefano MONTI (IAEA)

Rapporteur: Ferry ROELOFS (NL, Expert)

SESSION 1 - SUMMARY

Ferry ROELOFS

The session on Safety of Nuclear Installations contained 9 speakers and covered 26 collaborative projects sponsored by the European Commission. About 80-100 participants attended the session.

Introduction

The track on safety of nuclear installations covers a wide range of topics which are subdivided into:

- Reactor Performance, system reliability
- Long-Term Operation
- Instrumentation and control
- Advanced numerical simulation and modelling for reactor safety
- Innovative Gen-II -III Safety Systems
- Research Reactors' Fuels and Materials
- Safety assessments and severe accidents
  The impact of external events on nuclear power plants and on mitigation strategies
- Probabilistic Safety Assessment for internal and external events on nuclear power plants and on mitigation strategies

After a general introduction on the role of the Sustainable Nuclear Energy Technology Platform (SNETP) in the field of research and innovation in nuclear, each topic is shortly summarized by presenting the key messages and recommendations. Finally, a summary of the general discussion at the FISA conference for this track will be provided.

SNETP: Research and Innovation in Nuclear

SNETP is an industry-led stakeholder association recognised by the European Commission as key player in driving innovation, knowledge transfer and European competitiveness in the nuclear sector. Among the numerous activities, SNETP develops and maintains a research and innovation agenda supported by private and public funding for an implementation at EU but also national levels. SNETP believes that continuous technological innovation is fundamental to maintaining a high level of safety and competitiveness. This requires the establishment of a coordinated R&D&I programme at European level in close collaboration with international partners to 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 zero-greenhouse gas emissions source.

In the vision of SNETP, large light water reactors and SMRs are complementary to meet the objective of Net Zero by 2050. 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. RD&I must support the development of SMRs to make them safe and competitive with other production means within a global strategy of deployment within next decades. Therefore, SNETP has taken a leading role on the co-creation of the EU SMR partnership preparation, together with other institutions (FORATOM, the EC and ENSREG) and stakeholders, gathering the best efforts to make Europe play its part in the development of this very promising nuclear power plant type.

To keep the pace and to take stoke of the experience gained, the challenges of the European nuclear industry are established on two-time scales:

- Contribute to **achieving carbon neutrality in Europe by 2050**. This means maintaining a high level of safety for existing and future reactors, construction of new large-scale reactors, develop and build SMRs, and sustaining by modernizing and adapting nuclear reactors for recycling of fuel for light water reactors.

- Ensure the **sustainability of nuclear power over the long term** (beyond 2050) by limiting the dependence on natural uranium and therefore close the fuel cycle that allows reducing the volume of long-lived waste products, in particular actinides. This means development of Generation IV reactors and associated fuel cycles, pool efforts on reactors that are not industrially mature today, and bringing together players working on similar technologies.

The success of this industrial approach requires continuity in policy and apart from that 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 the vote is favourable. Nuclear power plants (and recycling facilities) are long-term investments (from launch to construction ~up to 15 years for large reactors, followed by an operating period of ~60 years). Their financing requires mechanisms to give investors visibility on revenues beyond short-term electricity prices. In return, customers must benefit from stable and competitive electricity prices over long period.

Reactor Performance and System Reliability

Nuclear is foreseen to facilitate the transition towards a predominantly renewable-based future. This target should be achieved, among other actions, by establishing long term operation (LTO) programs on existing European nuclear capacity. The understanding of the behavior of materials under long term irradiation is one of the key factors. The R&D in Europe covers the following aspects:

- the design of a new materials **database** for reactor pressure vessel steels,
- the development, demonstration and validation of **new destructive** and **non-destructive** evaluation tools for local and volumetric characterization of the embrittlement in operational reactor pressure vessel steels and for miniaturized specimens,
- the individual and synergetic effects of Ni, Mn and Si on reactor pressure steel embrittlement and the validity of existing embrittlement trend curves at **high fluence** regimes,
- the improvement of the **resistance of critical locations**, including welds, to environmentally-assisted cracking through optimising surface machining and treatments,
- the improvement of understanding of **phenomena influencing materials and components performance** and predictions of component fatigue lifetime when subjected to **environmentally-assisted fatigue.**

From a computational point of view, the integration of codes and tools is the focal point. New codes and tools are being developed and integrated. From the system approach to the local understanding of a phenomenon on a given component, from neutronics to operation optimization for long-term operation. Still, these methods and codes are constantly evolving in order to enable integration of new plant designs and components, to improve the results of modelling physical phenomena or to quantify and thus reduce the uncertainties on these results. The need for **harmonizing**, **benchmarking**, and ensuring the **quality** of the performance of the different codes and tools is underlined. Also, it is recommended to **share new developments** related to innovation in an early stage ensuring that new innovations can be assessed with different tools by multiple (regional) communities enhancing the innovation power. If possible, **common digital tools** should be developed and maintained which makes the necessity of sharing new developments less stringent. New code and fuel developments are also encouraged in the field of **independent supply** for the existing and future VVER reactors in Europe, especially with respect to the current Ukrainian crisis.

Apart from the materials to be used for the reactor pressure vessel and the primary system, long term operation also means that all equipment must keep satisfactory characteristics, with respect to normal operation but also during design basis accidents and design extension conditions. Polymers should be taken into account due to their necessity for the safe operation and due to their large number. Monitoring their integrity remains a challenge. Up to now, polymer ageing control methods are of two types. Firstly, sampling of deposit or real equipment and subsequently testing the material in a laboratory. If this method meets the criteria of reliability, this is invasive, expansive, and time-consuming. Secondly, non-destructive examinations like indentation. In this case, criteria are based on material-dependent and (poorly understood) correlations between the measured property and the end-of-life criteria. Within Europe, a new **multiscale approach and tools for polymer ageing** management in cables are being developed. Especially their insulation and jacket materials might be vulnerable to ageing degradation during normal operation and accidents. The aim is to establish **physics-based predictive tools** to ensure that cable ageing does not lead to unsafe operation. Apart from that, a **miniaturized and portable optoelectronic system** is under development which is able to characterize chemical changes in a polymer. This equipment, usable by a non-specialized operator or by a remote-controlled device, would allow instantaneous and non-destructive analysis which will increase the reliability and drastically simplify the operations (reducing maintenance costs but also an increase of radioprotection).

Advanced numerical simulation and modelling for reactor safety

Numerical simulations have always represented one of the pillars of nuclear reactor safety, with safety analyses carried out either in a deterministic or in a probabilistic sense. Although well-established methods have been used for the current fleet of reactors for decades, recent developments in modelling capabilities make it possible to address new situations and conditions. Among the latest advancements in simulation and modelling, various **multi-disciplinary**, **multi-physics**, **multi-scale** approaches are being developed, focusing on the (interaction of) neutron transport, thermal-hydraulic, fuel thermo-mechanic as well as dynamic structural and mechanical simulations. Those approaches combine various complementary modelling tools with different levels of sophistication tailored to match the target conditions and situations. They also allow to assess the area of validity of low order fast running models versus high fidelity computationally intensive tools.

These methods find their application, amongst others, in detection of existing perturbations in operating reactors, in the design and safety support of SMRs and in the seismic safety assessment of reactors. Modern techniques like **machine learning** and **artificial intelligence** are applied where needed. The assessment of the reliability of the simulations requires complementing the simulations with **uncertainty and sensitivity estimates**. For all these activities, it is essential that **experimental programs** complement development and validation of numerical tools. This as such, requires further development of **measurement techniques** and **experimental instrumentation**.

Methods under development should be directly applicable to **industrial contexts**, **easy in use**, **robust**, **transparent**, available with **validated** software.

Innovative Gen-II -III Safety Systems

Safety issues are at the forefront in the design of nuclear power plants. The Fukushima Daiichi nuclear accident showed the vulnerability of nuclear power plants to a long-term loss of electrical power and consequently the insufficient performance of residual heat removal. Prevention and mitigation strategies for these events were analysed and led to the need for more reliable residual heat removal solutions. New reactor designs, often rely on **passive safety functions** to ensure high level of safety with simplified systems. In Europe, on the one hand systematic methods for safety assurance of new and innovative reactors are being developed. The work aims to demonstrate that **experimental infrastructures** and **modelling tools** are ready to be used in the safety assurance of SMRs with passive safety systems. Initial work has focused on the identification of the safety approaches proposed by different SMR designs and the evaluation of phenomena critical to their operation. On the other hand, the work aims to develop the knowledge of innovative passive systems for residual heat removal focusing on two types, the **safety condenser** and the **containment wall condenser**. The ability of numerical tools to accurately model the key phenomena such as natural circulation and condensation are being evaluated using existing and new **experimental databases**.

Research Reactors' Fuels and Materials

In the European context, the innovation and qualification of **novel nuclear research reactor fuels** for conversion from highly-enriched uranium to **low enriched uranium** is an important topic as well as securing the supply chain of EU research reactors into the future. To this respect, significant progress has been made **developing and demonstrating a uranium-molybdenum fuel system**, demonstrating the viability of a high-density uranium-silicide fuel for high-performance research reactors. Especially, the know-how on **fabrication** and understanding of **fuel performance** of such fuel has increased. Such fuels are now being prepared for **test and demonstration** in various European research reactors.

Safety assessments and severe accidents, impact of external events on nuclear power plants and on mitigation strategies

Nuclear accident prevention and mitigation always receive much attention. This essentially breaks down to designing reliable systems capable of removing decay heat under any off-nominal condition, and to development of accurate assessing methods to estimate risks and for implementing efficient accident management measures. Currently, one activity is dedicated to demonstration of the feasibility and reliability of an **innovative passive decay heat removal system**, based on an **isolation condenser with non-condensable gases**. This concept can be applied to both water and liquid metal cooled reactors. Another activity aims to build a **harmonized approach** for the analysis of **uncertainties and sensitivities associated with severe accidents**. Major steps have been given in the identification and quantification of uncertainty sources and the familiarization with uncertainty and sensitivity analytical tools, and now the attention shifts to application both in reactor and spent fuel pools. Finally, hydrogen risks are addressed as well. Potential innovative enhancements will be assessed in the way combustible gases are managed in case of a severe accident, by conducting experiments addressing **hydrogen and carbon monoxide combustion** and **mitigation with passive autocatalytic recombiners**.

Probabilistic Safety Assessment (PSA) for internal and external events on nuclear power plants and on mitigation strategies

The response to the 2011 Fukushima nuclear accident has led to stringent safety requirements in many EU countries. To verify the fulfilment of the stringent safety requirements proven and justified safety analysis methods shall be in place in the European nuclear industry. In Europe the focus is on the following aspects. Firstly, the improvement of methodologies to be integrated in **PSA procedures** for nuclear plants in case of **single, cascade and combined external natural events**. To this respect, an **open-access framework tool** has been released to build **multi-hazard scenarios**, keeping only hazard parameters relevant for the safety assessment of the main critical plant structures, systems and components. A **purely probabilistic Bayesian-based framework** has been also implemented, dedicated to **technical and human risk integration** related to multiple hazards events. It has been compared to multi-hazard extended PSA, identifying their advantages and limits. Secondly, **harmonization of safety analysis methods** for best estimate evaluations of the **radiological consequences** in case of design basis accidents and design extension conditions without significant fuel melting is being aimed at. It is planned to improve models and upgrade existing simulation tools and calculation chains used in safety studies. **Guidelines** to design and implement new accident management procedures and safety devices are expected, as well as the development of innovative approaches (e.g. artificial intelligence) for anticipated accidental situation diagnosis. The final activity aims to support safety margins determination, by developing **best practices for safety requirements verification** against external hazards, using efficient and integrated set of safety engineering practices and PSA.

General discussion and research perspectives

During the general discussion, a number of topics were discussed in more detail.

- SNETP

  An explanation was provided on the international dimension of SNETP. While the focus of SNETP clearly is on Europe, international cooperation is important and included. Cooperation is ongoing with various international organizations, such as IAEA and OECD, but also bilaterally with cooperating countries.

- Licensing process and validation of tools
    - It was mentioned that speeding up the permitting process is important, not only for conventional large scale light water reactors, but especially in the light of the SMR partnership and deployment of advanced reactors. Harmonization of regulatory frameworks would be a strong enabling condition.
    - It was underlined that validation of tools is a very important aspect. This requires well performed experiments as well as high resolution simulations. There should be interaction with regulators on the acceptance of tools and possibly a push towards their use.
    - Databases of historic and new experimental and high resolution data should be developed, preserved, maintained, updated and made, as much as possible open access, available. Special attention should be paid to access of European collaborative project data after completion of the project.
- Material research
    - It was confirmed that the material research currently taking place in the various related European project is cross-sectorial.
    - A multi-scale approach is really helpful in the assessment of polymers because of their composition which may vary from application to application.
- Research into Russian design reactors
    - Some projects in this field were already ongoing before the conflict in the Ukraine started. There might be increased interest now in such activities. It is explained that the consortia are open for participants to join (although no extra funding can be foreseen) as partner or through an advisory board and most projects organize also open workshops.
- Overview EU projects

  The programmatic level of all the various EU projects is difficult to understand. A review of the process at program level could be helpful. The organization of FISA and EURADWASTE is one way of evaluating the programmatic progress. But also interactions with stakeholders and set-up of the technology platforms helps to streamline and identify priorities. Funding and budget is limited as well, so not always everything that should be done, can be done.

The following research perspectives were derived from this session:

- New testing techniques.

- Code and simulation tools improvements.
- Instrumentation for ageing management.
- New tool development for core monitoring, seismic, and uncertainty quantification.
- Passive safety systems.
- Fuel development for research reactors.
- Severe accidents and PSA.

SNETP
Sustainable Nuclear Energy Technology Platform

The challenges of future nuclear energy in Europe

Bernard SALHA,

President SNETP

The Nuclear in the EU : Overall vision of SNETP between 2021 and 2050

2021
- 104 power reactors (=50% of carbon free generation)
- 100 billions €
- 1.1 M jobs
- 29 research reactors
- Many applications (medical, chip doping, space, industry, etc.)

Industry & Research vision 2050
- Significant share of Nuclear across 2050 EU scenarios
- Nuclear brings dispatchable carbon-free power to a system w/ large share of vRES
- Nuclear is v. flexible / versatile & provides massive carbon-free energy for H2, district / industrial heat, etc.
- New technologies & applications have emerged (SMRs, Gen IV)
- Long Term solutions for High Level Waste available (inc repositories)

=>To achieve this & keep EU leadership, the nuclear industry needs:
- A conducive investment framework
- A performing, continuous & modernized supply chain, R&D labs and competences
- **Investing in Innovation & R&D in order to support Industry & Research Vision 2050**

SNETP

- **The association (AISBL, under Belgian law) gathers more than 110 stakeholders from industry, research centers, safety organisations, universities, non-governmental organisations, SMEs …**

Gen II = existing Light water reactor
GEN III = new LWR
GEN IV = advanced (modular) reactors

SNETP is the European Technology & Innovation platform for Nuclear Energy focused on Gen II-III and IV reactors with electric and non-electric application

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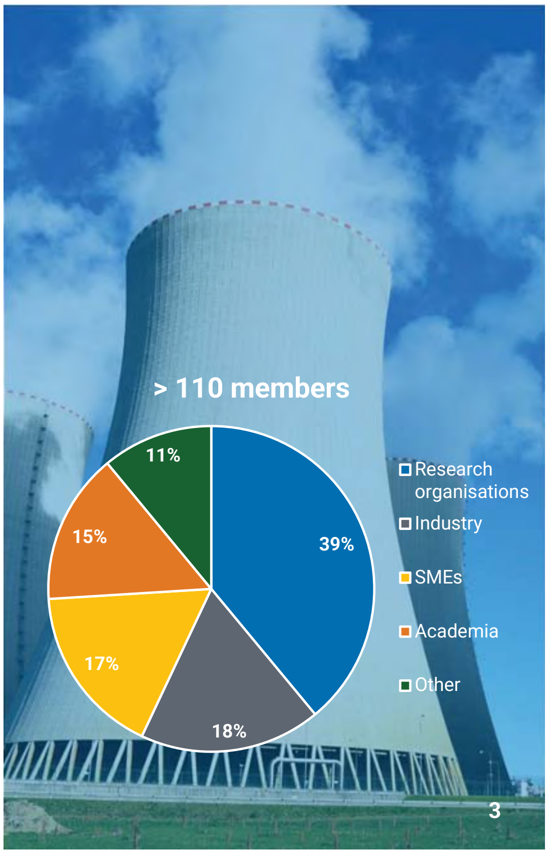

3

NUGENIA Vision

- **Importance of LTO for NPP economics & the grid:**
  - as nuclear has high fixed costs and low running costs
  - as it operates within a deregulated competitive electricity market
  - as nuclear remains essential to complement variable sources → Need for flexibility
  - as it supports the security of electricity supply
- **A European-wide, industrial-driven nuclear R&D programme:**
  - is key to maintaining nuclear competitiveness & safety in the EU
  - paves the way for the emergence of spin-offs in other sectors (health, energy, clean heat, hydrogen, construction, industrial manufacturing, etc.)
- **Three R&D & innovation priorities**
  - Innovation & competitiveness (inc. large NPPs, SMRs, passive safety, EATF, additive M, etc.)
  - Digital transition (digital reactor, multi-physics modelling, advanced computing)
  - Safety & environment (accidents & hazards, severe accidents, D & WM)

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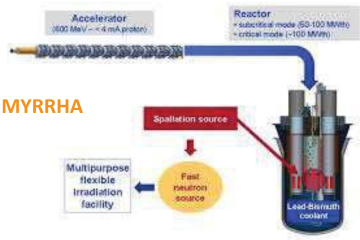
ESNII vision: Advanced (Modular) Reactors Technologies

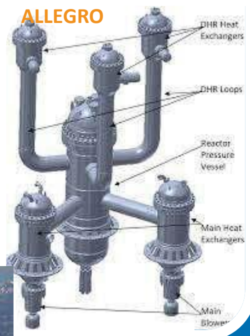
- **MYRRHA** (Multi-purpose hYbrid Research Reactor for High-tech Applications) , a **lead-bismuth Accelerator Driven System** to demonstrate transmutation of high-level waste, & to support the maturity of ESNII technologies
- The **Lead-cooled Fast Reactor (LFR)** and the **ALFRED** (Advanced Lead-cooled Fast Reactor European Demonstrator) project to build a European demonstrator of the LFR technology;
- The **Gas-cooled Fast Reactor (GFR)** and the **ALLEGRO** project (GFR demonstrator), an initiative with the goal to build an experimental facility to demonstrate the technological viability of the concept;
- The **Sodium-cooled Fast Reactor (SFR)** is the most internationally mature technology. Its industrial deployment in Europe necessitates still some improvements (safety, economic, …).

Demo Project at the soonest by 2035



MYRRHA


ALFRED



ALLEGRO

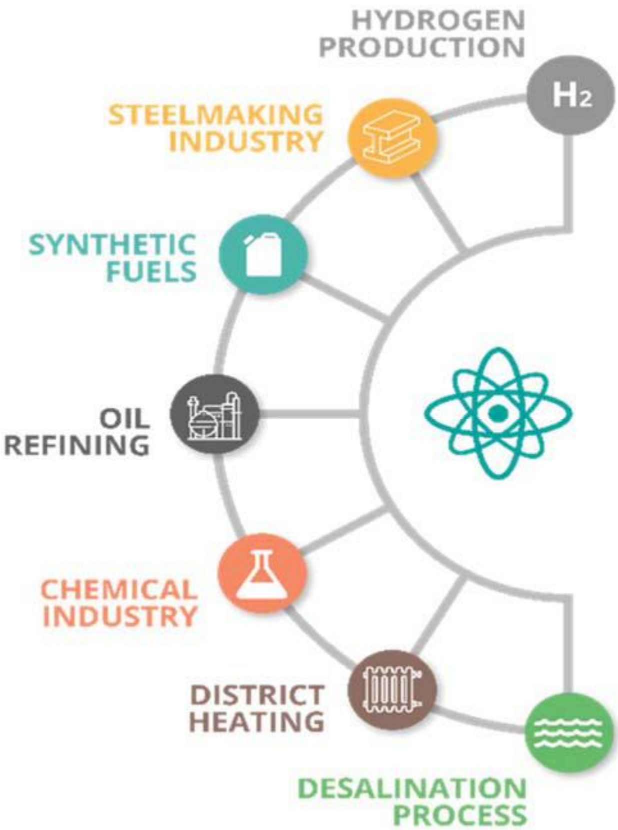
5

NC2I Vision

NC2I aims to make a significant contribution to Europe by providing clean and competitive energy beyond electricity by facilitating the deployment of nuclear cogeneration plants.

Based on a first HTGR demonstration by the end of the 2020s, it is possible to have 25% of process heat needs of industry delivered by nuclear high temperature cogeneration in 2050.

https://snetp.eu/wp-content/uploads/2020/10/NC2I-roadmap-October.pdf



SNETP strategy based on:

- **Nuclear Energy is one key element of electricity generation by 2050 according to EU long term scenarios (15% of the mix)**
- **Nuclear research and innovation is key to keep on strengthening safety, performance, dismantling, waste management**
- **The door shall be kept widely open for research and innovation on new reactors (such as SMR, Gen IV) which could provide enhanced safety, performance and waste management**
- **Nuclear is a transverse technology with strong impact on other fields such as medicine, but also data management, industrial software development, balanced energy mix with variable RES**

Digitalisation	Advanced manufacturing	Hydrogen

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The approach: *From Long Term Operation (now) , to new Commercial Light Water Reactors (2030 and beyond) followed by Commercial Advanced Modular Reactors*

- **Together with Renewables, Nuclear reactors are a key asset to reach Net Zero by 2050**
  - **Long Term Operation of existing Nuclear Power plant has to be strengthened in a safe and industrial way**
  - New Gen III reactors are to be built in time and in budget in order to play a significant role in the Net Zero Objective
  - **➔ Light Water Reactor (LWR), both big plants and Small Modular Reactors (SMR) is today the unique solution to reach this objective**

- **Nuclear has to be more sustainable on the long run**
  - Long Life wastes have to be reduced;
  - Uranium fuel has to be recycled
  - **➔ Advanced Modular Reactor , big and small plants (AMR), is the unique solution to reach this objective**
  - **➔ First demonstration projects could be available at the soonest by 2035 ; commercial projects beyond 2050**

- **Continuity in policy is necessary between those two paths:**
  - Nuclear industry is a long leading time industry (20 years from Lab to Industry)
  - Research development for LWR-SMRs in synergy with AMR
  - Huge synergies exist for Industrial supply chain and human competences between LWR and AMR

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EU SMR-partnership to start 2023

- **Scope:**
  - **Establishing in the EU a domestic/European SMR programme as defined in the EC's "Vision for a decarbonised energy sector including European Small Modular Reactors",**
  - **creating necessary enabling conditions for the first EU SMRs to start operation in 2030.**
  - **co-ordinate MS & industry strategies towards an integrated and Robust supply chain in Europe.**
- **Objectives**
  - **Develop the necessary industrial supply chain in Europe**
  - **Encourage the implementation of common (harmonized) licensing process across the EU.**
  - **establish a strategic research agenda :**
    - **LWR-SMR, as a mature technology to be deployed in 2030.**
    - **Advanced SMR (AMR-GENIV) design has to be matured by 2035 for long term prospect (sustainability) of fission technology.**
  - **Develop an international marketing strategy of the European SMR value chain**

SNETP Sustainable Nuclear Energy Technology Platform

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Take-away

- EU-citizens and industry need access to energy 24/7 in a **safe , resilient and affordable way;**
- Electricity demand is set to **increase from 3000TWh to 4808TWh by 2050** due to increased electrification;
- Nuclear provides **both flexible and dispatchable electricity**, **generating large quantities** of low-carbon energy **24/7** without the need for other backup sources of energy nor large-scale storage;
- SNETP as **the unique technological platform** for fission R&D&I to dialogue with the EC services and member states;
- **Big reactors and SMR development and deployment** in Europe is an opportunity for a **better mitigation of climate change, affordable energy prices, security of supply and Net-Zero emission by 2050**;
- **Together with big LWRs existing design, LWR- SMR are mature** to be deployed starting 2030 as a key asset to succeed with Net Zero by 2050;
- **AMR design to be matured by 2035 to ensure the sustainability** of fission technology;
- The multiple challenges require:
  - **high and continuous involvement of EU-Member states** together with EC services and industry (such as SMR partnership)
  - State of the art **experimental facilities** and demonstration
  - **Highly skilled competences** and **affordable supply chain in a continuous process**

SNETP Sustainable Nuclear Energy Technology Platform

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Invitation:

SNETP-FORUM-2022, June 2d, 2022 at Hotel de la région/Lyon

- Aim: discuss and analyse recent technological innovations in different selected Scientific and technical topics to the stakeholders of SNETP
- 6 technical topics:
  - **SMRs :** *Ferry Roelofs (NRG), Jozef Sobolewski (NCBJ)*
  - **Nuclear codes and standards and supply chain:** *Oliver Martin (JRC)*
  - **Digital and robotics:** *Eero Vesaoja (FORTUM), Christophe Schneidesch (Tractebel), Elisabeth Guillaut (ORANO)*
  - **R&D&I facilities:** *Pavel Kral (UJV), Petri Kinnunen (VTT)*
  - **Waste minimization and fuel cycle:** *Erika Holt (VTT), Anthony Banford (NNL)*
  - **The role of nuclear energy in mitigating climate change including non-electrical applications (hydrogen, heat, etc):** *Ronald Schram (NRG), Michael Fütterer (JRC)*

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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

Increase of nuclear installations safety by better understanding of materials performance and new testing techniques development (MEACTOS, INCEFA-SCALE, and FRACTESUS H2020 projects)

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Abstract. Research to better understand the phenomena influencing materials and components' performance is important for increasing the safety of Generation II and III nuclear plants. A crucial step for improving nuclear safety is the development of new experimental techniques that can provide the necessary data. The three H2020 projects presented in this paper, MEACTOS (2017–2022), INCEFA-SCALE (2020–2025), and FRACTESUS (2020–2024), cover the steps needed to realize those safety improvements. The goal of the MEACTOS project is to improve the resistance of critical locations, including welds, to environmentally-assisted cracking through optimizing surface machining and treatments. The project is currently in its final stage, and the complete analysis of the data is finished. The objective of INCEFA-SCALE is to improve predictions of component fatigue lifetime when subjected to Environmentally-Assisted Fatigue (EAF). The strategy consists of producing guidance on how to appropriately accommodate variable amplitude and plant-relevant loading in EAF assessments. Increasing the understanding of the EAF mechanism based on substantial testing, characterization, and analysis program will support the INCEFA-SCALE strategy. The FRACTESUS project will validate the use of miniaturized compact tension specimens by comparing the results of master curve-oriented fracture toughness tests performed with small and large specimens. The round-robin exercises will use irradiated and non-irradiated Reactor Pressure Vessel (RPV) materials. The material selection process is complete in time for the project to enter the testing phase. The output of the project will be beneficial from a long-term operation perspective and a saving in the material amount needed for RPV surveillance programs. Even though each project is devoted to different research areas, common aspects are clearly visible. All three projects investigate phenomena that are relevant to the performance and safe operation of the nuclear plant. Moreover, each project will provide valuable databases and analyses of test results for materials relevant to components in the nuclear plant. The output of these projects will be of great value to the nuclear industry. This paper presents the current progress for each project, emphasizing the common research domains between the projects.

1 Introduction

Most of the nuclear power plants (NPPs) in operation worldwide have already exceeded half of their initially planned service time, and the average age of the currently operating reactors is over 30 years. Over the last 30 years, the progress in material science may allow an increase in the operating lifetime of those NPPs beyond what was initially planned. The long-term operation (LTO) perspective for the existing NPPs fleet is crucial for satisfying the still-growing demand for electricity in modern societies.

The safety of nuclear installations is of the utmost importance in any activity related to LTO implementation. Therefore, many research activities are focused on this topic, including the projects financed within the H2020 Euratom program. To accurately inform the service time of NPPs, the Nuclear Industry is investigating the complex phenomena that influence and limit the performance of materials in nuclear applications. The output of such research is very important, not only from the LTO perspective but also for designing new NPPs.

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This paper presents an overview and current status of three H2020 projects oriented on the safety increase of generation II and III reactors, namely MEACTOS (2017–2022), INCEFA-SCALE (2020–2025), and FRACTESUS (2020–2024). All three projects investigate phenomena that relate to material performance and safe operation of NPPs, i.e., environmentally-assisted cracking (EAC), fracture, and fatigue of materials. It is impossible to produce materials without flaws in large-scale component manufacturing methods. Therefore, the fracture toughness of materials has to be investigated. In the case of cyclical loading, the alternating stresses and strains can initiate and propagate new and existing flaws. This underlines a need for research on the fatigue of materials. Moreover, conditions that may influence material degradation mechanisms at the surface of components, such as coolant environments and surface conditions, must be considered. When assessing material performance, the surface and subsurface state of parts and components is vital to improving resistance to cracking in service. In the case of materials used to build reactor pressure vessel (RPV) and internal reactor components, neutron irradiation induces changes in material microstructure which has a noticeable influence on their mechanical properties. Generally, long exposure of metallic materials to neutron irradiation increases their brittleness, which has to be monitored during service time. In the case of RPV, which is essential for preventing the release of radionuclides and safe operation of the NPP, surveillance specimens are used to monitor neutron irradiation-induced changes in material properties. Due to the limited capacity of surveillance capsules in nuclear reactors testing methods should prioritize the efficient use of the available space. Miniaturization of testing specimens is not straightforward, and additional analyses are required to introduce corrections to correlate laboratory testing to real structure performance. Translation of the laboratory results from tests on relatively small specimens requires deep scientific understanding. Two main research paths are visible in the projects described in this paper:

- Better understating of phenomena related to fracture and fatigue of materials used to build reactor components (environmental, surface, and scaling effect),
- Development of new testing techniques that allow for precisely determining mechanical properties with a relatively small amount of material needed (optimization of material usage in surveillance programs, upscaling from laboratory to real size components, new specimen designs).

The following sections will briefly describe each project with an emphasis on their common research domains.

2 MEACTOS – Mitigation of environmentally assisted cracking through optimization of surface

Environmentally Assisted Cracking (EAC) is one of the major failure modes occurring in light water reactors (LWRs), affecting safety and nuclear energy production. The condition of surfaces exposed to the primary coolant plays the main role in the susceptibility of components to EAC. Despite its relevance, many national and international guidelines and standards do not address the surface condition of critical components in NPPs [1].

The MEACTOS project aimed to address this critical issue by identifying and quantifying the link between EAC initiation susceptibility and the surface layer produced by various surface machining and treatment techniques. The specific surface conditions to be considered including those resulting from current procedures of fabrication and in-service repair for nuclear components as well as from mitigation techniques, which can be applied in-service or as a final treatment during fabrication.

The improvement in the resistance of alloys to surface and subsurface cracking is related to optimizing the residual stresses induced by machining and the microstructure. Operating experience and studies have shown that producing compressive residual stress in the surface/near-surface regions improves the resistance to EAC [2,3].

MEACTOS aimed to quantitatively assess advanced surface machining and treatment techniques to produce surface modifications via generating a compressive residual stress layer [4,5] and/or an improved microstructure [6–8] over those presently attained with current nuclear industry processes.

The effect of the surface machining and treatment technique on the material's EAC initiation behavior was quantified using accelerated testing methods developed in previous projects funded by the European Commission: NUGENIA+ projects MICRIN+ (MItigation of CRack INitiation) and ASATAR (Development and Analysis of the Suitability of Accelerated Testing methods for Assessing the long-term Reliability of environmentally assisted cracking of nuclear components). These methods are constant extension rate tensile testing (CERT) using tapered specimens [9] and multiple factor acceleration testing using notched tensile specimens [10]. The link between laboratory testing and component behavior has been examined in terms of EAC models.

The structure of the project and the relations between work packages are shown in Figure 1. In addition, this figure shows the project relationships between the work packages and the structure of the project and includes the projects of the NUGENIA+ call, on which the MEACTOS project has been based.

During the first project workshop, where state-of-the-art (SOTA) materials, manufacturing techniques, and test procedures were discussed, the consortium agreed on the interest in evaluating advanced manufacturing techniques according to two approaches: one as a possible mitigation technique, applicable as a treatment in those components where cracks have been reported in service and on the other hand as manufacturing techniques for new components. In terms of mitigation techniques, it was decided to also test a technique applied commercially to mitigate the effects of EAC, such as peening. Shot peening was included as a previous step in understanding other commercial techniques, such as cavitation, jet, or laser peening.

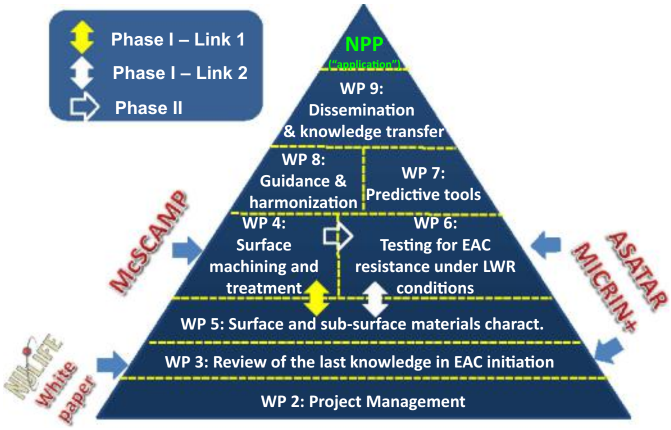

Fig. 1. WP structure of MEACTOS project and interaction with previous projects from NUGENIA+ call.

A comparison of the EAC resistance of surfaces machined by conventional practices with those obtained by advanced methods was made. Firstly, cryogenic CO_2 and cryogenic CO_2 + MQL (Minimum Quantity of Lubricant) machining was considered. The use of cryogenic CO_2 improved the roughness of the surface, as well as the level of residual stresses. However, it was observed that the surface hardness was increased markedly, which has been shown to be detrimental to the crack resistance of stainless steels in high-temperature oxygenated aqueous environments. Therefore, based on the recommendations of the partner responsible for advanced machining (Nuclear Advanced Manufacturing Research Center, NAMRC), the use of cryogenic CO_2 as coolant/lubricant was replaced by supercritical CO_2.

The possible benefits in terms of lubrication and behavior of the machined layer were evaluated throughout the project. Some preliminary results provided by NAMRC regarding machining maps using supercritical CO_2 + MQL indicate the possibility of generating compressive residual stresses under a certain combination of machining parameters (tool feed, lube/coolant injection nozzle diameter, flow rate, etc.).

Figure 2 compiles the decisions made in the SOTA workshop regarding materials to be tested, machining processes, additional surface treatments, and testing environments. The experimental campaign was divided into two phases. In the first one (screening phase), the objective was to determine threshold stress for crack initiation, and in the second phase (verification and validation), the aim was to obtain crack initiation times in-service conditions.

The results of both experimental campaigns served to feed the models of Work Package 7:

- EngInit: model proposed by SCK CEN, which defines cracking when a certain damage index has been reached. That model requires mechanical and environmental variables, such as strain rate, level of plastic deformation, and stress.
- ACETMA: purely empirical model proposed by CVR, based on some "acceleration factors" related to mechanical and/or environmental variables determined during the screening phase (task 6.1). These acceleration factors were used to determine initiation times for specimens tested in various service conditions and were determined during the verification and validation testing phase (task 6.2).
- Local Model: model proposed by EDF. This phenomenological model was applied exclusively to the Alloy 182 and is based on the preferential grain boundary oxidation as the main degradation mechanism. The model is implemented in the "Coriolis" finite element program developed by EDF in recent years and takes into account geometric, thermodynamic as well as kinetic parameters.

The main conclusions obtained from MEACTOS project are summarized below:

- The proposed machining with supercritical CO_2 does not seem to have any benefit compared to the traditional procedures in the case of stainless steel in any of the environments tested, even after applying a thickness reduction of around 14% by cold rolling. However, for Alloy 182, although with considerable dispersion in the results, machining with supercritical CO_2 slightly improves the behavior in LWR environments.
- Even with comparable results in terms of resistance to cracking, machining with CO_2 has environmental benefits since it reduces pollution and waste management of petroleum products. Likewise, from the operational point of view, it allows "in-situ" machining of components and the robotization of the process.
- In all cases, the outermost surface shows an ultrafine grain layer, which thickness depends on the process applied. Although affected by a notable dispersion in the results, the thickness of the layer varies in the direction from advanced machining through conventional machining and finally to manual polishing. At least for A 182, the improvement of resistance to crack initiation varies in the same direction, so, in principle, for this alloy, the crack resistance relies on the microstructure of this nanostructured layer more than on the possible residual stresses induced by machining.

Experimental results and calibrated models were used to prepare guidelines for mitigating EAC in Alloy 182 and 316L stainless steel in LWR environments by optimizing surface treatment. The project output was presented to the community at the final workshop. Partners will disseminate those results themselves once the project has finished.

3 INCEFA-SCALE – extrapolation of environmentally assisted fatigue results from laboratory to real components

Fatigue assessments are an important part of justifying the structural integrity of the nuclear plant, and hence their safe operation. There are multiple codes that provide methods for accounting for the fatigue behavior of the materials of plant components under relevant operating conditions [11–14]. For cases beyond the perceived

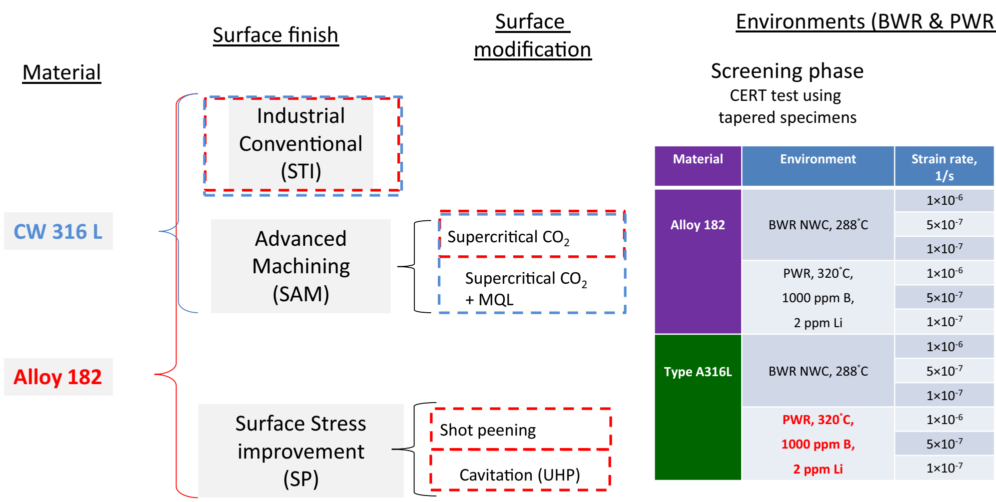

Fig. 2. Scheme of materials/test conditions carried out in the two experimental phases of the project.

scope of the codes, the technical basis for the methods may be presented separately. Environmentally-Assisted Fatigue (EAF) is one example where NUREG/CR-6909 presents the methods for accounting for an LWR environment [15].

There appears to be a discrepancy between the plant operational experience and the potential difficulty of obtaining an acceptable fatigue assessment result using the EAF methods [16]. This discrepancy has been the subject of substantial research efforts to understand the contribution of surface finish [17,18], strain rate [19], and thermo-mechanical fatigue [19]. These areas have yielded improved methods incorporated into codes, reducing this gap but not completely closing it.

A potential research area under investigation focuses on the effect of Variable Amplitude (VA) fatigue and how it is handled within the available codes. Taking the ASME Boiler and Pressure Vessel Code (BPVC) as an example, loading history (including VA loading) is intended to be accounted for in the application of adjustment factors on life and stress or strain to the mean air curve when forming the design fatigue curves [15]. However, a detailed treatment of the effect of loading history within an EAF assessment was not presented in NUREG/CR-6909, which creates a gap in dealing with this behavior [15].

The method defined in NUREG/CR-6909 for accounting for VA loading within the ASME BPVC is to use the modified Goodman relationship to account for mean stress effects on the best-fit curve [15]. The fatigue design curve is constructed by the application of adjustment factors that are considered to account for material variability and data scatter, size and geometry, surface finish, and the loading sequence. Once the relevant alternating stress intensities are calculated, Miner's rule is applied to these design curves for each cycle in the VA waveform to calculate partial usage factors [15]. The environmental cumulative usage factor (CUF_{en}) is calculated by applying the environmental effect F_{en} associated with each cycle in the VA waveform to the partial usage factors. The failure criterion is when the CUF_{en} reaches unity.

Research has indicated that the effect of VA loading on fatigue lifetime may be accounted for by understanding the material's behavior and resulting mean stress [20,21]. Therefore, a potential over-conservatism may exist within the current code method where the use of a mean stress correction combined with the loading history transference factors could double account for the effect of VA loading. Work on alternate methods that appear to better account for VA fatigue than current codified methods is already underway [22]. However, data studying the effect of VA fatigue on other materials in nuclear plant-relevant environments is very limited, and further work would be necessary to justify the adoption of such alternative methods.

Further opportunities to address the gap between material behavior in laboratory testing and plant experience investigation of multi-axial fatigue, notch sensitivities, and their incorporation into an EAF assessment [16]. Although methods are available to account for the complex loading states produced by such features and multi-axial loads, experimental data capable of differentiating or supporting their use is limited and unable to differentiate between the more advanced methods.

The goals of INCEFA-SCALE are to improve assessments of fatigue lifetimes of NPP components when subjected to EAF loading and provide guidance on the transferability of laboratory-scale testing results to component-scale behavior.

INCEFA-SCALE will achieve these goals by:

- Developing a better understanding of material performance through characterization of laboratory-tested fatigue specimens and data mining of the MatDB database (the JRC administered database in which INCEFA-PLUS and other data are already stored);
- Novel testing focused on defining the effects of Variable Amplitude (VA) loading, surface finish, notches, and multi-axial loading on the fatigue lifetime of 316L stainless steel;
- Delivering guidance, based on the technical output of the project, on the transferability of laboratory-scale

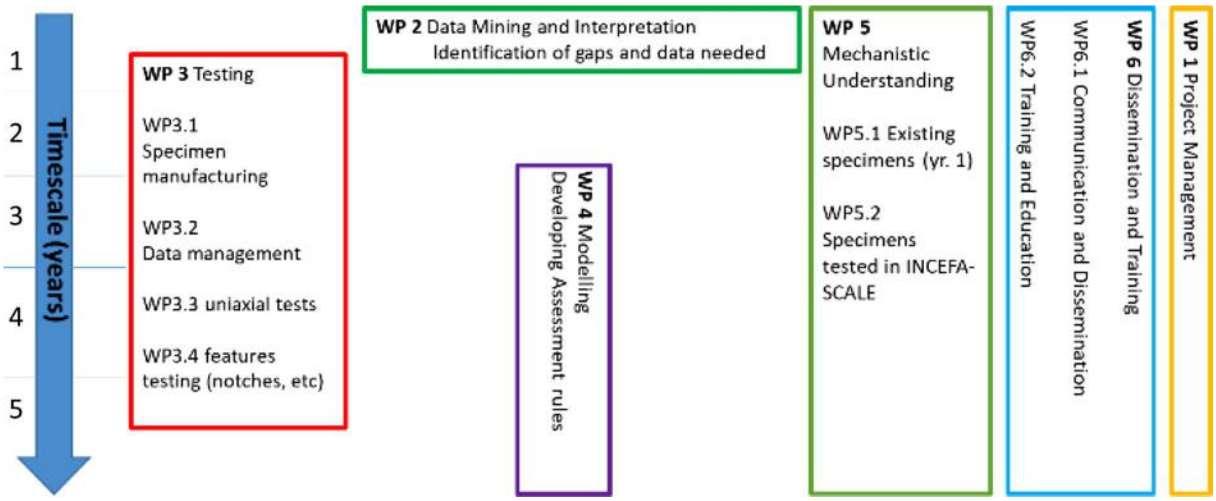

Fig. 3. INCEFA-SCALE work package structure plus timescales for WP activities.

data to component scale and plant-relevant loading conditions.

The INCEFA-SCALE project comprises six Work Packages (WP), illustrated in Figure 3.

The interactions between the INCEFA-SCALE WPs shown in Figure 4 highlight the substantial level of integration and collaboration within the project. Collaboration between the WPs will be essential to the success of INCEFA-SCALE. The WPs will need to inform and effectively define requirements between each other. For example, the collaborative definition of the test conditions in WP3 supports the ongoing work in WP4 and WP5. As test data becomes available from WP3, the assessment methods investigated in WP4 will evolve and may require future testing in WP3 to change so that further development can take place. An integral part of this way of working is the development of the existing experimental methods in WP3 and WP5 to support the provision of the information required to inform fatigue assessments.

The study of VA loading in INCEFA-SCALE is new to many of the testing laboratories and has required improvements in experimental control and data acquisition, as well as new procedures for extracting information from fracture surfaces developed through round-robin programs [23].

The integration of WP2 into WPs 3, 4, and 5 will allow the developments of INCEFA-SCALE to be placed into context with the global position of fatigue for the nuclear industry and ensure decisions made by these WPs are fully informed. This approach will maximize the impact, usefulness, and success of INCEFA-SCALE.

Since the project kick-off in September 2020, there have been several full project meetings and multiple further virtual gatherings of sub-groups with interests in mechanistic understanding, testing, data mining, and modeling activities. Key achievements at the time of writing are:

- A collaboration with EPRI through a non-disclosure agreement (NDA) (under development) has been agreed upon.
- WP2 has completed the development of a software application that will facilitate data mining activities using the information stored in MatDB. Additionally, significant external data will become available for examination from external collaborators, i.e., EPRI. Since work continues to overcome commercial challenges to the International Fatigue Database Agreement, further data will eventually be forthcoming from the US Nuclear Regulatory Commission (USNRC) and the Japanese Nuclear Regulation Authority (NRA).
- The WP 3, 4, and 5 members have combined thoughts on the aims of the respective WPs and the prioritization of the study areas.
- The WP3 uniaxial testing has started with support from the recently established Expert Panel and Data Management Committee.
- WP3 features testing is being defined by a Working Group specifically brought together to define and prioritize the scope of testing.
- WP4 modeling and assessment has kicked off and defined the scope of the WP. Discussions will occur throughout 2022 to create a clear plan for WP4 to deliver its aims.
- WP5 characterization continues to progress and support the INCEFA-SCALE aims. A round robin for striation counting has reached completion and issued a common method for calculating striation spacing [23]. The WP team is now in the process of engaging with the consortium to analyse pre-test specimens.
- WP6 has set up project dissemination channels consisting of a public website (https://incefascale.unican.es), ResearchGate, Twitter, and LinkedIn presences.

4 FRACTESUS – miniaturization in fracture toughness testing in surveillance programs

Acronym FRACTESUS stands for "Fracture mechanics testing of irradiated RPV steels by means of sub-sized

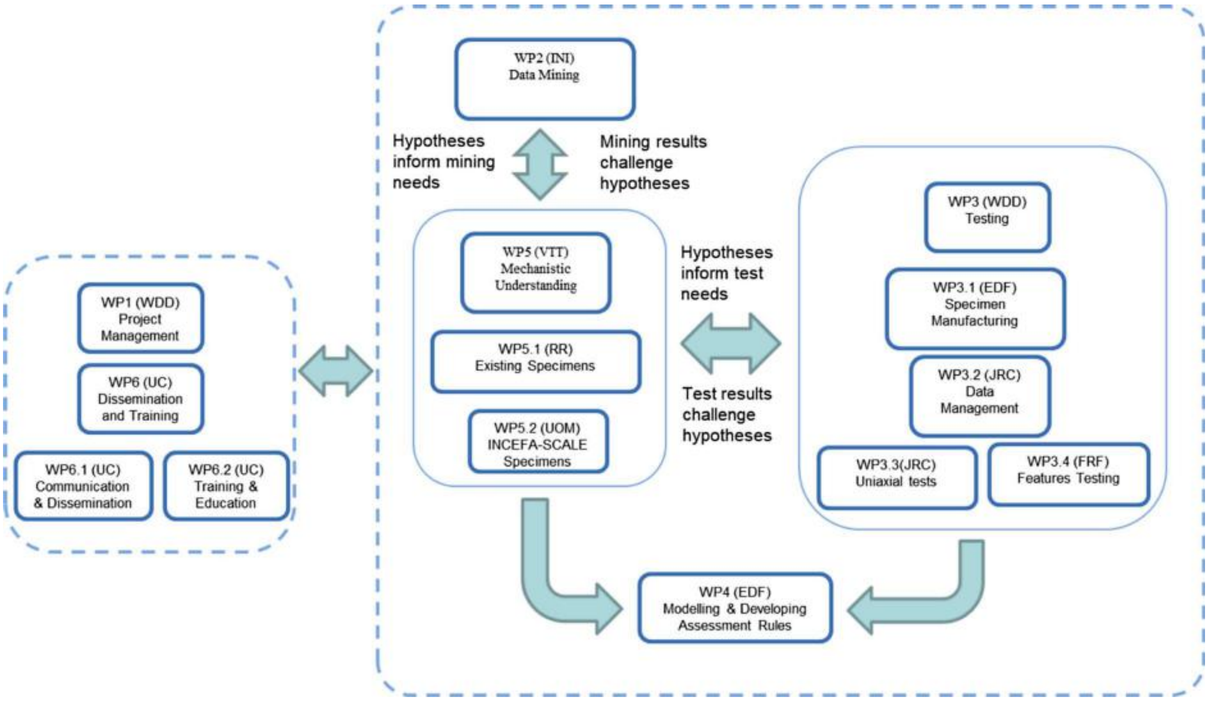

Fig. 4. INCEFA-SCALE work package inter-dependencies.

specimens". The project started in October 2020 and is planned for 4 years. Twenty-one partners supported by the Scientific Advisory Committee and End User Group are engaged in the research, which is aimed to validate the usage of miniature compact tension (MCT) specimens in Master Curve (MC) oriented fracture toughness (FT) testing. Details on the project consortium, its main aims, and its current status can be found on its official website [24].

As was already mentioned, many reactors operating today are close to the end of their initially planned service time. However, in many cases, their service time might be noticeably prolonged (long-term operation – LTO perspective), which is beneficial from the point of view of a still growing demand for electric power. In such cases, the remaining surveillance material usage has to be optimized, and miniaturized specimens have to be periodically tested, instead of large ones, to control if the irradiation-induced change of material mechanical properties is below the limits described in appropriate safety codes. As it is shown in Figure 5, MCT specimens allow for saving a noticeable amount of material. They might also be produced from already tested larger specimens, giving an opportunity for the re-usage of the surveillance material.

The usage of miniaturized specimens, especially for FT testing, is not straightforward. There are many concerns raised by various stakeholders regarding the reliability of the MCT test of RPV materials. The successful implementation of the FRACTESUS project is possible only if all the stakeholders' concerns have been considered at the very beginning of the project. Although miniature specimen usage is permitted even in the current MC standard [25], there are still many concerns related to the reliability of the results, briefly described in [26], and the current Technology Readiness Level (TRL) of MCT testing is estimated to 5. The first results of inter-laboratory trials show successful implementation of MCT specimens [27,28]. However, there are still many open questions that have to be answered before enabling the movement of this technology to TRL 7. That is the ambition of the FRACTESUS project. For instance, various laboratories use slightly different specimen geometries and the different locations of clip gauges, which might affect FT results and Master Curve reference temperature T_0 determined in accordance with ASTM E1921 standard. Production of miniaturized specimens, especially in hot cell conditions, is also challenging. Moreover, in the case of miniaturized specimen usage, an allowable testing temperature range is much limited compared to larger counterparts made of the same material. Furthermore, the potential inhomogeneity of material might have a much larger influence on the final testing results when only a small volume of material is used for specimen preparation. Having all those concerns in mind, the reliability of MCT testing has to be proved for various types of RPV steels, taking into account their initial properties, as well as properties change during exploitation, to convince stakeholders of their application.

The work in the project is planned within seven main Work Packages (WP), as schematically presented in Figure 6. Details of the structural organization of the project and main deliverables are presented in [29].

The work on identifying the knowledge gaps and the main stakeholders' concerns is foreseen in WP1. First of all, the project Scientific Advisory Committee (SAC) and End User Group (EUG) have been set up to provide the

Fig. 5. Standard and miniaturized specimens for FT testing. MCT specimen is the rightmost.

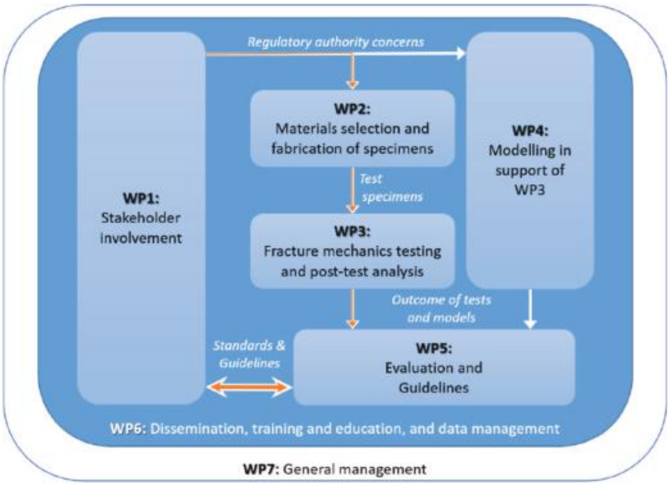

Fig. 6. Organisational structure of FRACTESUS.

expertise and to assess whether the information produced as a part of WP1 is appropriate to inform other work packages (WP). Work in this WP is oriented on three main areas: (1) to understand the content and limitations of current standards, (2) to understand the concerns of the various nuclear regulators, and (3) to understand the current extent of using sub-sized specimens in fracture toughness testing by operators and research organizations. All those topics, as well as initial material candidates for testing, were discussed at the 1st SAC/EUG meeting held in February 2021, and the final document collating identified concerns is now being finalized.

WP2 of the FRACTESUS project is devoted to the selection of materials for both irradiated and unirradiated specimens and MCT specimens machining. Having in mind the main stakeholders concerns, identified in WP1, the final test matrix has been prepared [30]. More than 650 MCT specimens are planned to be tested within WP3 of the FRACTESUS project. Materials for testing have been selected, taking into account already existing, reliable database of fracture toughness (FT) results, availability of materials for testing within numerous round-robin exercises planned in the project, and the coverage of a wide spectrum of properties (expected T_0 and upper shelf energy). It is worth noticing that not only base materials (BM) but also welds will be tested.

The general assumptions of the FRACTESUS material selection and testing processes are described in [26]. The main part of the testing campaign is focused on the round robin (RR) exercise, where seven selected materials will be tested. Specimens for each material will be produced and tested by at least three institutions. The results from MCT testing will be compared to the results obtained in large specimen tests. Due to the evolution of the MC standard from its introduction in 1997, the results for large specimens for the materials selected to be tested were reprocessed according to the current version of the standard with the usage of the same software [31]. Thus, the results delivered from MCT tests will not be biased by the calculation methodology. It is very important due to the complexity of MC calculations. More unirradiated and irradiated RPV materials, widely used in the nuclear industry, will be tested by the project partners. Finally, guidelines for MCT usage will be developed within WP5 in the final stage of the project. In addition to MCT testing, some project partners will provide in-kind contributions related to miniaturized specimen testing techniques, such as small punch tests [32]. At the date of this paper's writing, the unirradiated specimen preparation task is being finalized, and the first series of specimens have been tested in accordance with MC standards. Initial preparation of the irradiated 73W material, which has to be tested independently by seven different institutions, has also started.

The results comparison between large and MCT specimens will be supported by the numerical modeling planned in WP4. The first large task in WP4 is a numerical RR exercise. The institutions involved in this task have to provide the results of numerical modeling for a compact specimen of 25 mm thickness (1T-CT) and MCT specimens according to the RR specification with strictly imposed parameters for the most important model features (geometry, loading steps, material law, meshing near the crack tip, output data format). However, some options were left to be freely chosen by each institution (FEM code, model symmetry, meshing outside of crack tip region, way of loading introduction in the model) in their simulations. This task will allow identifying all the discrepancies related to the specific code usage and an individual interpretation (human factor) of RR specification before further usage of the models in the activities directly supporting experimental results interpretation. At the moment of the paper preparation comparison of the results delivered by nine institutions is ongoing.

Similarly to the other two projects described in this paper, dedicated WPs related to the results dissemination (WP6) and general project management (WP7) are also present in the FRACTESUS project.

5 Summary

The three H2020 projects described in this paper aim to increase the safety of nuclear reactors. Safety-oriented research activities have to focus on a better understanding of the material's resistance to complex degradation mechanisms involving static and dynamic loading. These research activities must also integrate how environmental and surface conditions influence these materials' degradation mechanisms. Moreover, new material testing techniques have to be developed and validated to optimize material usage and correlation of the properties determined in laboratory conditions with large components and structure behavior. The output of multidirectional research activities is important to ensure a longer and more reliable service of currently operated nuclear power plants and will also be taken into account during new facilities design. The results delivered in MEACTOS, INCEFA-SCALE, and FRACTESUS projects will have an influence on providing electric power in a safe and sustainable way to meet the ever-growing demand of modern European and worldwide societies.

MEACTOS investigated the influence of various machining techniques on EAC. It was proved that advanced surface machining methods have nearly the same impact on EAC initiation behavior as standard methods, i.e., they are not inferior. In combination with benefits like higher cutting speed and less pollution by lubricants, those methods are, therefore, a promising alternative to standard procedures. They can be used for future applications or if standard methods cannot be applied (e.g., robots for pipe repair).

INCEFA-SCALE is improving the safety of nuclear plant operations by improving fatigue assessments and working towards resolving the discrepancy between operating experience and the perceived difficulty in achieving an acceptable fatigue assessment result. This goal will be achieved through improving the understanding of the behavior of materials subject to fatigue loading through material characterization, improved experimental methods for studying EAF, and the provision of new methods and guidance for accounting for plant-relevant loading conditions in fatigue assessments.

The work planned in the FRACTESUS project is related to the validation of a new FT testing technique that can be used in surveillance programs for RPV materials and is aimed at a better understanding of scaling effect phenomena in FT testing. The output of the project is expected to elevate the TRL of MCT testing technology from 5 to 7. That will be an important step before its final implementation by the NPPs operators.

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.

Author contribution statement

TOMASZ BRYNK: coordinator of the FRACTESUS project, Writing – original draft, Writing – review and editing, Visualization, Project Administration. FRANCISCO JAVIER PEROSANZ LOPEZ: coordinator of the MEACTOS project, Writing – review and editing. ALEC MCLENNAN: coordinator of INCEFA-SCALE, Writing – review and editing

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Review Article

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Codes and methods improvements for safety assessment and LTO: varied approaches

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Abstract. Nuclear safety has always been at the heart of the concerns of nuclear power plant operators and developers, as well as of various nuclear research organizations and regulatory authorities. Over the last decades, all these nuclear actors have developed and integrated a large number of calculation codes and other tools into their safety work. From the system approach to the local understanding of a phenomenon on a given component, from neutronics to operation optimization for long-term operation, these methods and codes have been constantly evolving since their appearance, in order to be able to integrate new plant designs and components, to improve the results of modeling physical phenomena or quantify and thus reduce the uncertainties on these results. Currently, several H2020 Euratom projects are working on the improvement of these codes and methods. This article will focus on three of these projects: CAMIVVER (Codes And Methods Improvements for VVER comprehensive safety assessment), APAL (Advanced PTS Analysis for LTO), and sCO2-4-NPP (innovative SCO2-based heat removal technology for an increased level of safety of Nuclear Power Plants) in order to illustrate our thinking on the improvement of calculation frameworks. First, we will present the work and the approach adopted with regard to the different calculation codes and methods used in each of these three projects. We will then conclude with an overall analysis of these three approaches, highlighting the difficulties and successes of these three projects, and identifying areas of work for the general improvement of the calculation codes.

1 Introduction

Nuclear safety has always been at the heart of the concerns of nuclear power plant operators and developers, as well as of various nuclear research organizations and regulatory authorities.

Over the last decades, all these nuclear actors have developed and integrated a large number of calculation codes and other tools into their safety work.

Currently, several H2020 Euratom projects are working on the improvement of these codes and methods. Our article will focus on three of these projects: CAMIVVER (Codes And Methods Improvements for VVER comprehensive safety assessment), APAL (Advanced PTS Analysis for LTO), and sCO2-4-NPP (innovative SCO2-based heat removal technology for an increased level of safety of Nuclear Power Plants) in order to illustrate our thinking on the improvement of calculation frameworks.

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2 Euratom Projects presentation

2.1 The APAL project

The reactor pressure vessel (RPV) is a key component of a nuclear power plant (NPP), and its integrity must be ensured throughout its entire operating lifetime including long-term operation (LTO) in accordance with applicable regulations.

The dominant degradation mechanism of the RPV material is embrittlement due to neutron irradiation, especially in the core (beltline) area. If a flaw of critical size existed in an embrittled RPV and if a certain severe system transient occurred, the flaw could propagate very rapidly through the vessel, possibly resulting in a through-wall crack, which challenges the integrity of the RPV.

The pressurized thermal shock (PTS) analysis is one part of an RPV structural integrity assessment. PTS is characterized by rapid cooling (i.e., thermal shock) of the reactor downcomer and internal RPV surface, followed sometimes by re-pressurization of the RPV. Thus, the PTS event poses a potentially significant challenge to the structural integrity of RPV in pressurized-water reactors

(PWRs) and water-cooled water-moderated energy reactors (WWERs).

Currently, in the European Union, PTS analyses are based on deterministic assessments and conservative boundary conditions. The PTS analyses of this type are reaching their limits in demonstrating the safety of PWRs and WWERs facing LTO, and they need to be enhanced. However, inherent safety margins exist, and several LTO improvements applicable to the NPP, as well as advanced methods of PTS analyses, may be able to increase these safety margins. Additionally, the quantification of the safety margins in terms of risk of RPV failure by advanced probabilistic assessments becomes more and more important because the probabilistic methods ensure more comprehensive assessments in PTS analysis, and they enable the quantification of uncertainties in the results.

To address this challenge, the project Advanced PTS Analysis for LTO (APAL) has been launched in October 2020 with a duration of four years. The main objectives of the APAL project are the development of advanced probabilistic PTS assessment methods, the quantification of safety margins for LTO improvements, and the development of best-practice guidance. The project will address multidisciplinary and multi-physics challenges related to the RPV safety assessment of PTS. The planned work to achieve these objectives is divided into six technical work packages (WPs), presented in Figure 1.

The first work package (WP1) consists of an extensive literature review and collection of partners' experiences to identify the state of art of LTO improvements that may have an impact on the results of PTS analysis.

After establishing the LTO improvements, thermal-hydraulic (TH) calculations are performed, including uncertainty quantification relevant to the PTS assessment (WP2). The impact of both LTO improvements and human factors on the results of TH analysis will be quantified and later assessed by subsequent structural mechanics and fracture-mechanics benchmarks within WP3 and WP4.

The third work package (WP3) consists of performing deterministic structural and fracture-mechanics analyses to quantify the safety margins related to both LTO improvements and uncertainties in TH analyses. The analyses to be used for deterministic margin assessments by the APAL partners will first be tested on a common deterministic benchmark.

In the fourth work package (WP4), probabilistic margin assessments based on probabilistic fracture-mechanics analyses will be performed. They will enable the quantification of safety margins in terms of the risk of RPV failure. An appropriate benchmark for the probabilistic fracture-mechanics analysis will be defined in accordance with the benchmark performed for deterministic margin assessment.

In the fifth work package (WP5), recommendations and conclusions will be gathered from the work to define the best practices for advanced PTS analysis for LTO. Close cooperation with APAL Advisory Board (AB), regulatory bodies, and end users (NPP owners, suppliers, etc.) during the project will help to increase the acceptance of the best-practice guidance. For that purpose, several workshops will be organized (WP6) to discuss the best-practice guidance with regulatory bodies and the end users in order to analyze potential barriers, integrate feedback, and obtain broad acceptance of the best-practice guidance for an advanced PTS analysis for LTO within the nuclear community.

2.2 The CAMIVVER project

The European nuclear fleet is composed of Gen. II and Gen. III reactor types. This fleet is currently going through LTO upgrades and it remains an important challenge for the European Community. As several VVER reactor units are planned for construction – or are currently under construction. It's realistic to think that VVER-type reactors will keep playing a strategic role in the European energy and economic stability, its decarbonation strategy, and Europe's safety in general. In this framework, the Euratom Supply Agency underlines as a matter of concern the 100% reliance on a single Russian supplier and therefore an issue for all EU countries operating VVER reactors [1]. Dependence on a single supplier constitutes a significant risk and qualifying an alternative supplier could take several years because of licensing and testing requirements.

In order to support the development and the qualification of fuel and more generally to provide the required elements for the safety analysis report (SAR), an important place is reserved for the development, improvement, verification, and validation of computer codes and methods used in the VVER safety analysis. The codes and methods continuous update needed for answering the regulatory requirements for reactors LTO is the basis of CAMIVVER (started in September 2020), for the improvement of codes and methods for VVER comprehensive safety assessment in support of other activities, carried out concerning VVER fuel development and qualification. CAMIVVER is oriented to the VVER-1000 reactor type.

The CAMIVVER project activities (Fig. 2) have been built to reach four main objectives:

- the improvement of scientific computer codes, models, and methods to be used at an industrial level for the comprehensive safety assessment of Generation II and III reactors.
- The promotion of 3D neutronics-thermalhydraulics coupled calculations to improve the safety assessment by a better representation of the physical phenomena (e.g., accidental transient characterized by strong heterogeneities in power or coolant fields), an important aspect for the LTO upgrade when considering the evolution of margins with respect to safety criteria.
- The promotion of the use of advanced mathematical methods (metamodels, deterministic sampling, etc.) for the assessment of uncertainty propagation within numerical simulations.
- The integration of the VVER context (VVER-1000), slightly different from western PWR but with some common features, challenges the robustness of codes and methods and their validation strategy.

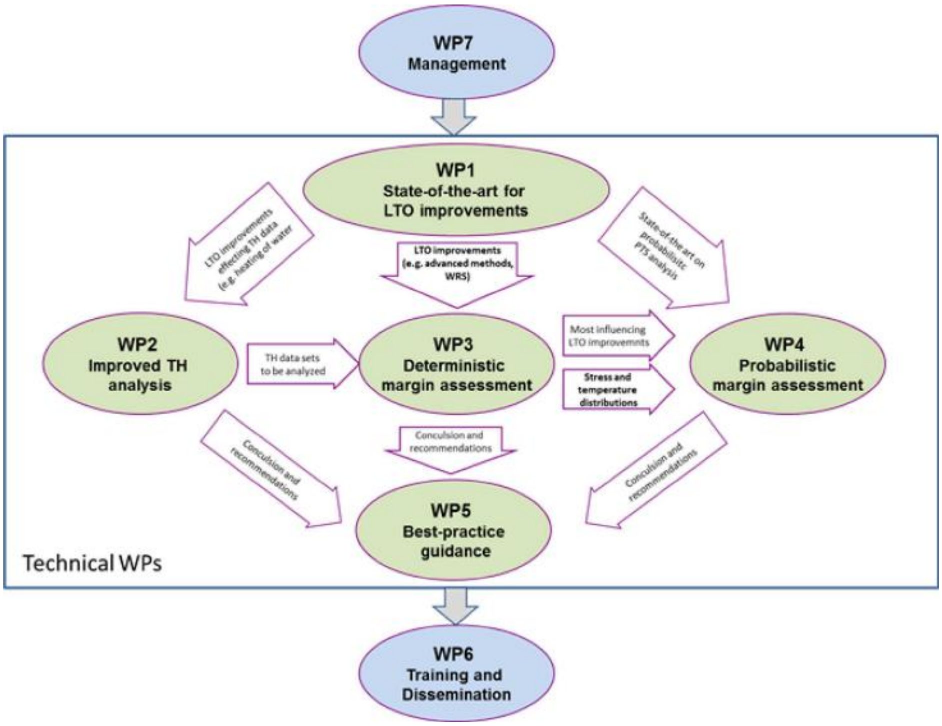

Fig. 1. APAL Project structure.

The project is organized into 7 Work Packages (WP2–WP8). Each WP is dedicated to a specific part of the safety assessment calculation chain, except WP2 dedicated to Project Management, WP3 dedicated to VVER data collection and WP8 dedicated to Communication, Dissemination, Educational, and Training activities. This structure has been chosen following the type of codes used in each technical WP (lattice codes in WP4, core neutronics, and thermal-hydraulics codes in WP5, CFD codes in WP6, and systems codes in WP7), the skills to be involved, and the dependency between the different actions. WP8 is dedicated to communication, dissemination, and education. This structure allows maintaining an overall consistency through the technical links existing between each WP, as indicated in Figure 2 while keeping separate the implementation of work programs and therefore limiting the risk of strong dependencies that may result in planning fulfillment delay.

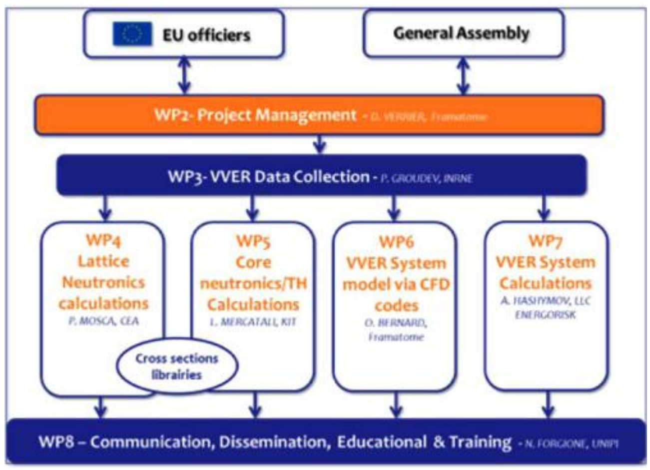

Fig. 2. CAMIVVER Project structure.

2.3 The sCO2-4-NPP project

The Fukushima Daiichi nuclear accident demonstrated the vulnerability of NPP to the loss of electrical power and the loss of the ultimate heat sink (UHS) events. Among the lessons learned to overcome the above-mentioned vulnerability was the need for safer and more reliable fuel heat removal solutions. Safety standards have hence been improved at an international level requiring the development of new technologies for improving the safety of both existing and future nuclear reactors.

New innovative heat removal technologies are currently being developed for different types of energy production sources (nuclear, solar, fossil, etc.). Among these, technologies based on the use of supercritical CO_2 (sCO_2) can significantly increase the level of safety in the case of accidents, since sCO_2 is non-flammable and non-toxic and, when attached to an NPP as a backup cooling system, delays the need for human intervention. In addition, it can potentially lower the costs of energy production and subsequent recovery of the reactor thanks to the compact size of the equipment. The compact size and high energy density of the system also mean an overall smaller plant footprint.

The former Horizon 2020 project sCO_2-HeRo developed and proved the concept of a heat removal backup

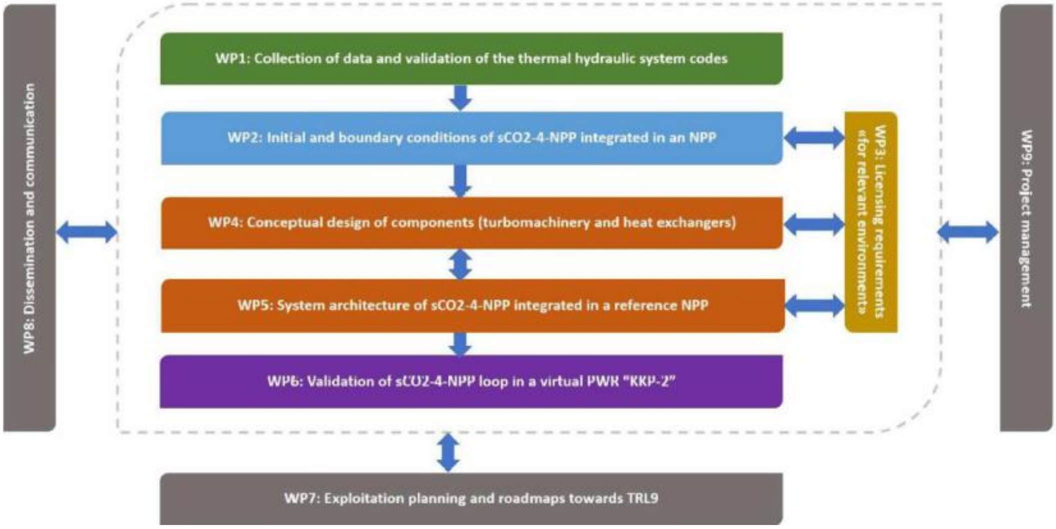

Fig. 3. sCO2-4-NPP Project structure.

technology based on sCO_2 making it an excellent backup cooling system for the reactor core in the case of a station blackout (SBO) and loss of UHS. The concept consists of several modular sCO_2-systems, attached to the existing heat removal system, to remove decay heat from the reactor.

By bringing this technology closer to market, sCO2-4-NPP (started in September 2019, for 3 years) offers a new solution to the various NPP operators that will improve plant safety in the case of an accident with minimal impact on existing reactors. The sCO2-4-NPP solution can potentially also lead to improvements in energy efficiency in other energy and industrial sectors.

The project is organized into seven technical work packages as shown in Figure 3. WP1 carried out the experiments at the 200 kW sCO2-HeRo cycle attached to the glass model in Essen, Germany, in order to obtain initial data on the performance of the sCO2-based system, as well as to validate the simulation models in the ATHLET and CATHARE codes. This WP finished in June 2020.

The output of this WP fed WP2 to specify the initial and boundary conditions of the sCO2-4-NPP modular system integrated into a real NPP. The results from WP2 (finished in June 2021) allowed the improvement of the design of components and their necessary adaptations to the nuclear environment in WP4.

The optimized design specifications from WP4 were integrated into WP5 for updated technical specifications of the components of the system. Prior to this, WP5 delivered the system's overall architecture when integrated into a reference NPP. With the system architecture and the improved component specification, the models in ATHLET, ATHLET/Dymola, and CATHARE were updated and simulation of sCO2-4-NPP modules integrated into a real NPP will be carried out.

The Dymola results will be used to build the real-time simulator of the sCO2 heat removal system for coupling to the existing KONVOI simulator. WP6's objective is to validate the sCO2-4-NPP system in the virtual KONVOI NPP.

In parallel with WPs 2–5, WP3 will document regulatory requirements and provide input to those WPs regarding the specific requirements to be considered in the design of components and the system as a whole.

Similarly, in parallel to the work in WP1–WP6, WP7 will develop the technological, regulatory, financial, and organizational roadmaps for reaching TRL9.

3 Numerical codes and related work

3.1 Numerical codes used in APAL

3.1.1 Codes and methods descriptions

Several codes and software are used in APAL, in order to reach the objectives of the project. These tools can be categorized following the different approaches studied in the PTS analyses. The PTS analyses are performed using various types of sophisticated software. The full PTS analysis consists of three specific consecutive analyses.

- *System thermal-hydraulic analysis*

It's the analysis of the behavior of the whole NPP system (primary and secondary circuits, emergency core-cooling systems, auxiliary systems, etc.) from the thermal-hydraulic point of view. The resulting parameters include, among others, temperatures, pressures, flow rates, velocities, and heat transfer coefficients in all modeled components and piping. The goal of the system thermal-hydraulic calculations is, in addition to the coolant pressure calculation, to give the initial and boundary conditions for thermal-hydraulic mixing calculations. In some cases, the system thermal-hydraulic calculations directly provide the boundary conditions for structural analyses.

For this analysis, APAL partners use RELAP5, ATHLET, and TRACE software.

- *Mixing thermal-hydraulic analysis*

It's the detailed analysis of coolant mixing inside the reactor, namely in the reactor downcomer. The resulting parameters include detailed distributions of coolant temperature in the reactor downcomer and/or detailed distributions of both inner surface RPV wall temperature and heat transfer coefficients at the RPV inner surface. There are two types of TH mixing codes – (1) codes based either on engineering models or regional mixing models, and (2) codes based on Computational Fluid Dynamics (CFD). The goal of the thermal-hydraulic mixing codes is to give the boundary conditions for structural analyses.

The thermal-hydraulic codes used for this analysis are GRS-MIX, KWU-MIX (regional mixing codes), and FLUENT (CFD code). There is no development of both system and mixing TH codes expected within APAL. Some still existing TH models were adjusted or transferred to other TH codes for application within APAL.

- *Structural and fracture mechanics analyses*

The structural and fracture-mechanics analyses can be performed using either a deterministic or a probabilistic approach. The software tools for both approaches significantly differ.

– Deterministic approach

For structural analysis, commercial "general" finite-element method (FEM) software tools are used. Among many capabilities of general FEM codes, the solutions of heat-transfer problems and mechanical problems (either linear-elastic or elastic-plastic) are used for PTS analysis. The results from thermal-hydraulic mixing analyses (see above) serve as boundary conditions for solving the heat-transfer problem with the FEM code. Results of the heat-transfer problem solution (time-dependent temperature field in the RPV wall) serve as the load for the mechanical problem together with the load due to pressure (which is the result of system TH analyses under point 1). The mechanical problem is usually solved by the same software and on the same FEM mesh as the heat-transfer problem. The results of the mechanical problem solution are time-dependent displacements, strains, and stresses in the RPV wall (calculated in all nodes of the FEM mesh).

The fracture-mechanics analysis is generally performed in two different methods.

The first method is based on the formulae from standards, which allow for calculating fracture-mechanics parameters (namely stress intensity factor, K_{I}) based on stresses exported from the FEM model. In this method, the FEM model of the RPV does not contain any cracks. These fracture-mechanics calculations are usually performed by in-house auxiliary software, together with the final assessment of RPV integrity (comparison of stress intensity factor with its allowable value, establishing the maximum allowable transition temperature, preparing the resulting graphs and tables, etc.).

The second method of performing the fracture-mechanics analysis is based on the FEM model of the RPV with the assessed crack included in the FEM mesh. Fracture-mechanics parameters (J-integral or energy release rate, G) are calculated directly in the post-processor of the commercial FEM software. All major commercial FEM software has this capability. Some in-house auxiliary codes (or EXCEL spreadsheets) are used only for the final assessment of RPV integrity.

In APAL, the codes used for this deterministic approach are ABAQUS, ANSYS, SYSTUS, etc.

There is no development of commercial FEM codes expected within APAL. New FEM models will be created by all partners for application within APAL.

– Probabilistic approach

The probabilistic approach differs from the deterministic one by taking into account the randomness and uncertainties of input data and calculating probabilities of crack initiation or RPV failure. Because commercial software is not suitable for this type of analysis, a specific software especially for the fracture-mechanics assessment, frequently created in-house, is used. Sometimes commercial FEM software can be used as a pre-processor for structural analysis (calculation of temperature and stress fields). In other cases, the specific or in-house software has its own pre-processor for this purpose. The structural assessment is usually based on a deterministic approach and treatment of uncertainties on temperature and stresses requires additional investigations. The main task of the probabilistic software for fracture-mechanics analysis is sampling some of the input data, which are treated as statistically distributed, and to calculate the conditional probability of crack initiation or RPV failure. Usually, a Monte Carlo method or FORM/SORM method (First Order Reliability Method/Second Order Reliability Method) is used for this purpose.

Most APAL partners plan to use the FAVOR code (developed by Oak Ridge National Laboratory for the United States Nuclear Regulatory Commission (USNRC) and available upon request to the USNRC). PROVER, SIF-Master, ISAAC, PASCAL, PROST, and other in-house codes will be used by other APAL partners. Significant modifications of almost all used probabilistic codes are expected within APAL, as some formulae or data prescribed for APAL benchmarks are different from those used in probabilistic PTS analyses performed routinely by APAL partners.

3.2 Numerical codes used in CAMIVVER

3.2.1 The ambition

CAMIVVER's ambition for reaching its objectives is to push new generation codes and methods towards an industrial use for VVER and PWR safety assessments. The selected new generation codes, namely APOLLO3® [2] and CATHARE3 [3], are still under development at the laboratory level. Their industrialization process is ongoing and CAMIVVER is directly contributing to this effort. This laboratory-to-industry process is illustrated in Figure 4. The CAMIVVER project is identified as one

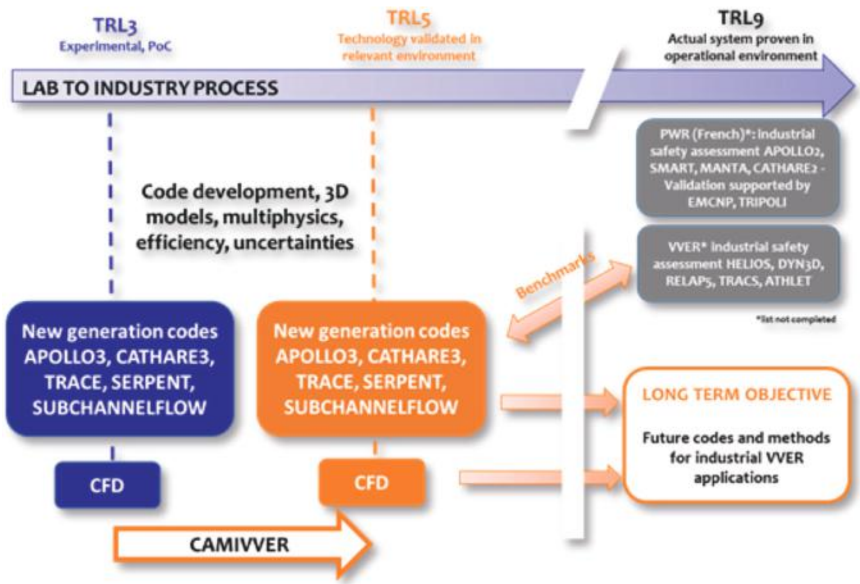

Fig. 4. Codes development within CAMIVVER.

step in that process. Post-CAMIVVER steps could be considered in the frame of the next EU R&D programs.

To achieve that significant progress, CAMIVVER relies on:

- performing code development of a neutrons library generator prototype based on APOLLO3® code and of a proof of concept of an innovative coupling based on APOLLO3®/CATHARE3 codes.
- Benchmarking those new generation codes against codes currently used for VVER and PWR safety assessment and high-fidelity calculations based on Monte Carlo codes (TRIPOLI-4 and SERPENT, [4–6], coupled with subchannel codes (SUBCHANNELFLOW) for steady state and transient calculations.
- Performing methods development based on 3D modeling to improve system thermal-hydraulics modeling of the VVER plant, especially by challenging the robustness and validation of CATHARE3 against reference RELAP5 and TRACE models.
- Performing methods development based on 3D modeling and uncertainty propagation in CFD analyses, using partners codes (STARCCM+, CFX, FLUENT, TRIO-CFD).

Both APOLLO3® and CATHARE3 bring potential advantages and improvements to the safety analysis studies with respect to the codes currently used in France. The developments of these codes have been initiated several years ago and are achieved outside the CAMIVVER framework. Within the CAMIVVER scope, essential adaptations of APOLLO3® required for VVER applications are implemented in WP4, focusing on the industrialization of the lattice part, and in WP5, by coupling neutronics with thermal-hydraulics models. In that respect, CAMIVVER will include a demonstration of the feasibility of the APOLLO3®/CATHARE3 coupling.

CATHARE3 development and validation are also involved regarding VVER plant system thermal-hydraulics. Within CAMIVVER that code is benchmarked with updated RELAP5 and TRACE codes on some selected transients: MCP (main circulation pipeline) start-up, LOCA (loss-of-coolant accident), and MSLB (main streamline break).

CFD modeling of VVER is addressed in WP6 of CAMIVVER especially as regards mixing phenomena in the primary vessel. Specific works within CAMIVVER are consisting of calculations based on the Kozloduy-6 mixing experiment [7]: CFD models development and upgrades by contributing partners, benchmarking results of CFD analyses and performing uncertainty propagation analyses by using the Deterministic Sampling method [7]. The ambition is clearly to improve the validation files.

3.2.2 The progress

Half the way of CAMIVVER has just been crossed recently. It is worth noticing that the project is proceeding normally despite the pandemic. Detailed information can be found in project deliverables, the majority of them being public and available on the project website (www.camivver-h2020.eu).

The first technical activities consisted in collecting all necessary reference data to be used by project partners. Those essential tasks have been conducted within WP3 and have been achieved since the summer of 2021.

In WP4, the activities are dedicated to setting up the framework (first steps) for the industrialization of a computing platform capable of performing lattice neutronic analysis and generating multi-parameter neutron data libraries based on the new lattice code APOLLO3®, up to now developed mostly as a research computational tool. Two important tasks have been completed in 2021 in relation to the multi-parameter library generator: the definitions of test cases for the verification phases, and the definition of representative use cases and specification requirements. Work is now progressing with the aim to have the first version of the library generator this summer and perform the validation steps against an existing validated generator (APOLLO2) and reference Monte Carlo calculations.

WP5 is tightly connected to WP4 and consists of three main tasks: (1) the definition of the VVER and PWR reduced size core reference test cases with their corresponding initial and boundary conditions; (2) the evaluation of the test cases with coupled neutronics and closed channel thermal-hydraulics tools (APOLLO3®, SERPENT/SUBCHANFLOW, PARCS/TRACE); (3) the development of a 3D neutronics-thermal-hydraulics reference calculation based on APOLLO3®/CATHARE3 coupling based on the outputs from (1) and (2). The first task has been successfully completed in 2021: the VVER and PWR test cases have been specified with all necessary information: geometries, materials, thermophysical properties, transient scenarios (initial/boundary conditions), and output parameters to be observed. Test cases consist of so-called "mini cores" of 7 fuel assemblies for the VVER case and 32 fuel assemblies for the PWR case. Such small configurations have been chosen to limit necessary calculation resources and times. Information related to those WP4 and WP5 activities has been recently published [8].

Works performed in WP6 during the first half of the project consisted of the development of the VVER-1000 vessel CFD models by each of the five contributing partners to the benchmark exercise, each with his own calculation tool. This task has been completed in 2021. Steady-state conditions have been simulated and compared between models and results have been released at the beginning of 2022. The Kozloduy-6 mixing experiment exercise is now progressing.

A comparable progression was achieved in WP7 in the field of system analyses. Each partner has developed his own model and steady-state calculations have been produced in 2021. The first transient calculations have been achieved at the very beginning of 2022. A new document has been recently produced about the Kozloduy-6 MCP start-up transient benchmark, showing consistency of results with test data.

3.3 Numerical codes used in sCO2-4-NPP

3.3.1 Codes and methods description

- *The THERMAL-HyDraulic SYSTEM CODE ATHLET*

The thermal-hydraulic system code ATHLET [9,10] is developed by the Gesellschaft fuer Anlagen- und Reaktorsicherheit gGmbH (GRS). The highly modular code structure of ATHLET includes advanced thermal-hydraulics as well as physical and numerical models.

ATHLET is able to calculate single or two-phase flows. To simulate the thermo-fluid-dynamic behavior of the fluid, the user has to specify the system configuration by connecting basic fluid dynamic elements, the so-called thermo-fluid dynamic objects (TFOs). These TFOs can be divided into several segments, the so-called control volumes (CVs), to refine the simulation's resolution. The user can choose between the classic 5-equation model, also called the 1-M model, (with drift flux approach) and a two-fluid model with separate momentum balance equations for liquid and vapor, also called the 6-equation model or 2-M model.

The ATHLET code system performs spatial integrations based on a finite volume approach, which leads to a set of first-order differential equations, stemming from two mass and energy conservation equations per control volume and one or two momentum conservation equations per junction. The code also distinguishes homogenous CVs, where all phases are distributed uniformly and no directional quantities exist, and mixture-level CVs, which contain a horizontal mixture level. Below the mixture level, only pure fluid with vapor bubbles may exist, and above, only vapor with liquid droplets.

- *The Thermal-Hydraulic Code CATHARE*

The CATHARE (Code Avancé de THermohydraulique pour les Accidents de Réacteurs à Eau) code is a French thermal-hydraulics system code developed since 1979 and extensively validated in collaboration between CEA, EDF, IRSN, and FRAMATOME [11]. It is internationally used in plant simulators and for nuclear power plant safety analysis and licensing. It was originally devoted to best estimate calculations of thermal-hydraulic transients in water-cooled reactors. The CATHARE 2 has then been extended to gas applications in the 2000s. However, the gas was then considered ideal in this version of the code. This is one of the reasons for the development of a new version of the code CATHARE 3 [12] which enables the consideration of real gas instead of an ideal one in simulations. Therefore, the CATHARE 3 code allows expanding CATHARE 2 ability to model nuclear reactors such as new generation reactors with sodium application and closed Brayton cycles [13–16]. Its major feature is the possibility to choose field numbers from one (pure monophasic) to four: two continuous fields (liquid and vapor) and two dispersed fields (droplets and bubbles). Furthermore, CATHARE 3 can use the Equation Of State (EOS) component which enables the calculation of gas properties from several libraries especially the NIST Reference Fluid Thermodynamic and Transport Properties Database (REFPROP).

The CATHARE 3 solves a two-phase six equation model including additional equations for non-condensable gases and radio-chemical components transport. These equations correspond to the local instantaneous mass, momentum, and energy conservation. They are averaged for each phase over a cross-section over time and allow to represent mechanical and thermal disequilibrium between phases. The system of the equations is closed by physical closure laws of momentum and energy transfers between phases. Finally, the global non-linear system is solved using a Newton–Raphson iterative method.

CATHARE 3 allows modeling the coolant circuits of any reactor by assembling axial (1-D), volume (0-D), and three-D (3-D) hydraulic modules. Thermal and hydraulic sub-modules such as thermal walls, heat exchangers, pumps, valves, turbines, a fluid source, and a sink can be added to these main modules.

- *DYMOLA modeling and simulation tool*

To build and simulate the sCO_2-loop numerical model, the Dymola [17] modeling and simulation tool was used by the project partner CVR. Supporting the simulation of the models that are written in the Modelica programming language, the sCO_2-loop Dymola model was prepared using the Modelica library and ClaRaPlus, TSMedia, ClaRa_DCS Modelica language-based libraries developed by XRG [18] and TLK [19] companies. In this way, the sCO_2-loop Dymola model is a 1D model capable of capturing basic characteristics of the non-steady fluid flow and heat transfer based on the finite volume approach. In a case of a two-phase flow, the fluid is treated as a homogenous mixture of liquid and steam. TS Media library also allows for subcooled CO_2 and water to be modeled.

3.3.2 Developments and results

- Developments and results for ATHLET
  - ATHLET extensions for the Simulation of sCO_2 Cycles

For the modeling of sCO_2 cycles, Venker [20] implemented the first version of the thermodynamic and transport properties of sCO2. In terms of enthalpy and density, data points were generated on a temperature-pressure grid with the computationally expensive equation of state for CO_2 (developed by Span and Wagner [22]).

In the frame of project sCO2-4-NPP and project sCO2-QA [23], ATHLET was further improved and extended for the modeling of sCO_2 cycles [24,25]. The accuracy and the range of the thermodynamic properties of sCO_2 were improved by applying a biquadratic spline interpolation on a pressure-enthalpy grid, similar to Kunick [26], and calculating the enthalpy from the inverse function of the temperature. In addition to the temperature, the density, the entropy, and the speed of sound were provided as spline fits. In the subcritical region, this approach was also applied but there and especially in the transition between the regions some numerical issues need further investigation [23]. For the simulation of turbines, the available model for axial steam and gas turbines may be used. For the simulation of radial turbines, a new efficiency correlation was added to this model [27]. Additionally, a new performance map-based turbomachinery model was implemented. This model allows the simulation of compressors as well as turbines and applies a real gas similarity approach [28] to account for changing thermodynamic inlet conditions for the machines. For the simulation of the heat transfer to the UHS in the sCO2 cycle, an additional heat transfer correlation for the finned air side was implemented [25,29]. On the water side, another correlation for the film-condensation [30,31] was implemented and in general, it was found that the available standard heat exchanger modeling approach in ATHLET may also be applied for the modeling of the heat exchangers in the sCO_2 cycle [24,25,31].

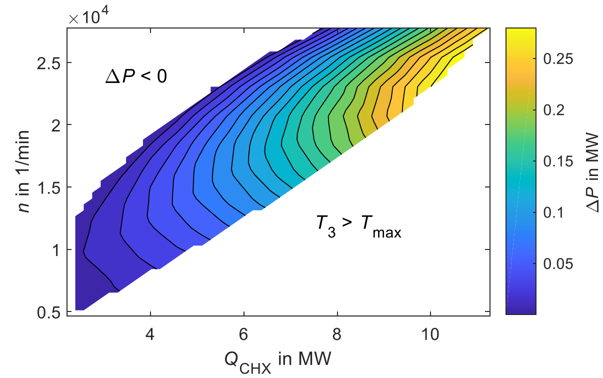

Fig. 5. Excess power output of the cycle at $T_1 = 55$ °C and $T_{\mathrm{air,in}} = 45$ °C with type 2 turbomachinery.

– Selected simulation results of ATHLET

First, a stand-alone analysis of the sCO_2 heat removal system was studied [21,32]. The heat removal system is not designed for efficient electricity generation but for self-propelling heat removal over a wide range of conditions. Therefore, it must be ensured that the cycle operates in a region with an excess power ΔP higher than zero, as shown in Figure 5. The color map indicates that the excess power is decreasing both with decreasing Q'' (power of the compact heat exchanger) and decreasing n (turbomachinery rotational speed). Moreover, Figure 5 shows regions in white where the cycle cannot be operated. First, in the lower right, the operation range is limited by the heat transfer in the CHX (compact heat exchanger) and the maximum steam temperature. Secondly, in the upper left, the operation range is limited because ΔP drops below zero. This is mainly a result of the reduced turbine power caused by the decreased turbine inlet temperature T_3. At the design speed of 23 krpm, the minimum allowable T_3 is 181 °C. With decreasing speed, the minimum allowable T_3 also decreases, e.g. at 13 krpm it is 140 °C. Therefore, it can be concluded that the turbomachinery speed should be decreased with decreasing thermal power input to the CHX.

Thirdly, selected results from the simulation of the sCO_2 heat removal system coupled to a pressurized water reactor are shown. A detailed description of the coupled simulations and the results are provided in the reference [33]. During the analyzed SBO scenario, the decay heat is transferred driven by natural circulation, first from the primary loop to the steam generators and then further to the CHXs of the CO_2 cycles and finally to the ambient air. In the analyzed case, each of the four steam generators is equipped with one CO_2 cycle. Figure 6 shows the decay power compared to the total thermal power of all CO_2 cycles of the heat removal system. From an operational readiness state, the CO_2 cycles are ramped up (start-up) to their design thermal power. After the equilibrium of the decay power and the removed thermal power, the hot-side temperatures of the nuclear power plant and the CO_2 cycles start to decline (cooldown).

- Developments and results for CATHARE
  - Extensions for the simulation of sCO_2 cycles

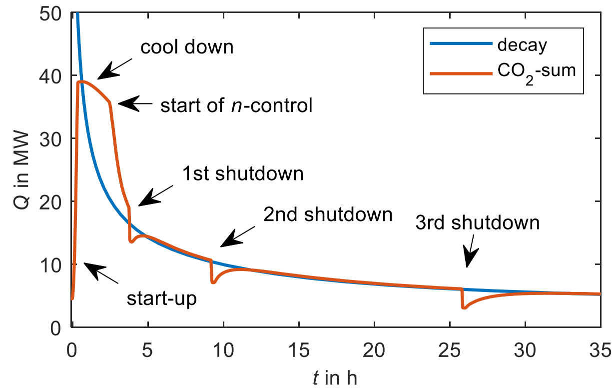

Fig. 6. Decay power and total thermal power removed by the CO_2 cycles over time including different operation modes and the shutdown of single CO_2 cycles.

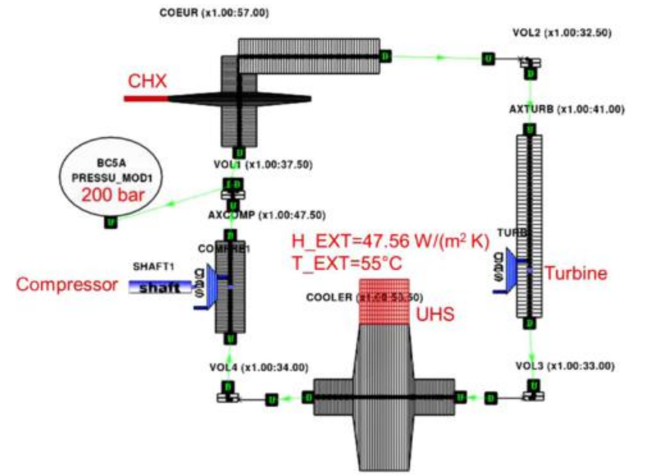

Fig. 7. Layout of the sCO_2 loop modeled with CATHARE 3.

Many developments have been made in CATHARE 2 to represent all kinds of possible Brayton cycles with turbomachinery [16], a perfect gas turbomachinery module was developed from the CATHARE 2 pump module to describe either a compressor or a turbine that can be coupled to a shaft and an alternator. The behavior of the code has been validated on four real loops. This has therefore demonstrated the ability of the code to accurately represent the dynamic behavior of Brayton cycles in particular the turbomachinery behavior. But the Brayton cycles modeling was then only available for ideal gases.

Therefore, in the framework of the NEPTUNE project [34], REFPROP has been implemented as a new library in the EOS component to use several real gas equations of state in CATHARE-3 such as supercritical CO_2. Thanks to the REFPROP library, CATHARE 3 can compute the real thermodynamic and transport properties of fluids such as supercritical CO_2.

However, the perfect gas turbomachinery model developed in CATHARE 2 was no longer consistent with the new real gas model from REFPROP. Some work has therefore been performed to extend the non-dimensional representation of turbomachinery for a real gas based on turbomachine performance equations. In the perfect gas turbomachinery model, the efficiency is deduced from two reduced values, respectively assessing the flow rate and the shaft rotating velocity. The new real gas turbomachinery model uses the speed of sound of the fluid (instead of temperature) to adequately compute these reduced values without using the ideal law. Performance characteristics are calculated with the real speed of sound and the gas entropy that are available in the REFPROP equation of state.

– Selected results of CATHARE

A stand-alone sCO_2 heat removal system modeling has been performed with the turbomachinery composed of a turbine and a compressor coupled and two heat exchangers CHX (heat source) and UHS (heat sink) (see Fig. 7). The loop is designed to dissipate around 10 MW from one steam generator. Some tests have been done using approximate boundary conditions in the CHX similar to those present in the safety condensers (SACO) of the EPR nuclear plant during a transient SBO scenario. The tests were satisfactory with one or two sCO_2 loops in parallel. Indeed, the power to dissipate on one steam generator is quite high compared to the design of the sCO_2 loop. Therefore, several sCO_2 loops in parallel should be used.

The coupling of the sCO_2 loops with the EPR at the localization of the SACO led to numerical and physical issues. For now, only one sCO_2 has been coupled with one steam generator and there are still numerical issues. The first comparison with an SBO scenario without SACO shows that the sCO_2 loop allows to cool down of the primary circuit but the power dissipated is too low and several sCO_2 loops are needed. A lot of work has still to be done, especially during the regulation phase of the calculation. We think that the initialization and the start-up of the sCO_2 could be the cause of the numerical and physical issues observed.

- Developments and results for DYMOLA
  – Developments for the sCO_2-loop model

Besides the libraries' components, the sCO_2-loop Dymola model comprises new components like turbomachinery and heat exchangers that were built with respect to the project partner's designs under the limiting conditions of the 1D modeling capabilities. As for turbomachinery, the non-dimensional performance curves were implemented to consider changing inlet conditions. When modeling heat exchangers, the 2D nature of the real design was addressed by a proper connection of the hot and cold side heat connectors.

The Dymola sCO_2-loop model needs to be coupled with some external code if we want to simulate the nuclear power plant SBO scenario. Such an external code was ATHLET with the Temelin VVER-1000 nuclear power plant model prepared by UJV. An interface between the Dymola and ATHLET codes was the wall between the CO_2 (Dymola) and steam/water (ATHLET) side of the CHX. To a couple, the Dymola and ATHLET models, the TISC Suite software package (developed by TLK company) was used together with the supervisor code

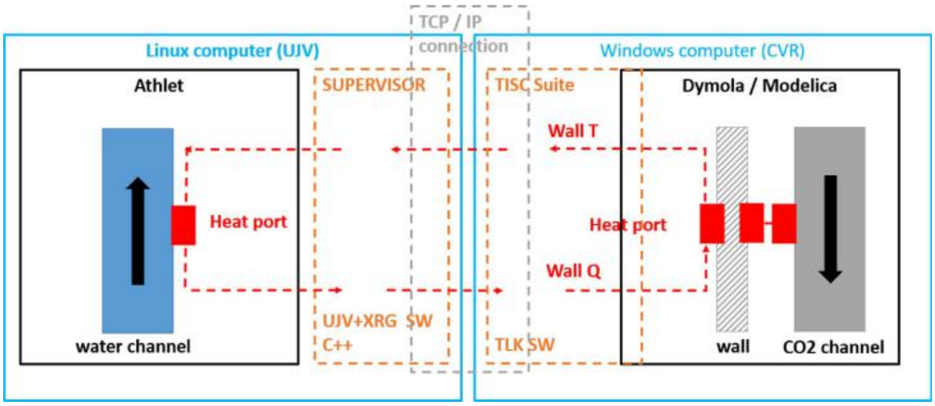

Fig. 8. Dymola-ATHLET coupling schematics.

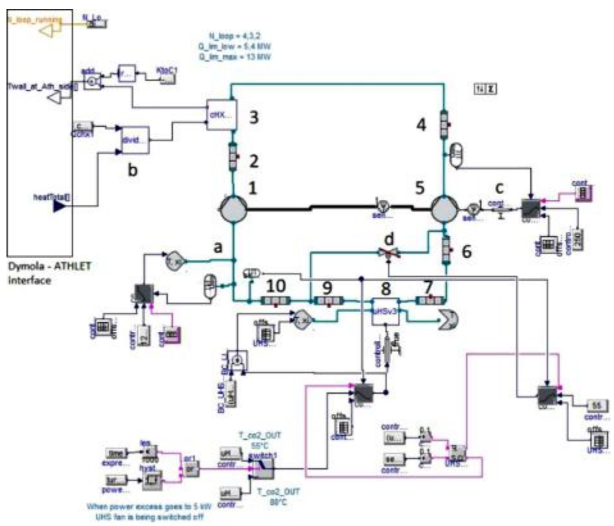

Fig. 9. Dymola model components .

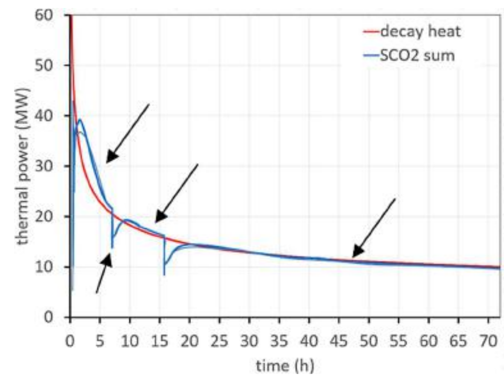

Fig. 10. Decay heat and sCO_2 system total heat (ATHLET data).

developed previously by UJV for coupling of ATHLET and FLUENT. This supervisor code was adapted for the current application with the help of XRG company. The block diagram of the coupling is depicted in Figure 8.

The Dymola sCO_2-loop model basic structure is shown in Figure 9. Here, the basic components are as follows: radial turbocompressor (1), CHX CO_2 side (3), radial turbine (5), and UHS (8). As the decay heat gradually decreases with time, so does the number of the sCO_2-loops needed to dissipate the decay heat to the atmosphere. As only one sCO_2-loop was modeled in the Dymola, the information about the number of the sCO_2-loops currently in operation was also transferred between the two codes. For each constant number of running sCO_2-loops, the loop thermal capacity was accommodated by the turbomachinery speed of revolution control. Two transient Dymola-ATHLET coupled simulations were performed including that with changing ambient air temperature during the decay heat removal campaign. One of the simulations basic results, namely the comparison of the decay heat and sCO2-loop heat dissipation is depicted in Figure 10. During the whole 72 hours campaign, the maximum core cladding temperature stays within the safety limits.

4 Conclusion

For each of the projects, the work relating to the various numerical codes was initially the subject of a thorough analysis of the characteristics and differences in the treatment of the methods or phenomena studied in the project. These analyses allowed the different consortia to establish comparison grids for the codes used and also the steps to be taken to optimize and harmonize the results of these different codes, for the same phenomenon or the same method analyzed.

It emerges from the work of these three projects, a need to continue to carry out joint work, within the framework of collaborative projects such as the European projects, to be able to:

- undertake the necessary comparisons and harmonizations for these different codes, thus ensuring that the results obtained will be of acceptable quality for the different nuclear studies in cases where keeping different codes is necessary.
- Share new developments related to innovations. Innovations (new components, new systems, new methods) are often associated with new developments of libraries or models in a code. When the sharing of these innovations to a wider audience is desired, this sharing may come up against the fact that the new developments

are only available in a given code, and therefore limit the dissemination of these innovations (for example, the developments related to the system studied in sCO2-4-NPP began in 2015 for the ATHLET code, and only in 2021 for the CATHARE code).

- Moving towards common digital tools. Sharing common developments can also lead the different actors towards the choice of a common tool, and not the multiplication of codes.

Conflict of interests

The authors declare that they have no competing interests in 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 reasons.

Author contribution statement

All *authors contributed* equally.

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Review Article

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Methodologies for efficient and reliable NPP polymer ageing management

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Abstract. The lifetime of existing Nuclear Power Plants (NPPs) can potentially be extended to between 60 and 80 years if safety and operability of facilities can be guaranteed. This requires efforts in terms of equipment qualification and ageing management to support stakeholders and decision makers. Polymer ageing is of concern due to their widespread use in NPPs (e.g. each NPP contains approximately 1500 km of cables). Predicting their lifetime and monitoring their integrity remain a challenge. Here, we present a cross-cutting review of two on-going Horizon 2020 projects (TeaM Cables and El Peacetolero). The combination of these 2 projects allows to provide the community with non-destructive and predictive tools that can help assess the reliability and functionality of polymer-based components such as cables or pipes. The paper discusses scientific challenges faced in the beginning and achievements made throughout the projects, including the industrial impact and lessons learnt. Two specific aspects highlighted concern the way the projects sought contact with end users and the balance between industrial and academic partners. The paper concludes with an outlook on follow-up issues related to the long-term operation of NPPs.

1 Introduction

The effective maintenance of nuclear power plants (NPPs) is essential for their safe operation. Maintenance ensures that the level of reliability and effectiveness of all safety-relevant components and systems remain in accordance with design assumptions. Scheduling preventive and corrective maintenance operations requires an understanding of ageing mechanisms for different components and materials used in plants, as well as a thorough and quantitative assessment of the health and reliability of safety-relevant components.

The projects addressed in this paper attempt to answer this challenge. TeaM Cables aims to improve the understanding of ageing mechanisms on cables used in plants (specifically to polymers used in cable insulation), to model this ageing mechanism, and to devise NDE and monitoring techniques for health assessment. El Peacetolero aims to set up a miniaturized and portable optoelectronic system able to not only identify a polymer but also determine the degradation level. This equipment, usable by a non-specialized operator or by a remote-controlled device, would allow instantaneous and non-destructive analysis which will increase the reliability and drastically simplify the operations (reducing not only maintenance costs but also an increase in radioprotection).

This paper deals with achievements, challenges and impacts of these projects rather than giving exhaustive descriptions, with the aim to identify potential follow-ups to cover the terrain not dealt with throughout these projects. We therefore restrict the project descriptions to brief portraits in the following paragraphs (Tab. 1).

1.1 TeaM Cables project

TeaM Cables focuses on European tools and methodologies for an efficient ageing management of NPP cables and addresses the challenge of long-term operation for cables – more precisely, their polymer insulation, which is subjected to ageing. The use of numerous cables in a NPP (about 1500 km for one nuclear unit) makes the replacement of cables economically unfeasible, which require accurate predictive models for their safe lifetime as well as for generic tools and methods for on-site monitoring.

TeaM Cables develops a novel multiscale approach for a more precise estimation of the cable lifetime. Cable lifetime is governed by polymer layers' lifetime. A large part of the project is hence dedicated to polymer science. The project analyses the effects of irradiation and

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Table 1. Key figures for projects discussed.

Project	Duration	Funding	Lead	Partners	Framework
TeaM Cables[1]	2017–2022	4,2M€	EDF	13	H2020
El Peacetolero	2020–2023	1,0M€	Sorbonne Université Paris	9	H2020

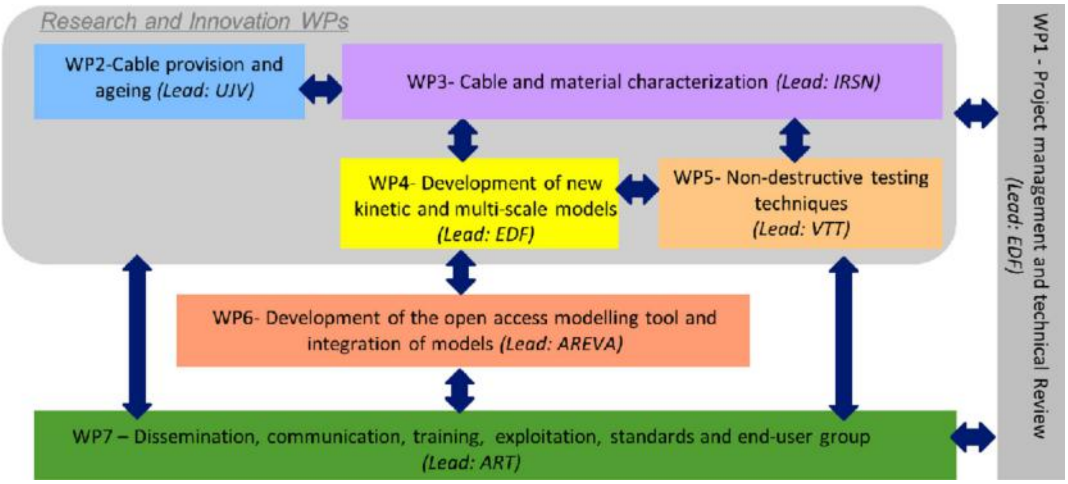

Fig. 1. TeaM Cables work plan.

temperatures on polymers from micro- to macroscale levels, to develop multiscale models of ageing. Ageing in normal operation conditions and accidental conditions will be addressed. The unique multi-scale and kinetic models are integrated into a numerical tool, which will be based on the fusion of a currently used European cable management instrument with a polymer ageing modelling tool. In parallel, criteria and protocols are proposed for on-site use of non-destructive testing techniques.

The programme combines highly scientific work packages for actual polymer ageing kinetics models with experimental work packages to obtain data throughout accelerated ageing (cf. Fig. 1). The consortium is comprised of stakeholders, cable manufacturers, academic partners with specific experience in polymer ageing kinetics modelling, as well as applied institutes for experimental and NDE aspects.

1.2 El Peacetolero project

Polymer ageing control methods are of two types. The first one is the sampling of deposit or real equipment (for example, coring) and subsequently experimental testing of the material in a laboratory. If this method meets the criterion of reliability, this is invasive, expansive, and time-consuming. The second one is the non-destructive exam like indentation. In this case, criteria are based on material-dependent and poorly understood correlations between the measured property and end-of-life criteria. These correlations are material dependent and require previous establishment of relationships between the material's behaviour and environmental conditions. Early detection of abnormal behaviour and embrittlement are therefore impossible with these approaches.

In this respect, El Peacetolero aims to design a TRL 7 hand-held, low power, embedded optoelectronic system that can deploy AI for in-situ real-time measurement, identification and diagnosis of polymers' ageing in an industrial environment. The system performs measurements of material reflectance at specific wavelengths according to InfraRed Attenuated Total Reflectance (IR-ATR). This concept has been recently patented and has been verified and successfully tested by a laboratory prototype (TRL3) [1]. Figure 2 is a block diagram representing an overview of the El-Peacetolero system and its component parts.

The work plan of the project is divided into two distinct large blocks of work as illustrated in Figure 3. The first concerns material's ageing and characterization, data generation and AI and algorithms that will be derived from this for on-site verification. The second one concerns the device itself with the development of the LED and laser heads and the optoelectronics needed. The overall device has been tested, and the results have been compared with "well-known" destructive and other non-destructive methods of characterization.

2 Challenges, achievements, and impact

2.1 Scientific challenges and achievements

TeaM Cables is funded under the framework of the section "Continually improving safety and reliability of Generation II and III reactors" of the Euratom Program 2016 and

[1] Public website: https://www.team-cables.eu/

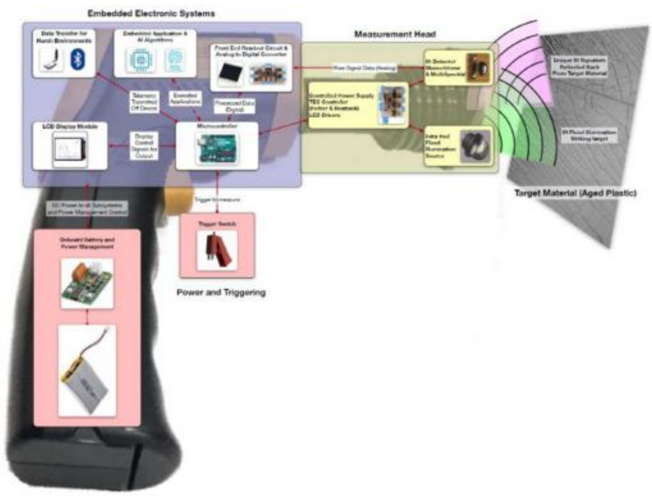

Fig. 2. El-Peacetolero System block diagram.

El-Peacetolero under the framework of the section "Innovation for generation II and III reactors" of the Euratom Program 2019. The main scientific challenge of these two projects is to obtain a deeper understanding of operation-induced degradation mechanisms. This will be notably carried out by developing NDE methods.

TeaM Cables faces multiple scientific challenges related to polymer ageing, which are in part covered by three PhD collaborations with academic partners. The overall ambition of TeaM Cables is to allow NPP operators to improve their capacity to safely manage the lifetime of cables and thereby contribute to ensuring the lifetime extension of NPPs to 60–80 years. To achieve this, a radically new way to predict the lifetime of cables (In terms of mechanical, physical and electrical parameters) is developed, using much more precise information about material composition and more relevant methods for analyzing the data based on multi-scale studies of the materials [2–7].

2.2 Industrial impacts

In a short term, TeaM Cables intends to achieve industrial impact through two end-user workshops, and a closing symposium. Both projects will deliver tools capable of delivering additional substantial information regarding the degradation parameters used for the assessment of lifetime, non-destructively, fast and reducing the material monitoring time. TeaM Cables will organize a training workshop for NPP operators and researchers on the developed tool.

In the medium term, these projects shall provide the background for robust national and EU strategies regarding various polymer components in the field of nuclear reactor safety.

In the long term, results of these projects should strengthen the competitiveness and growth of companies by developing innovations meeting the needs of European and global markets, and notably for El-Peacetolero, by delivering such innovations to the markets. Indeed, the El-Peacetolero tool will be an innovative TRL7 product that will have demonstrated a real use in a safety critical industry. The real-time data that are captured by El-Peacetolero will allow for better scheduling of preventative maintenance and curtail safety issues related to polymer degradation. This will reduce the costs related to shutdowns and will be transferable to many industries where polymer degradation can have implications.

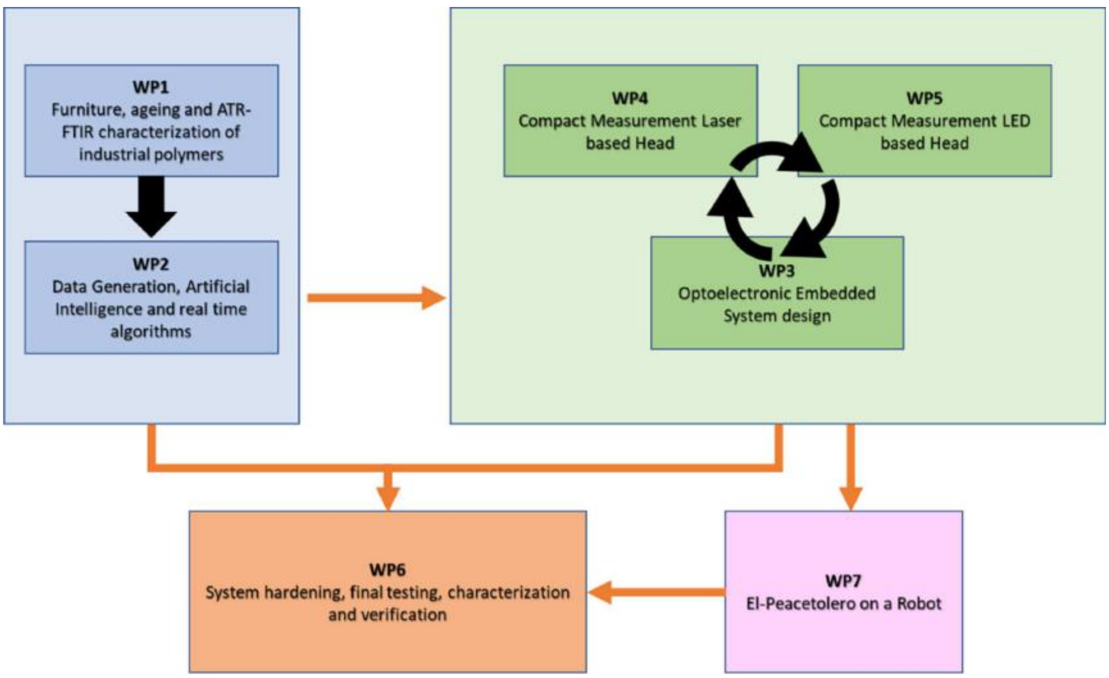

Fig. 3. El-Peacetolero work plan.

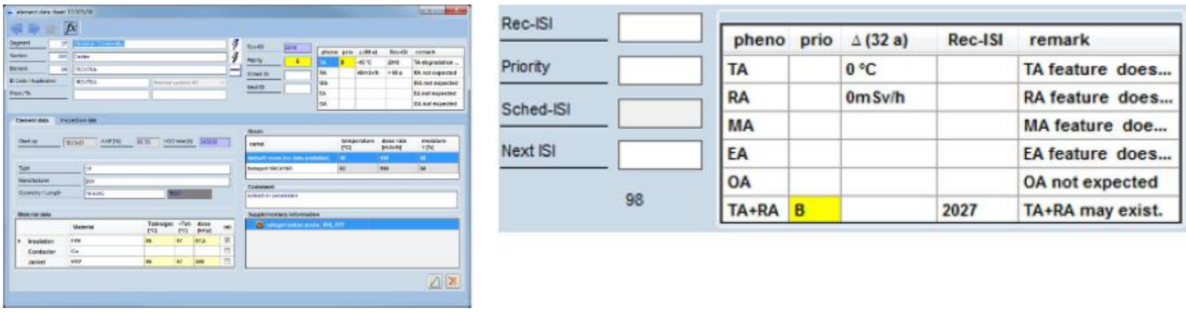

Fig. 4. Component data sheet window (at the left side) and zoom on the evaluation of the duration life of a cable according to the exposure conditions (at the right side).

2.3 End-user's implication

Horizon 2020 focuses on dissemination, which clearly emerges in all ongoing projects. These two projects have designated dissemination work packages.

The El-Peacetolero project will realize a system prototype demonstration in operational environment. EDF engineering is fully integrated into this first demonstration. TeaM Cables involves special task forces providing expert advice on specific R&D related issues and assessing the results, such as materials, methods and tools in nuclear safety measures or S/T advice. These advisory boards are:

- an end-user group: to ensure the industrial applicability of models and tools developed in TeaM Cables. The end-user group members participate in project consortium meetings and in specific end-user workshops dedicated to the assessment of models and tools (Tecnatom, Engie Laborelec, Airbus, Forsmark, Paks II, EDF, NEXANS).
- A technical advisor: appointed by the NUGENIA Executive Committee, he is invited to project consortium meetings and review the deliverables produced by TeaM Cables.
- Advisors on standards: TeaM Cables collaborates with external advisors as Empresarios Agrupados to discuss standardization aspects. They are also invited to project consortium meetings.

To sum up, TeaM Cables pushes this idea particularly far, with a winter school, two end-user workshops, a training workshop for NPP operators and researchers as well as a final symposium.

2.4 Academic involvement

TeaM Cables collaborates with the University of Bologna and ENSAM Paris, with a total of three PhDs. They worked on the development and validation of a kinetics model for polymer ageing, and the use of the output of the kinetics models and multiscale models to predict mechanical, physical and electrical parameters. Three PhD theses are on-going in El-Peacetolero project works with two well-known university Sorbonne Universit Paris (L2E-SU) and Universitat Jaume I (UJI). Their work focuses on the three main scientific areas of the project: the embedded optoelectronic system, artificial intelligence and robotics.

3 Lessons learnt and follow-up issues

One of the challenges concerns the capitalization of achievements made. TeaM Cables realized this already at the proposal stage and centres its capitalization effort around a software tool as a federating item. Indeed, a novel "open access" tool, hereinafter referred to as the "TeaM Cables tool", has been developed integrating the multiscale model and providing the residual lifetime of cables knowing material data and the exposure conditions (wiring network in the NPP). On the one hand, experimental characterizations are carried out at different scales to bring out ageing mechanisms and consequences. On the other hand, models are developed to relate the scales using experimental data as input or validation for modelling. Then, multiscale models have been integrated into the "Virtual Polymer" tool provided by EDF. This tool is then interfaced with some functionalities of the COMSY Cable tool provided by Framatome (cf. Fig. 4).

A first distribution of the TeaM Cables Tool to the partners and end-user group has been recently done. The end-user group is checking the transposability of the models developed on data coming from in-service cables or from databases of previous projects.

To obtain a deeper understanding of operation-induced degradation mechanisms, accelerating ageing campaigns have been performed. Particular attention was paid to maintaining the representativeness of the degradation mechanisms observed under NPP conditions in these two projects. For instance, in El-Peacetolero project, ageing conditions have been chosen to remain as close as possible to the degradation mechanisms involved for pipe applications. Figure 5 shows the dedicated accelerating ageing loop designed within the framework of El-Peacetolero project considering numerous environmental factor (immersion in chlorinated and salted water in temperature).

4 Conclusions

The lifetime of existing NPPs can be potentially extended to between 60 and 80 years if safety and operability of facilities can be guaranteed. This requires efforts in terms of equipment qualification and ageing management to support stakeholders and decision makers. Polymer ageing

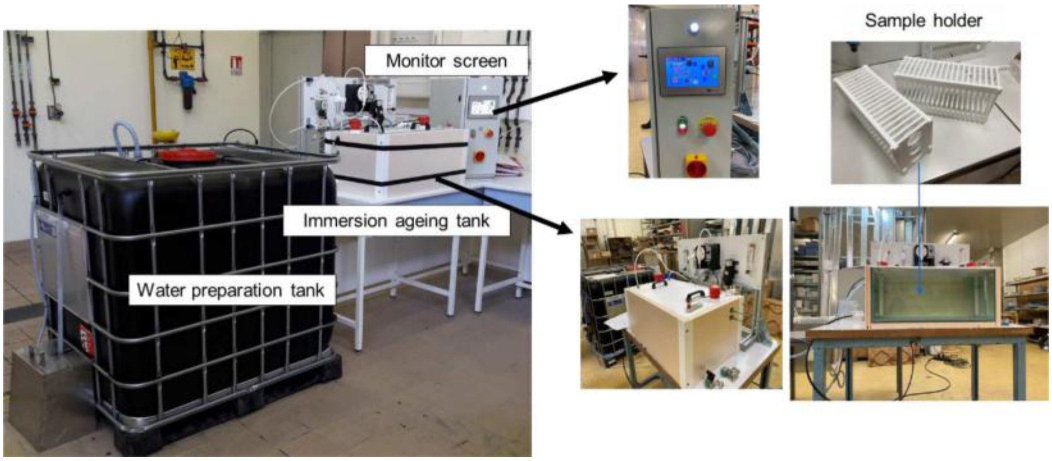

Fig. 5. Design specific accelerated ageing loop.

is of concern due to their widespread use in NPPs (e.g. each NPP contains approximately 1500 km of cables). Predicting their lifetime and monitoring their integrity remain a challenge, which led to the origin of the two ongoing H2020 projects discussed in this paper. The combination of these 2 projects allows to provide the community with non-destructive and predictive tools, that can help assess the reliability and functionality of polymer-based components such as cables or pipes. TeaM Cables not only highlights the importance of ageing models' choice (multiscale approach vs. empirical approach), but also the need to crosscheck the results with data from continuous monitoring and in-service inspections, which allows for predictive maintenance (as opposed to scheduled maintenance).

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 other reasons.

Author contribution statement

Dr. Morgane Broudin is in charge of the overall supervision of the TeaM Cables project as coordinator. Dr. Mohamed Ben Chouikha is the El-Peacetolero project coordinator.

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Review Article

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Advanced numerical simulation and modeling for reactor safety – contributions from the CORTEX, McSAFER, and METIS projects

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Abstract. This paper gives an account of three projects funded by the European Union that heavily rely on numerical modeling and simulations of nuclear reactors: the CORTEX project (CORe monitoring Techniques and EXperimental validation and demonstration), the McSAFER project (High-Performance Advanced Methods and Experimental Investigations for the Safety Evaluation of Generic Small Modular Reactors), and the METIS project (MEthods and Tools Innovations for Seismic risk assessment). The CORTEX project focuses on neutronic simulations, the McSAFER project considers neutronic, thermal-hydraulic, and thermo-mechanic simulations, whereas the METIS project investigates simulations for seismic assessments. Although the projects have different objectives, they present some common features in terms of the complementary modeling approaches used in each project and in terms of verification and validation programs. The main achievements of the projects are presented in the paper covering the technical aspects of the respective projects, training, education, and dissemination activities, as well as utilization and cross-fertilization. All three projects lead to the advancement in nuclear reactor modeling in the above areas, with the development of new simulation capabilities beyond the state-of-the-art.

1 Introduction

Numerical simulations have always represented one of the pillars of nuclear reactor safety, with safety analyses carried out either in a deterministic or a probabilistic sense. Although well-established methods have been used for the current fleet of reactors for decades, recent developments in modeling capabilities make it possible to address new situations and conditions. This paper overviews the latest advancements in simulation and modeling in the Euratom-funded projects CORTEX, McSAFER, and METIS.

In CORTEX, deterministic and Monte Carlo neutron transport simulations of postulated anomalies are combined with machine learning architectures to detect existing perturbations in operating nuclear reactors, classify them and, when relevant, identify the location of the perturbation. In McSAFER, the existing simulation platforms based on the multi-physics and multi-scale approach are adapted to Small Modular Reactors, focusing on neutron transport, thermal-hydraulic and fuel thermo-mechanic simulations, and their interdependencies. An experimental program in three European facilities (MOTEL, COSMOS-H, and HWAT) to investigate safety-relevant thermal-hydraulic phenomena in the core, reactor pressure vessel, and heat exchanger of integrated SMR concepts complements the numerical investigations. In METIS, a multidisciplinary approach is proposed for the seismic safety assessment of reactors, based on numerical simulations, the use of observations for model updating, and the uncertainty propagation through the three steps of the analysis, from hazard via structural and equipment fragility analyses to risk quantification.

Although the three projects have different objectives, they also present common features. First, various complementary modeling tools with different levels of sophistication are used depending on the target conditions and situations. This also allows for assessing the area of validity of low order fast running models versus high-fidelity computationally intensive tools. Second, all modeling approaches require extensive verification of the tools and validation against experiments. Finally, the assessment of the reliability of the simulations requires complementing the

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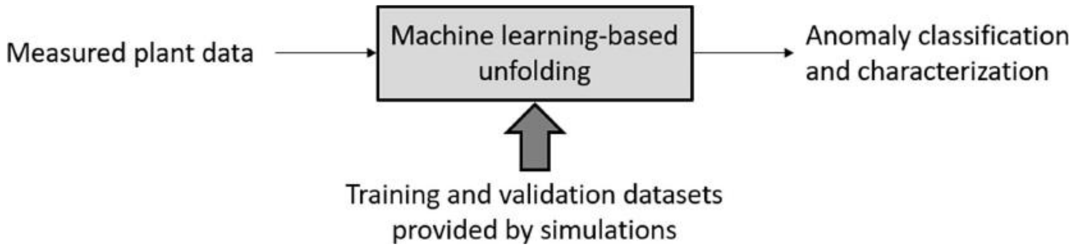

Fig. 1. Overview of the overall core monitoring methodology applied in the CORTEX project.

simulations with uncertainty and sensitivity estimates. The paper details the development of the modeling capabilities within the three projects, the lessons learned, and the required future developments.

2 Short description of the respective projects

2.1 CORTEX

Maintaining the high availability of nuclear reactors has always been a top priority for the industry. With the aging fleet worldwide, operational problems become more frequent and may impact plant availability. Being able to detect anomalies early before they have any inadvertent effect on plant operation, availability and safety is thus of paramount importance. As nuclear power plants are very large and complex systems, detecting anomalies is particularly challenging, despite the multitude of sensors monitoring the health of the system and the recent progress in surveillance, diagnostic and prognostic techniques [1]. The part of the system where this is most difficult is the nuclear reactor core, i.e., the part of the system containing the nuclear fuel assemblies. The system contains very few detectors, especially in-core. The existence of neutrons originating from the core nevertheless offers a unique opportunity for monitoring: due to the transport of neutrons via fission and scattering reactions, a neutron detector can "sense" any perturbation, even when this perturbation is far away from the considered neutron detector.

In this respect, the spatial dependence of the inherent time fluctuations in the neutron flux – the so-called *neutron noise* – may also be used for core monitoring [2]. Neutron noise is formally defined as the instantaneous neutron flux at a given spatial point from which its mean value in time has been subtracted. The main advantage of using neutron noise is that such fluctuations are always present. They are the results of mostly turbulence (in the case of a Pressurised Water Reactor – PWR) and possibly coolant boiling (in the case of a Boiling Water Reactor). The evolution, during the fuel cycle, of the spatial signature of the neutron noise and its spectral content is thus of high diagnostic value, as the monitoring of the neutron noise may help in the early identification of conditions possibly leading to a reactor transient or malfunction. In general, core diagnostics using noise analysis can be seen as a set of hierarchical tasks. The first task is to detect the anomalies. The second task is to classify them, i.e., to determine the type of anomaly. Subsequently, and depending on the type of anomaly, further characterization is possible, such as locating the perturbation, determining the vibration pattern, if relevant, etc.

In the Horizon 2020 CORTEX project (which ran from September 1st, 2017, to August 31st, 2021 – https://cortex-h2020.eu/), advanced reactor modeling tools were combined with Artificial Intelligence/machine learning techniques for detecting, characterizing, and potentially localizing anomalies [3]. As annotated measurement data, i.e., measurement data for which the anomaly is known, do not exist, another approach was followed in CORTEX, as presented in Figure 1. The training and validation data sets were provided by simulations. By postulating a neutron noise source, the induced neutron noise can be calculated accordingly, assuming that the necessary modeling tools are available. The training and validation data sets can thus be built by varying the type of noise sources and their characteristics.

The method was demonstrated to be efficient for identifying anomalies in commercial nuclear reactors – see, e.g., [4–6]. Machine learning-based unfolding can thus correctly identify and classify different types of perturbations and, when relevant, successfully localize such fluctuations.

Although the entire core monitoring methodology highlighted above is based on simulations, measurement plant data, and processing, all combined in dedicated machine learning architectures specifically developed for neutron noise-based core monitoring, emphasis is put in the following of this paper on the simulation tools only.

2.2 McSAFER

The High-performance advanced methods and experimental investigations for the safety evaluation of generic Small Modular Reactors (McSAFER) project is a research and innovation project funded by the Horizon 2020 research program of the European Commission (www.mcsafer-h2020.eu). McSAFER started in September 2020 and will last until August 2023. Thirteen partners from nine countries form the consortium. The main objective of McSAFER is, first of all, to provide new experimental data gained in three different facilities (at KIT, KTH, and LUT) under conditions relevant to light water-cooled Small Modular Reactor (SMR)-concepts. Moreover, the purpose of the project is to compare different safety analysis methodologies (industry-like standard methods, advanced and high-fidelity numerical tools) to analyze the behavior of the core, the Reactor Pressure Vessel (RPV), and the integral plant under selected transient conditions [7]. The safety evaluations focus on four SMR concepts: the French F-SMR, the Argentinian CAREM design, the US NuScale design, and the Korean SMART reactor. The advanced numerical tools selected for the safety investigations are based on multi-scale (RPV and plant) and multi-physics (core) methods. Beyond the involvement of industry (PEL, JACOBS, TRACTEBEL) and research centers (VTT, CEA, HZDR, UJV, CNEA), universities (KIT, KTH, LUT, UPM) are also engaged.

The McSAFER project is structured around six Work Packages (WP) – WP2 (Experimental investigations and validation), WP3 (Multi-physics core analysis), WP4 (Multiscale RPV-analysis), and WP5 (Multi-scale and physics plant analysis). WP6 is devoted to dissemination, exploitation, and communication, and the last one is devoted to project management (WP1).

2.3 METIS

Methods and Tools Innovation for Seismic Safety Assessments (METIS `https://metis-h2020.eu/`) started in September 2020 under the EURATOM Horizon 2020 program and is running until 2024. It addresses the three ingredients of seismic safety assessment in an overall approach: seismic hazard, structural and equipment fragility analyses, and integration in the full Probabilistic Safety Assessment (PSA) framework to determine plant failure probabilities. In nuclear and non-nuclear engineering, the general concepts of seismic risk assessment are due to the pioneering work of Cornell and co-workers [9]. The overall framework for probabilistic safety assessment is well established, but the partitioning into disciplines prevents the integration of common approaches, for example, uncertainty propagation. It is proposed to work in a multidisciplinary framework based on advanced methodologies that will be jointly applied to different parts of safety assessment. Moreover, in the last decades, there have been notable advancements in the development of the Performance-Based Earthquake Engineering (PBEE) approach [8,10]. The PBEE is now entering international civil engineering design codes such as FEMA 2012, ASCE/SEI in the USA but has not yet fully impacted nuclear engineering practice and codes. On the other hand, there have been significant advances in nuclear engineering regarding modeling and tools for dynamic structural and mechanical analyses. METIS follows these paths and further develops methods to improve the predictability of (non-linear, best-estimate) beyond design analyses required to consider Design extension earthquakes. The project further develops the use of databases, numerical simulations, and machine learning to improve the fidelity and accuracy of the engineering models and to comfort, confront and update expert judgment by Bayesian approaches. The developed methodologies will allow for a more objective assessment of safety margins and failure probabilities, thus improving the plant safety analyses.

3 Key objectives in modeling needs

3.1 Introduction

As highlighted above, CORTEX, McSAFER, and METIS heavily rely on simulations. Despite the complexity of the systems being considered, it is important to develop simulation tools adapted to the target situations being investigated. Although state-of-the-art high-fidelity simulations capable of handling all types of scenarios might be desirable, the associated computing time is, in some cases, unnecessarily prohibitive.

In addition to developing such "high-order" solvers, "low-order" solvers, i.e., solvers resolving the dominating physics in simplified terms while giving meaningful results, might represent in some situations a reasonable alternative. Low-order solvers also have the advantage of much cheaper computing costs compared to their high-order counterparts.

3.2 CORTEX

Various modeling approaches were followed in CORTEX. At the frequencies of interest, the effect of the thermal-hydraulic feedback is negligible, and thus the modeling of neutron transport solely is sufficient. In this respect, existing low-order computational capabilities were consolidated and extended. Simultaneously, new and advanced solution methods were developed. In essence, the different approaches are the result of simulation choices and paradigms that can be summarized as follows:

- the calculations can be performed in the time or frequency domain. The time domain requires a sufficiently small time discretization to be able to capture phenomena at typical frequencies of 0.1–20 Hz. The frequency domain, on the other hand, directly considers the frequency of interest. Whereas time-domain codes can easily handle non-linear terms and possible thermal-hydraulic feedback, the modeling in the frequency domain is often limited to linear terms only.
- The calculations can be performed using deterministic or probabilistic methods (i.e., Monte Carlo). Whereas deterministic approaches have a much lower computing cost as compared to Monte Carlo, Monte Carlo approaches do not need to rely on a discretization of the multi-dimensional phase space.
- For deterministic methods, as they rely on discretization, several levels of refinement are possible:
  - for the angular variable, from coarse (i.e., diffusion) to fine (i.e., transport) discretization.
  - For the spatial variable, from coarse (i.e., fuel assembly) to fine (i.e., fuel pin) discretization.
  - For the energy variable, from coarse (i.e., two energy groups) to fine (i.e., several tens of energy groups).

Different tools were used and/or developed in CORTEX depending on a combination of the various alternatives listed above. As those tools use macroscopic cross-sections as input data, a model representing the noise source in terms of perturbations of macroscopic cross-sections needed to be developed for each noise source type, irrespective of whether the solver used for estimating the induced neutron noise is deterministic or probabilistic. The modeling of the noise source is equally important as the modeling of the corresponding induced neutron noise. While expert opinion was, in most cases, used for expressing the effect of physical perturbations in terms of nuclear macroscopic cross-sections, the application of structural mechanics models was demonstrated to be of great help – see, e.g., [11].

3.3 McSAFER

The overall goal of the McSAFER project is to validate and apply advanced numerical tools for safety analysis of water-cooled SMRs taking into account the national regulatory guidelines for the deployment of SMRs in Europe, as well as to generate unique thermal-hydraulic data for the validation of thermal-hydraulic codes to be used for the safety demonstration. Specific goals of the McSAFER project are:

- the development and improvement of multi-physics and multi-scale numerical simulation tools.
- The generation of key experimental data at three facilities, e.g., COSMOS-H, MOTEL, and HWAT, relevant for water-cooled SMRs.
- The demonstration of the advantages of the use of high-fidelity codes for safety demonstration and the complementarity of low-order and high-order solvers.
- The reduction of the degree of conservatism in safety margins.

3.3.1 Multi-physics core analysis tools

Improved reactor physics, thermal-hydraulics, and thermo-mechanics coupled tools are used in addition to industry codes for analyzing four different SMR-cores under nominal and accidental conditions (Rod Ejection Accident – REA, cold water injection). The goal is to demonstrate the complementarity of multi-physic high-fidelity methods with traditional ones. Hence, the following methods are considered:

- the development of advanced deterministic solvers (SP3-pin-by-pin/subchannel) to improve core analysis, achieving higher prediction accuracy, i.e., at the pin level compared to the traditional lower-fidelity codes.
- The demonstration of the need for high-fidelity novel multi-physics and multi-scale codes to improve the traditional low-fidelity codes and methods in use by the industry and regulators for routine simulations.
- The verification of the appropriateness of the high-fidelity multi-physics solutions based on Monte Carlo methods as the reference solution for reduced-order solutions, especially in cases where no experimental data are available.
- The extension of core analysis tools for simulating an SMR core loaded with Accident Tolerant Fuel (ATF).

3.3.2 Multi-scale Reactor Pressure Vessel (RPV) analysis method

Improvement of the simulation of three-dimensional thermal-hydraulic phenomena inside the RPV of integrated SMR designs is achieved by applying multi-scale thermal-hydraulic tools (CFD, sub-channel TH, and system TH) in addition to the traditional ones. Therefore, the spatial resolution of the computational domains is increased to achieve a higher prediction accuracy than traditional one-dimensional coarse mesh codes. The Design Basis Accident (DBA) sequence selected for NuScale is a boron dilution event, and for SMART, an Anticipated Transient Without Scram (ATWS).

3.3.3 Multi-scale/multi-physics plant analysis method

The multi-scale/multi-physics plant analysis is oriented towards the application of the improved and validated numerical tools to the analysis of selected accidents in SMR plants, e.g., SMART and NuScale, and comparing the results with the ones of the traditional methods. The selected accident scenario for NuScale and SMART is a Main Steam Line Break (MSLB). A comparison of the different safety analysis approaches will be performed and discussed.

The thermal-hydraulic models developed in WP4 are extended to include the relevant safety systems of the SMART and NuScale SMRs that are necessary for the simulation of the Steam Line Break (SLB) scenarios. For this purpose, plant data, including the one for the involved control and safety systems and reactor control and protection system of each design (setpoints), were collected in the databases.

3.4 METIS

One major technical objective of the METIS project is to develop, improve, and disseminate open-source tools for seismic hazard, fragility, and risk assessment.

Open-source tools for Probabilistic Seismic Hazard Assessment (PSHA) and structural analyses are getting more and more commonly used both by the scientific and engineering communities and allow for numerous collaborations. None of the PSA tools currently used in the industry are open-source though this would help to improve quality and simplify the exchange of methods and data. One of the high-level objectives of METIS is the development and dissemination of an open-source tool for PSA computations.

The open-source tools identified for METIS are summarized in Figure 2. Openquake [12], code_aster [13] and OpenSees are already largely used for engineering and research. New studies cases will be created, and the codes will be further developed to fully support METIS methodologies. Moreover, METIS will create a new PSA tool based on the existing SCRAM open-source code.

The project then relies on numerical “best-estimate” simulations accompanied by uncertainty quantification and propagation to improve the fidelity and accuracy of seismic response and reliability analysis.

OQ OPENQUAKE calculate share explore	code_aster	salome_meca EXPERIENCE OPEN SIMULATION	OpenSees	SCRAM
PSHA code	General purpose FEM code available with salome_meca platform	Simulation platform including pre and post processing (geometry, mesh, analyses, visualization)	FEM tool dedicated to earthquake engineering	PSA code

Fig. 2. Existing open-source codes used and developed by METIS.

In addition to simulation, METIS also takes advantage of growing databases and experience feedback for validation and to detect and eliminate bias or misfits in models. The developed methodologies will allow for a more objective assessment of safety margins and failure probabilities and, thus, an improvement in the plant safety analyses.

4 Key achievements

4.1 Introduction

In the area of simulations, the verification and validation of the modeling tools are essential [14–16].

Verification targets the demonstration of the proper numerical implementation of the governing equations corresponding to a chosen model. Typically, verification consists in comparing the results of the modeling software to reference analytical or semi-analytical solutions. To derive such reference solutions, the system to be modeled needs to be drastically simplified. Validation, however, relies on comparing the results of the modeling tool and experimental data. Validation also includes the comparison against any other verified and validated software, which may use other assumptions compared to the tool being validated. The corresponding modeling exercises are thus referred to as benchmarks.

Furthermore, estimating the effect of uncertainties on the modeling results has become increasingly important in recent years, as demonstrated in some international efforts, such as [17]. Uncertainty analysis aims at assessing the variability of the output of a modeling software due to the variability of the input parameters. Sensitivity analysis aims to estimate how sensitive the code output is to the variability of the input parameters. This allows identifying the input parameters having the largest effects on the code results. From this knowledge, efforts can be targeted at reducing the uncertainties of those input parameters so that the uncertainty of the code output can be significantly reduced.

4.2 CORTEX

In CORTEX, all newly developed algorithms were verified by comparing the results of code simulations to analytical or semi-analytical solutions – see, e.g., an illustrative example of a verification exercise in [18]. Moreover, an extensive program of validation of the tools was undertaken, based either on benchmarking exercises between codes or comparisons between simulations and experiments. Representative cases in each of the two categories are given below. A methodology to evaluate the uncertainties associated with the code inputs and the corresponding sensitivities was also developed.

4.2.1 Benchmarking activities

In terms of benchmarking, different exercises were developed. An example is reported in Figure 3 [19]. In this exercise, a fuel assembly in an infinite lattice was considered, and the properties of a fuel pin were assumed to oscillate around a mean nominal value at a frequency of 1 Hz. The figure represents the amplitude and phase of the Fourier transform of the neutron noise calculated by the various codes along the main diagonal of the fuel assembly crossing the perturbed fuel pin. As Figure 3 demonstrates, all codes provide similar answers.

4.2.2 Comparisons between simulations and experiments

Beyond the successful comparisons of the various codes, a great effort in CORTEX was dedicated to validating the codes against neutron noise measurements carried out at the AKR-2 reactor at TUD, Dresden, Germany, and the CROCUS reactor at EPFL, Lausanne, Switzerland. Three experimental campaigns were undertaken at each facility [20]. The first experimental campaigns aimed to give a first fingerprinting of the neutron noise and resolve the issues for the following campaigns. The second experimental campaign targeted general improvements, better estimates, uncertainty reduction, and better coverage of the spatial distribution of the noise for CROCUS. The third experimental campaign had objective repeatability and enhanced spatial dependence of the induced neutron noise.

As illustrative examples, the summary of some of the comparisons between measurements and calculations is given in Figure 4 for AKR-2 and CROCUS, for a representative experiment of the second campaigns at each facility. As seen in those figures, the code predictions typically fall within the uncertainty band of the measured

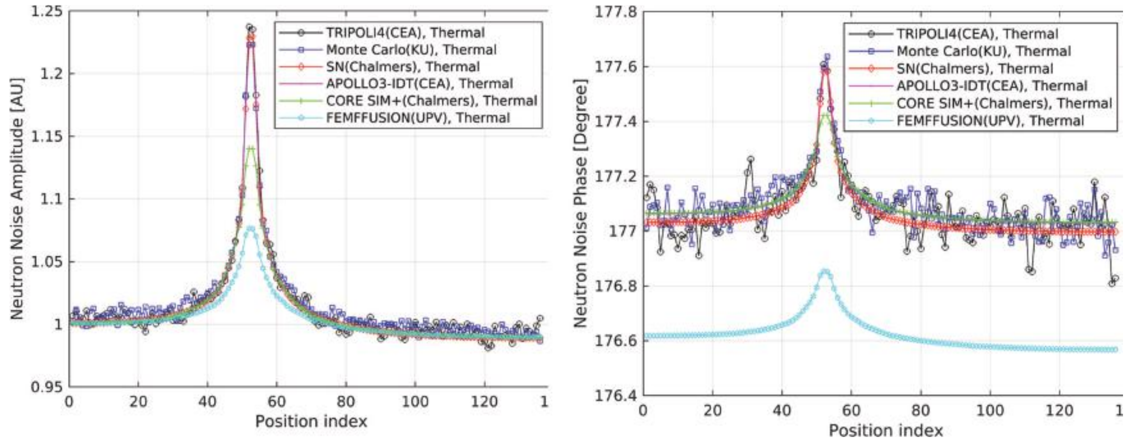

Fig. 3. Spatial variation of the amplitude (left) and phase (right) of the Fourier-transform of the thermal neutron noise induced by a vibrating fuel pin in an infinite fuel assembly lattice in one of the benchmark exercises. Figure derived from [19].

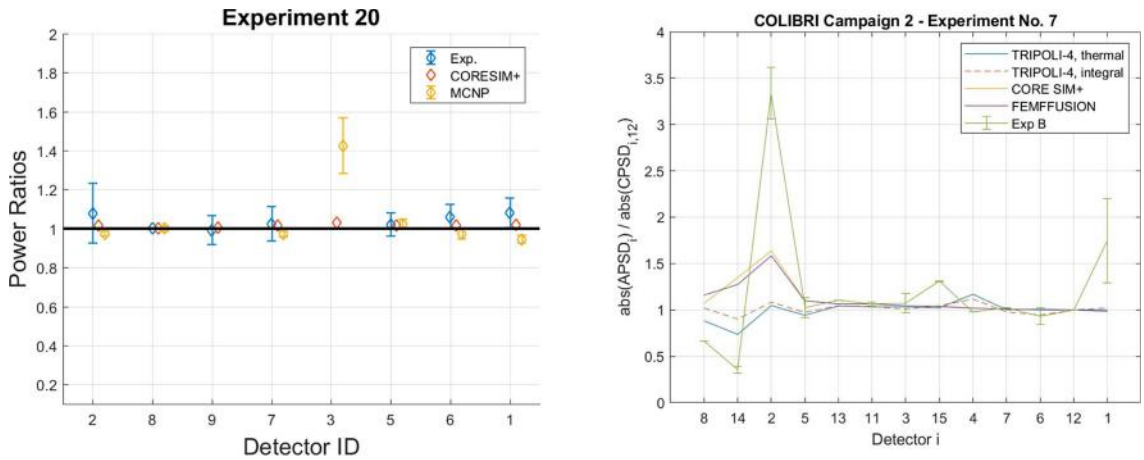

Fig. 4. Comparisons between the calculated and measured neutron noise (given with uncertainties) of the 2nd campaign at AKR-2, experiment #20 (left) and of the 2nd campaign at CROCUS, experiment #7 (right). The figures give the amplitude of the auto-power spectral density of the relative neutron noise (estimated in relation to a reference detector). Figure derived from [21].

values. The comparisons are given at the location of the detectors, ordered at increasing distances from the noise source. It can nevertheless be noticed that in the extreme vicinity of the noise sources, some larger discrepancies can be observed. At those locations, the diffusion-based and transport-based codes also give slightly different predictions, resulting from the difficulty for diffusion theory to properly reproduce steep flux gradients.

4.2.3 Assessment of uncertainties and sensitivity analysis

In CORTEX, a methodology for estimating the uncertainties associated with neutron noise calculations was also developed based on the GRS methodology [22]. In this approach, the input data are perturbed as random variables following their respective uncertainty distributions. By constructing samples of input parameters using Simple Random Sampling, the corresponding samples of output parameters can be computed by the code, from which the uncertainty of the code estimates can be assessed. This method is often referred to as a sampling-based approach.

The sensitivity of the code output to the input parameters can also be evaluated. In the present case, a variance-based approach was considered [23]. It was found that the sensitivity of the neutron noise on the input parameters greatly depends on the spatial distance between the computed neutron noise and the noise source. The closer one is to the noise source, the bigger the effect of the uncertainties on the noise source parameters is. Further away from the noise source, the sensitivity of the computed neutron noise to the uncertainties in the nuclear data becomes more significant [24].

4.3 McSAFER

4.3.1 Experimental investigations

The experimental program is progressing as expected at the MOTEL facility and with some delays at the other facilities (COSMOS-H and HWAT) due to technical and/or delivery issues in the supply chain. In general, the status of the tests can be summarized as follows:

- the commissioning, calibration, and instrumentation checking tests were successfully performed at the three facilities [25].
- The preparation of the first test series at HWAT and COSMOS-H is ongoing, with the following tests being planned:
  - at the HWAT facility: heat transfer for subcooled boiling and CHF, the study of the appropriateness of two critical components (heated riser and pool type condenser) for future transient tests [26].
  - At COSMOS-H: the first test plan consists of a single heated tube made of Zircalloy-4 arranged in an annular gap with an outer glass tube [27]. The heat transfer between the cladding and the coolant is measured for an increasing heat flux. It ranges from subcooled boiling up to critical heat flux conditions.
- The first test series at MOTEL was successfully performed and focused on the helical coil steam generator behavior, including primary/secondary heat transfer at different steady states with different core power levels [28].

Figure 5 shows the axial temperature distribution of the primary side steam generator measured at four different power levels during the MS SG02 test. The averaged axial temperature profiles of the four helical tube groups of the steam generators measured for different power levels are given in Figure 6.

The first results have shown that the MOTEL facility behaves as expected. These data are made available by LUT to the partners involved in code validation. As soon the data of COSMOS-H and HWAT are measured, they will be used to validate the codes by partners. The following MOTEL tests focus on the investigations of the core behavior, including cross-flow under non-symmetrical core conditions considering different axial power profiles.

4.3.2 Code validation program

Another important part of the work program is the validation of the thermal-hydraulic codes (Computational Fluid Dynamics – CFD, subchannel, and system thermal-hydraulic codes) with the experimental data generated within the consortium to increase the confidence in the numerical tools used for a safety demonstration. More precisely, the following activities are considered:

- the validation of CFD codes, e.g., CFX, FLUENT, OpenFOAM, TrioCFD, using the experimental data of COSMOS-H, MOTEL, and HWAT.
- The validation of subchannel thermal-hydraulic codes, e.g., CTF, Subchanflow, VIPRE, with the experimental data obtained from the proposed tests.
- The validation of system thermal-hydraulic codes, e.g., TRACE, RELAP-3D, APROS, using the generated test data.

4.3.3 Multi-physics core analysis

Different numerical simulation tools are applied to analyze the core behavior under rod ejection (NuScale, SMART) and cold water injection (CAREM, F-SMOR) transients. Nuclear data libraries for the different simulations are generated with lattice physics codes (deterministic and Monte Carlo), considering the geometrical and material data and operational conditions of the different SMR-cores. The analysis with coupled nodal diffusion codes of the mentioned transients is in an advanced stage, while the high-fidelity simulations are under preparation (SP3 transport and Monte Carlo). Details about the geometry/material of the cores can be found in [29] while the cross-section generation methods for the different solvers (diffusion:

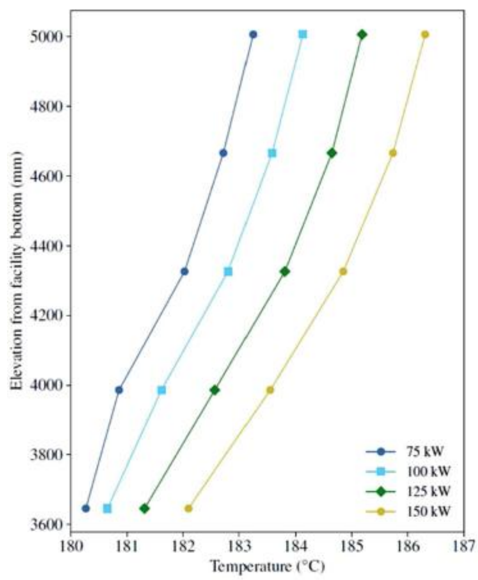

Fig. 5. Primary side steam generator axial temperature profiles with different core power levels during the MS-SG02 experiment.

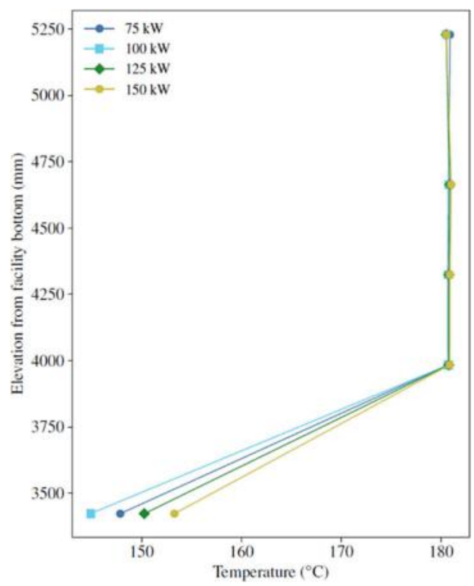

Fig. 6. Averaged axial temperature profiles of all steam generator tubes with different core power levels during the MS-SG02 experiment.

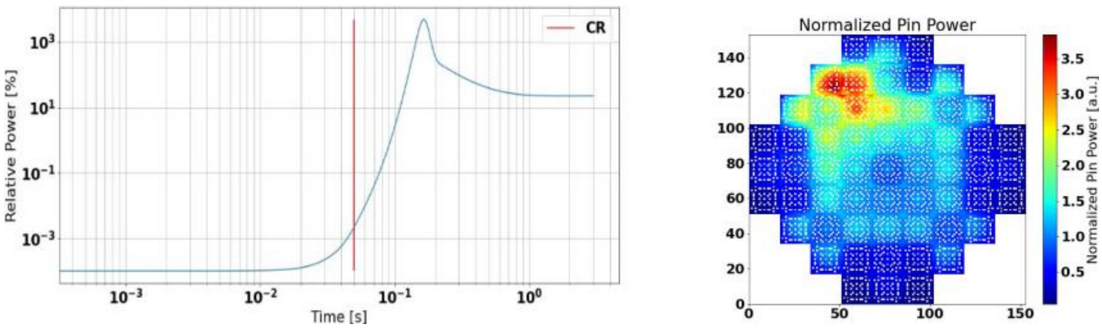

Fig. 7. PARCS/Subchanflow Relative power evolution (left) and radial power distribution (right) in the SMART-core during a REA.

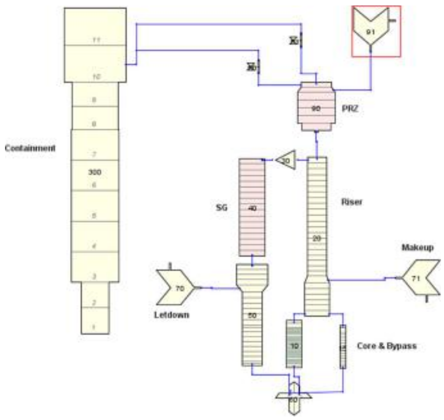

Fig. 8. SMART RPV one-dimensional model for TRACE developed by TRACTEBEL [34].

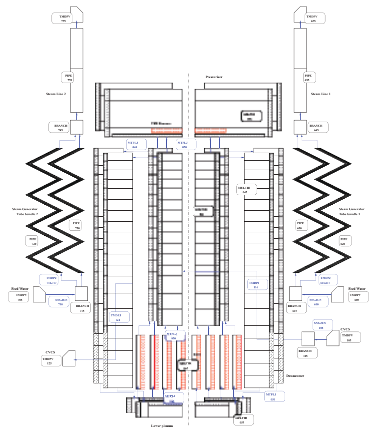

Fig. 9. NuScale RPV three-dimensional model for RELAP-3D developed by UJV [35].

DYN3D, PARCS, APOLLO3, SIMULATE S3K, ANTS, PUMA, PANTHER, transport: PARCS-SP3, APOLLO3, DYN3D-SP3) are described in [30].

In Figure 7, the relative power increase and the 3D radial power distribution predicted with PARCS/Subchanflow for the SMART core in the case of an REA scenario are shown [31]. There, the localized power release at each pin of the fuel assemblies around the position of the ejected control rod is clearly seen.

The methods for the generation of cross sections at pin level for the different low-order transport solvers are developed [31] and the respective REA analysis is at an advanced stage.

4.3.4 Multi-scale RPV and multi-physic/-scale plant analysis

Different coupled versions of thermal-hydraulic codes will be applied to evaluate the three-dimensional thermal-hydraulic phenomena inside the RPV and core of the NuScale and SMART reactors. In Figures 8 and 9, one-dimensional and three-dimensional models of the RPV of SMART and NuScale are shown, developed for TRACE and RELAP5, respectively [32,33].

In Figures 10 and 11, the different CFD models being developed for the SMART and NuScale SMRs and the analysis of the SLB with multi-scale/physic coupled codes are shown. An important step for multi-scale analysis of SMRs is the development of the thermal-hydraulic models of the whole plant and parts of it with different codes, which later on will be combined based on domain decomposition to analyze the plant behavior under accidental conditions.

4.4 METIS

4.4.1 Numerical simulation to allow for site-specific analyses

Seismic risk assessments require the analysis of structural response in order to evaluate the reliability of structures, systems, and components (SSCs). This includes accounting for the impact of local site conditions and soil-structure interaction analysis. This can be achieved simply through generic empirical models, however, these cannot accurately account for the particular conditions of a particular site.

The accurate evaluation of site effects requires the simulation of seismic wave propagation from the source to the site under study. Detailed site response analyses require costly numerical computations. The first task aims to develop simplified (1-D) models that can be used for conducting Soil–Structure Interaction (SSI) analyses. EDF has started working on a strategy to identify 1-D

Fig. 10. TrioCFD model of the downcomer and lower plenum of NuSCALE developed in [36].

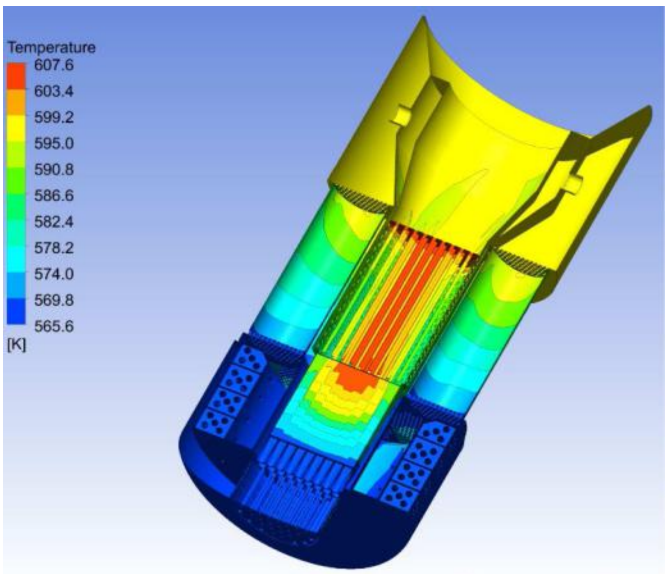

Fig. 11. CFD model of the integral SMART plant developed by KIT [37].

soil columns reflecting observed variability and realistic attenuation due to damping and wave scattering. However, because more complex configurations exist, such as the presence of a sedimentary basin, folded non-horizontal layering, or significant topography, it might be necessary to develop 2-D or 3-D numerical models. For this purpose, we are developing a probabilistic classification scheme to identify sites more likely to be affected by 2-D/3-D side effects, indicating that more complex ground-motion modeling is required. Realistic physics-based 3-D earthquake simulation for source-to-structure wave propagation consists of a powerful numerical tool for seismic response prediction of critical structures submitted to high safety standards [38]. Structural response considering SSI is usually estimated by the Finite Element Method (FEM) approach, as it is considered the most flexible numerical approach for non-linear structural dynamics. The Domain Reduction Method (DRM), which allows for considering a 3-D complex incident wave field as an input to the SSI model, is used here in a Spectral Element Method (SEM) – FEM weak coupling approach with code_aster (see [38] for more details). Moreover, a strategy to represent soil variability at a local scale has been developed. The soil variability is modeled by random fields; the approach is made feasible in a 3D context by HPC capabilities and by optimizing the random field generator by means of the selection of predominant eigenmodes in the Karhunen-Loève representation of the 2-D and 3-D random fields.

The resulting seismic load time histories are then used for the numerical computation of structural and component fragility curves, that is, the failure probability as a function of seismic load intensity.

4.4.2 Uncertainties

One of the main issues in seismic safety assessments is the problem of double counting uncertainties and the accumulation of conservative assumptions arising from the partitioning in disciplines when conducting the analysis from the source to the equipment – see, e.g., [39]. Collective brainstorming has allowed for the development of an integrated approach to account for uncertainty in site response and soil-structure interaction analysis.

4.4.3 Testing model performance by comparison to data and model updating

The work related to verifying and validating Probabilistic Seismic Hazard Assessment (PSHA) models and tools used to define seismic load has started. For this purpose, PSHA models from France and Germany have been implemented into the OpenQuake Engine format, which in conjunction with the 2020 European Seismic Hazard Model, will provide an important suite of complex PSHA models with large numbers of seismic sources and logic tree branches to account for epistemic model uncertainty from which to make comparisons against observations. For the test data, a database of strong and weak motion records has been compiled from the European Integrated Data Archive, and work is ongoing to assess the station quality, database completeness, and the feasibility of using weak motion data to complement the observed strong motions in Europe and to expand the number of sites that can be used for potential testing purposes. Work is underway to begin implementing the "testing, verification and updating toolkit" developed by the partner GFZ Potsdam, Germany.

5 Utilization and cross-fertilization

The CORTEX project had clear ambitions to develop an innovative core monitoring technique for industrial applications. The project required scientists from different disciplines to collaborate and understand each other's paradigms. Those disciplines were: reactor physics, reactor dynamics, reactor modeling, experimental reactor physics, measurement techniques, signal analysis, and artificial intelligence. The project resulted in the demonstration of the usefulness and application of the proposed technique to the industry. In addition to the technical achievements, the project established tight collaborations between the project partners, which extended beyond the project itself. Two project partners were from outside the European Union: an American partner and a Japanese partner. Those collaborations made the partners well equipped for tackling complex problems requiring a cross-disciplinary approach in the future. In order to remain aligned with the needs of the industry, the project made extensive use of its Advisory End-User Group, made of five utilities, two fuel/reactor manufacturers, one technical support organization, and one additional research organization. In the consortium, two consultancy companies servicing the industry were also present. Contacts were also initiated with other US projects using machine learning applied to nuclear engineering.

McSAFER ambitions are twofold: (a) to provide key-experimental data for safety-relevant phenomena of water-cooled SMR for the validation of CFD, subchannel, and system thermal-hydraulic codes and (b) to demonstrate the potentials of advanced and high-fidelity numerical simulation tools for the safety demonstration compared to the traditional codes used in current licensing processes. The wider application of multi-scale/multi-physics numerical tools will contribute to improving the prediction accuracy and reducing the conservatism embedded in current methods. The new generation of tools has large potential to be used not only in safety evaluations (by regulators, TSOs, etc.) but also in the nuclear industry to optimize the design of reactor systems towards higher operational flexibility and enhanced economics while keeping high-safety levels. Many stakeholders may profit from those "new generation" tools if sufficient validation is provided. Finally, yet importantly, the Monte Carlo-based multi-physics tools can provide reference solutions to any low-order simulation, especially for situations where experimental data is not easily available. In view of the powerful HPC cluster nowadays available to the research community at low cost or free of cost, the role of simulation-driven design and optimization, as well as safety evaluations, will greatly increase in the next years.

The open-source strategy adopted by METIS facilitates innovation, international collaborations, and knowledge transfer, and by this means, contributes to increasing the innovation capacity of the nuclear industry and consulting companies. By developing and validating modern state-of-the-art seismic risk assessment methods and open-source simulation tools, it is expected that METIS will contribute to developing new knowledge related to seismic PSA and facilitate innovation in European practice. METIS will influence several technical and scientific sectors, including seismology, seismic hazard analysis, and seismic risk assessment, with opportunities for cross-fertilization among different scientific sectors. The proposed open-source tools help advance the state-of-the-art while at the same time lowering the barrier of entry for aspiring researchers.

6 Conclusions and future recommendations

In CORTEX, it was demonstrated that, for large PWRs, machine learning-based unfolding of the measured neutron noise could correctly identify different types of perturbations and, when relevant, successfully localize such fluctuations. In terms of localization of the noise source, the method can predict the actual location of the perturbation with a mean absolute error below the radial size of one single fuel assembly [40]. Considering the complexity of a nuclear reactor core, its large size (about 4 m in height and radial diameter), and the limited core instrumentation, these results are truly remarkable. To develop an industrial demonstrator, the core monitoring methodology needs to be further refined, improved and tested so that its robustness in industrial setups can be guaranteed. Moreover, following the European Commission Coordinated Plan on Artificial Intelligence 2021 Review [41], the machine/deep learning methods should be transparent, trustworthy, and accountable so that the analysts and users of the methods can better understand the estimates provided by such techniques. Finally, the core monitoring technique should be user-friendly and easy to use so that it can be utilized by analysts and nuclear engineers without any intervention from machine learning or nuclear reactor modeling experts.

At the current stage of advancement of McSAFER, it can be stated that the project is developing as scheduled in the work program. Despite minor delays in delivering some devices for one experimental facility, the test program has started. The development of the models of the core for the four SMR designs is done, and a large part of the analysis is close to being finalized. For the multi-scale analysis of the RPV behavior during the ATWS (SMART) and boron dilution (NuScale) transients, work has been started with the different simulation roots. Finally, the optimization and development of the multi-scale coupling of different thermal-hydraulic codes are near their end. The coupling approaches are being tested with the combination of different TH-modelling approaches for the SMR plants (SMART, NuScale). First, results are produced and evaluated. At the end of the project, a systematic comparison of the different simulation methodologies applied to various SMR designs will be performed, and important conclusions and recommendations to the end-users will be proposed and given.

The METIS project is developing as scheduled with a short delay due to difficulties in the selection and obtaining of data for the METIS case study. The upcoming milestones related to the above-discussed topics are:

- methodology and tools to compute fragility curves (report and code developments + documentation).

- Improved and new tools to compute PSHA with aftershocks and vector-valued seismic intensity measures in Openquake (code and documentation available on github and Openquake website).
- New seismic ground motion simulation tools (codes & documentation).
- METIS Andromeda-SCRAM PSA tool available (report and PSA tool developments with documentation).

All three projects have/had activities dedicated to training, education, and dissemination. Those typically included courses/workshops, publications in open-access journals or conference proceedings, many public deliverables, presentations at conferences/workshops/meetings, the involvement of young scientists in the project, and networking activities with other international projects/initiatives. In addition, various communications channels were developed (websites, social media, newsletters, and popular science presentations/videos).

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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

C. Demazière, V.H. Sanchez-Espinoza and I. Zentner wrote and reviewed the manuscript.

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REVIEW ARTICLE

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Innovation and qualification of LEU research reactor fuels and materials

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Abstract. Two projects within the Euratom Research and Training Programmes 2014–2018 and 2019–2020 are focused on the innovation and qualification of novel nuclear fuels for conversion from highly-enriched uranium to low-enriched uranium (LEU) and for securing the supply chain of EU research reactors into the future. The LEU-FOREvER project is drawing to a close and has made significant progress in developing and demonstrating the uranium-molybdenum fuel system, demonstrating the viability of a high-density uranium-silicide fuel for EU high-performance research reactors (BR2, RHF, FRM-II, JHR). This project has significantly increased the fabrication know-how and fuel performance understanding of the uranium-molybdenum and high-density uranium-silicide dispersion fuel systems. Further, a new, innovative and increased performance design for the LVR-15 research reactor fuel assembly has been engineered and a demonstration is planned in 2022. In the EU-QUALIFY project, which began in 2020, the planning of four demonstration irradiation tests has been nearly completed and fabrication development of the various fuel systems is ongoing, including the establishment of an EU monolithic uranium-molybdenum fabrication capability. It is expected that the results of this project will begin or complete the data gathering necessary for generic fuel qualification of the LEU uranium-molybdenum dispersion and monolithic fuel systems, and the LEU high-density uranium-silicide fuel system.

1 Introduction

Two projects targeting innovation and qualification of LEU research reactor fuels and materials are currently being executed within the Euratom Research and Training Programmes, i.e. the "Low Enriched Uranium Fuels fOR REsEarch Reactors" (LEU-FOREvER) [1,2] and the "EUropean QUALIFication approach for low enriched fuel sYstems for secure production supply of medical isotopes" (EU-QUALIFY) [3]. These projects are complimentary and overlapping (started 3 years apart in 2017 and 2020) and they follow a general framework for fuel qualification planned by the HERACLES consortium to support the worldwide non-proliferation efforts. The HERACLES consortium is comprised of 4 research institutions with respective high performance research reactors: Commissariat á l'énergie atomique et aux énergies alternatives (CEA in France), Institut Laue-Langevin (ILL; France), Technische Universität München (TUM; Germany), SCK CEN (Belgium), and the EU research reactor fuel fabricator Framatome (CERCA; France). The two projects presented herein are consecutive initiatives of HERACLES to further develop research reactor fuels to enable conversion from highly-enriched uranium (HEU) to low-enriched uranium (LEU) specifically for high-performance research reactors (HPRR), for which the physical form and/or demonstrated fuel performance behavior of the classical LEU (4.8 gU/cc) silicide fuel is insufficient for direct use or application. The main route of accomplishing this, e.g. for the European HPRRs given in Table 1, is to increase the uranium loading over the aforementioned 4.8 gU/cc through various means and to demonstrate the behavior of these novels fuels at high-performance conditions through irradiation testing and post-irradiation examinations. Other prime objectives include ensuring the fabrication capabilities are established and qualified, and that all fabrication, irradiation, and PIE data are collected and usable for fuel performance modeling to support LEU qualification and conversion reports. These activities naturally combine to secure the European supply chain of both research reactor services and the global supply of medical isotopes into the foreseeable future. The structure of the HERACLES consortium program with completed, ongoing, and planned irradiation campaigns is shown in Figure 1 and a simplified fabrication route description of the here studied fuel systems is shown in Figure 2.

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Table 1. European HPRRs, operators, and their target fuel system(s) for conversion.

Reactor (primary type)	Operator/Organization	Current fuel system(s) targeted for potential conversion
BR2 – Belgian Reactor 2 (material test reactor)	SCK CEN Mol, Belgium	U_3Si_2 / UMo dispersion
FRM-II – Forschungs-Neutronenquelle Heinz Maier-Leibnitz (neutron source, beam-tube reactor)	Technische Universität München (TUM) Garching bei München, Germany	UMo monolithic
RHF – Réacteur a Haut Flux (neutron source, beam-tube reactor)	Institut Laue-Langevin (ILL) Grenoble, France	U_3Si_2 / UMo dispersion
JHR – Jules Horowitz Reactor (material test reactor) *Note*: Under construction	Commissariat à l'Energie Atomique (CEA) Cadarache, France	U_3Si_2 / UMo dispersion / UMomonolithic[1]

[1]The driver fuel for the first years of nominal operations of JHR will not be High Assay LEU (HALEU; <20 % U-235 enrichment). For the JHR reference fuel after this period, CEA is deeply involved in the international collaborations aiming to develop and qualify the various HALEU fuels, in particular within the HERACLES consortium (high loaded U_3Si_2, UMo dispersion and monolithic fuels) [38,39].

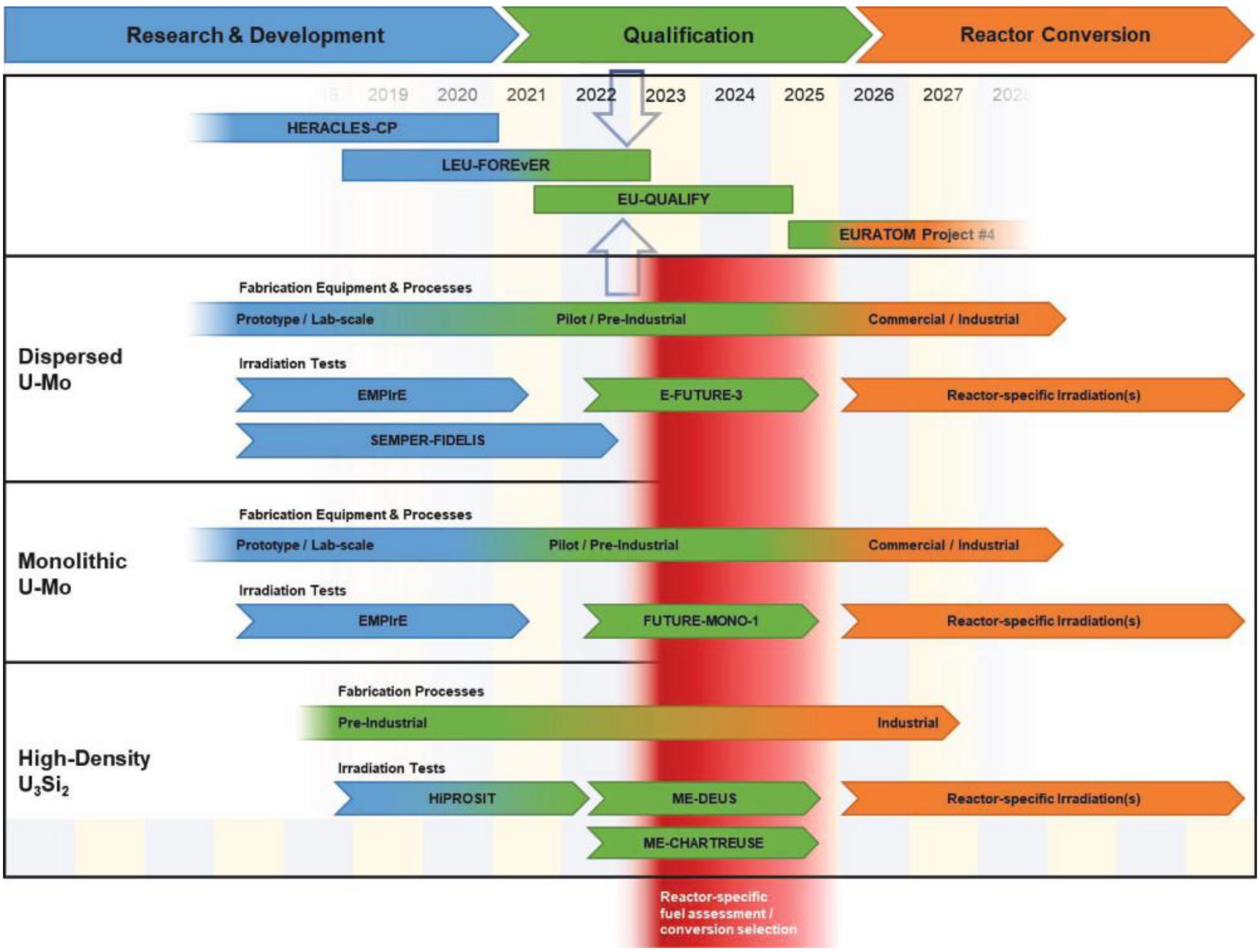


Fig. 1. The HERACLES consortium program with planned irradiation campaigns for advanced research reactor fuels. The LEU-FOREvER and EU-QUALIFY projects are indicated with arrows.

2 Fuel loading and systems

The research reactor (RR) fuel systems that the HERACLES consortia are developing and qualifying have differences in the uranium loading that makes them interesting for different reactor-specific conversion projects. Many LEU conversions are constrained by limited or no geometrical/dimensional changes of the fuel plates and assemblies. In many cases, this leads to the uranium loading being the limiting factor in the choice of a suitable fuel system for the RR conversion. Also, HEU to LEU conversion necessitates countering the neutronic penalty of U-238 to fulfill the reactor-specific fuel performance requirements such as cycle length and the neutron flux.

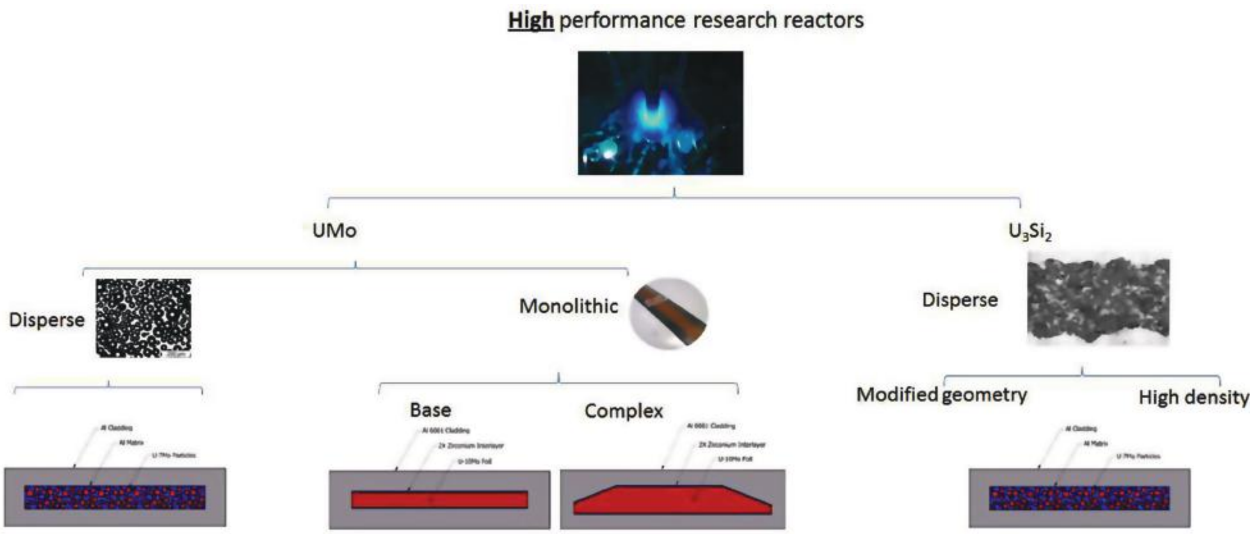


Fig. 2. Fuel system fabrication routes studied in LEU-FOREvER and EU-QUALIFY.

Naturally, the reactor design itself will limit the available meat dimensions, e.g. the maximum fuel zone thickness, obtainable without affecting safety parameters in the existing fuel core design. A higher loading or density increases the flexibility to find a suitable design option (e.g. increasing total uranium in the same volume/fuel core thickness) and can accommodate a larger range in suitable meat thicknesses (in relation to the classical 4.8 gU/cc U_3Si_2) [4,5] with the same surface loading or gain in surface loading at a constant meat thickness. It should be noted that many factors interplay in the selection of a suitable reactor-specific conversion alternative. The following paragraphs outline the three (3) key fuel systems being pursued for qualification.

2.1 High-loaded U_3Si_2 dispersion fuel

The experience and fabrication status of the LEU 4.8 gU/cc loading U_3Si_2 fuel system is explained in greater detail in [4] and this fuel is widely used in research reactors throughout the world. This fuel type is a roll-bonded dispersion fuel core, with U_3Si_2 fuel dispersed in a pure aluminium matrix. The silicide fuel at 4.8 gU/cc loading is fully qualified and this fuel has been manufactured by Framatome since the1980s, with a well-established manufacturing process, thus with high manufacturing and technology readiness level. However, the U_3Si_2 high-loaded or high-density (HD) fuel development, e.g. 5.3 $\rightarrow$ 5.6 gU/cc at higher power conditions, for specific RR needs revision regarding quality criteria, optimized fabrication processes, and actions for reducing cost and fabrication time in order to increase the security of supply of suitable LEU fuel for the low and medium power research reactors [5–7,32,33].

2.2 UMo dispersion fuel

The UMo-based fuel systems have a rather high intrinsic density of about 16 gU/cc in UMo. When used in the typical aluminium matrix dispersion fuel, with a fabrication-based limit of about 50 volume percent, the achievable fuel meat loading is ~8 gU/cc in the fuel meat. The UMo dispersion fuel behavior has been studied in the irradiation experiments such as FUTURE, IRIS, E-FUTURE, and SELENIUM, [8–12], and most recently in the LEU-FOREvER project irradiation named: SEMPER FIDELIS [13,14] (all irradiated in BR2). The current state-of-the-art development is targeting the reduction of the detrimental swelling of UMo-Al fuel plates at high power and high burnup by heat treatment, ZrN PVD coating of the UMo particles [15], and adding a small amount of silicon in the matrix. Further development will continue in the EU-QUALIFY project, through the execution of the E-FUTURE-III experiment, planned for irradiation in BR2.

2.3 UMo monolithic fuel

The UMo monolithic fuel is currently the fuel system that is closest to producing fission densities for HEU to LEU conversion of the very high-power research reactors, e.g., FRM-II and the ATR reactor in the US. The U.S. Department of Energy's United States High-Performance Research Reactor (USHPRR) Conversion Project has investigated low-enriched uranium (LEU) since 1978 as an alternative to highly enriched uranium. Due to the high loading and good fabrication performance, U-10Mo was chosen as the most promising LEU fuel for the conversion of all USHPRRs [9,18–20,23–27].

The fabrication of the UMo monolithic fuel with a U loading of ~16 gU/cc is significantly different from the dispersion UMo and silicide fuel systems [21]. Monolithic fuel foils are a solid alloy clad in aluminium [22]. The USHPRR fabrication process of the monolithic fuel foil and plate requires multiple complex thermo-mechanical processes including casting, homogenization, hot/cold rolling, annealing, and hot isostatic pressing.

This fuel pate type has the highest possible uranium density of all current state-of-the-art options. The monolithic plate bonding method developed at CERCA, i.e. C2TWP [16] will be further developed to encompass full-size plates. The development of the EU process and capability was first demonstrated in the "European Mini-Plate Irradiation Experiment" (EMPIrE) which was irradiated in the ATR and evaluated in the LEU-FOREvER project and will continue in the EU-QUALIFY project, in the form of the FUTURE-MONO-1 experiment (planned for irradiation in BR2).

3 Fuel performance development and qualification

Fuel development and qualification projects for research reactor fuel have been conducted in the EU and abroad for many decades. These projects have had a similar process including:

- identification of suitable candidate fuel(s).
  - Typically through preliminary/simple neutronic and fabrication studies.
  - Typically through optimizations/improvements to existing fuel systems.
- Fabrication development and demonstration.
- Irradiation testing.
- Post-irradiation examinations (PIE).

Depending on the complexity of the change, fuel development is normally a feedback loop, where information obtained from the various development steps is normally fed back to the beginning to continue to optimize the fuel design until a suitable fuel can be demonstrated to be:

(1) acceptable for meeting reactor-specific fuel performance requirements,
(2) stable, predictable, and safe (including at reactor-specific safety requirements),
(3) affordable, such that the reactor can sustainably obtain and dispose of the fuel.

The transition from development to qualification is often marked by the irradiation and examination of various fuel plates that are similar or identical after the design has been chosen. This may also be followed by irradiation in fuel assemblies with multiple fuel plates. The typical progression of an MTR experiment to build upon the previous knowledge or experience to reduce the likelihood of an unintended event during irradiation (e.g. fission product release) includes the following steps:

- Step 1: identify/document previous relevant fuel performance or perform a mini-test
  - Document existing fuel performance from relevant development, qualification, or reactor operation
  - Perform an irradiation test with mini plates
- Step 2: perform an initial full-size fuel plate irradiation at moderate fuel performance conditions
  - Moderate heat flux: 250–350 W/cm^2
  - Moderate U-235 burnup: 40–50% U-235 burnup
- Step 3: perform a fuel plate irradiation (e.g. FUTURE device) at high-performance conditions
  - High heat flux: 400–500 W/cm^2
  - High U-235 burnup: 65–80% U-235 burnup
- Step 4: perform a fuel assembly irradiation at typical performance conditions
  - Typical conditions for the specific reactor.

Irradiation testing and subsequent PIE can have significant costs and time durations. It is, therefore, necessary to adequately plan these projects based on existing data, previous experience, and expert judgment. Two international expert groups have been established within the framework of the HERACLES group to enable this review and planning: the Fuel Development Expert Group (FDEG) and the Fuel Manufacturing Expert Group (FMEG). The FDEG provides expert opinions and recommendations on fuel performance-related issues and potential design changes, while the FMEG provides this type of information on fabrication processes and equipment. They work together to identify fuel design improvements (e.g. materials, composition, fabrication processes, and equipment) in the feedback loop of development and qualification. The FDEG group also leads the establishment of fuel performance databases and fuel qualification reports.

3.1 Irradiation testing

Irradiation testing includes extensive neutronics calculations to ensure the appropriate experiment conditions are obtained and verified. At SCK CEN, the MCNP software, which utilizes Monte Carlo methods to estimate the particle interactions during an irradiation cycle is used for pre-and post-irradiation calculations. The pre-irradiation neutronics is based on an *assumed BR2 reactor core* and the post-neutronics on the *actual BR2 reactor core* and BR2 power and control rod histories. The neutronic calculations are conducted to evaluate essential exposure statistics, usually determined at beginning of cycle (BOC), 3 days into the irradiation (3D), and at the end of cycle (EOC). The main parameters estimated and verified are:

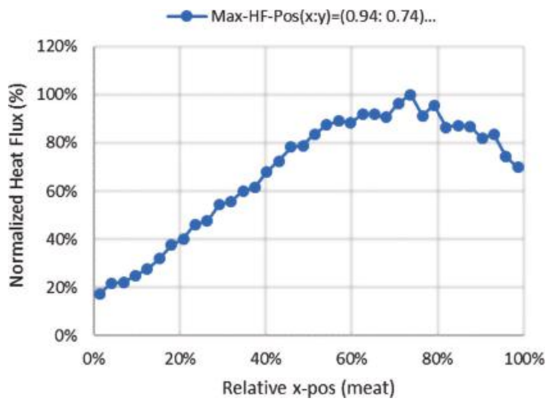
- peak and average heat flux (W/cm^2), "target" values with the pre-irradiation neutronics, and 'acquired' results with the post-irradiation neutronic calculations over the plate "meat" section.
- Peak and average U-235 burnup (%), target and acquired.
- Peak and average Fission distribution (e.g. fissions/cc meat), target and acquired.

An example of a heat flux distribution, here normalized by the maximum for visualization purposes, is shown in Figure 3 with a typical FUTURE plate calculation mesh.

3.2 Post-irradiation examinations

Post-irradiation examinations are conducted in two phases: non-destructive exams (NDE) and destructive

X-Z (cm)		← -2.15		TOP of plate (ID or UNID side depending on rotation, c						+2.15 →
		1	2	3	4	5	6	7	8	9
↑ +37.17	1	12%	13%	15%	14%	13%	15%	16%	16%	17%
	2	17%	16%	16%	17%	16%	18%	16%	17%	22%
	3	19%	18%	20%	17%	19%	19%	20%	21%	22%
	4	21%	21%	23%	20%	22%	22%	23%	24%	25%
	5	24%	25%	23%	24%	26%	26%	26%	26%	28%
	6	27%	27%	24%	27%	28%	29%	30%	29%	32%
	7	32%	27%	31%	30%	33%	33%	30%	36%	38%
	8	37%	35%	35%	37%	38%	38%	34%	37%	40%
	9	37%	38%	39%	37%	38%	40%	39%	40%	46%
	10	44%	44%	44%	41%	44%	44%	46%	47%	48%
	11	51%	44%	47%	48%	47%	46%	48%	52%	54%
	12	55%	53%	49%	50%	53%	51%	52%	52%	56%
	13	58%	58%	57%	59%	58%	57%	57%	60%	60%
	14	65%	62%	60%	61%	63%	62%	63%	61%	61%
	15	72%	68%	63%	66%	62%	61%	66%	66%	68%
	16	74%	69%	69%	69%	68%	70%	69%	70%	72%
	17	78%	75%	73%	71%	69%	71%	69%	76%	78%
	18	84%	75%	76%	72%	71%	72%	73%	74%	79%
	19	87%	84%	79%	78%	79%	77%	76%	76%	84%
	20	92%	84%	83%	81%	81%	81%	81%	83%	87%
	21	96%	88%	86%	81%	85%	80%	80%	82%	89%
	22	97%	87%	89%	86%	87%	83%	81%	87%	88%
	23	94%	91%	90%	87%	83%	86%	86%	89%	92%
	24	96%	92%	90%	84%	87%	87%	90%	88%	92%
	25	96%	95%	85%	84%	86%	87%	89%	91%	91%
	26	96%	93%	91%	86%	88%	88%	88%	90%	96%
	27	98%	94%	91%	90%	85%	86%	90%	88%	100%
	28	96%	92%	90%	86%	80%	85%	81%	87%	91%
	29	96%	88%	88%	86%	88%	82%	84%	88%	96%
	30	94%	87%	86%	86%	86%	83%	81%	89%	86%
	31	92%	85%	84%	80%	82%	83%	86%	84%	87%
	32	90%	87%	81%	79%	80%	79%	80%	83%	87%
	33	87%	84%	81%	80%	78%	78%	77%	79%	82%
	34	82%	79%	74%	75%	68%	71%	73%	75%	84%
	35	76%	74%	74%	69%	69%	70%	68%	71%	74%
↓ -37.17	36	76%	70%	69%	68%	68%	68%	67%	69%	70%



A

B

Fig. 3. (A) Example of calculated BR2 heat flux distribution at BOC (normalized, full plate) and (B) length distribution at the maximum location.

A

B

Fig. 4. (A) FUTURE-5 basket with plates, (B) fuel plates in the in-pile section (IPS) [5].

exams (DE). The NDE is performed to identify any abnormal conditions on the outside of the irradiated fuel plate, quantify the fuel swelling, and verify post-irradiation neutronics analysis results. The exams may include:

- when the BR2 FUTURE-5 basket is used, inter-cycle observations can be performed where both sides of each fuel plate (see Fig. 4) are examined underwater from video recordings of the plates being pulled out of the basket. The underwater observations after each cycle verify the absence of abnormal indications, oxidation, excessive swelling, and buckling and that the plates remain fairly flat.
- Detailed photography of the surface of both sides of each plate can be obtained to review any defects or discolorations that may lead to further investigation.
- High-precision (+/−1 µm) profilometry and oxide thickness measurements of each plate with the SCK CEN Bench for non-destructive analysis of plate and

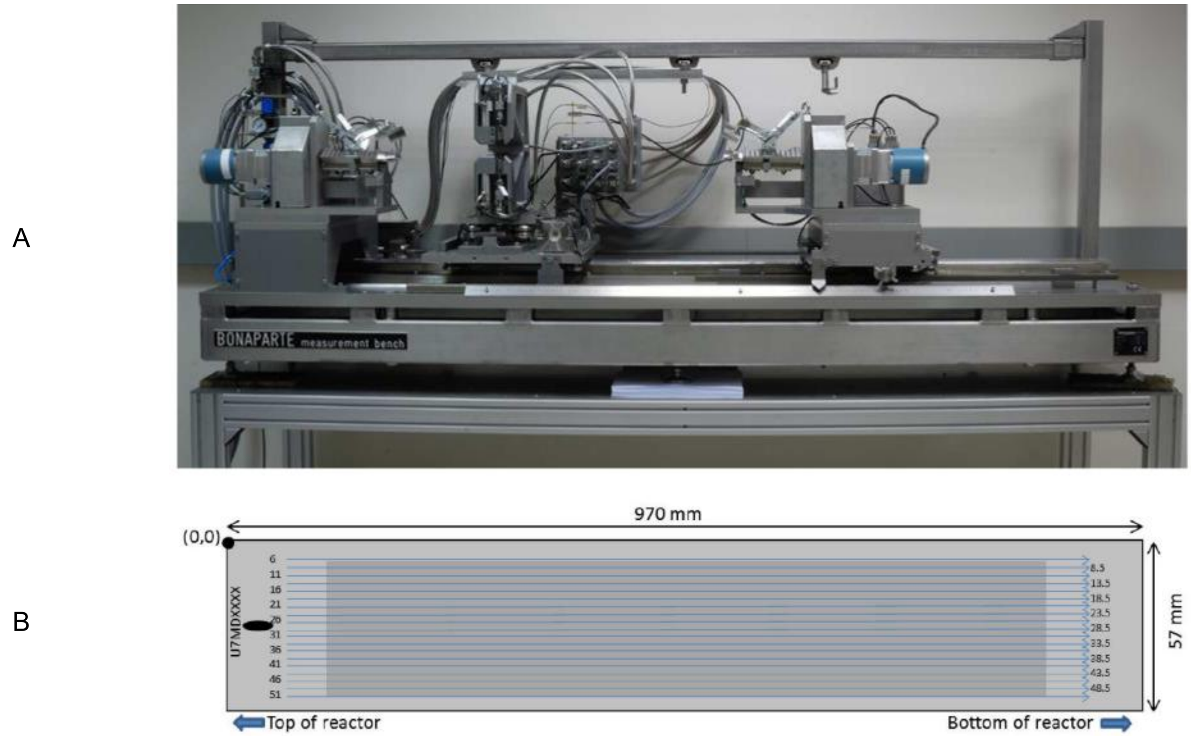


Fig. 5. (A) The BONAPARTE measuring device. (B) Coordinate system adopted for the BONAPARTE measurement results for a typical FUTURE plate.

rod-type fuel elements (BONAPARTE) measurement device (see Fig. 5). This data is used to perform detailed fuel swelling calculations. The oxide layer composition can vary on a fuel plate depending on the cladding type and the pH of the reactor. The RR plates that are tested in BR2 typically result in the formation of a multi-layered aluminium oxide that is mostly a boehmite layer [AlO(OH)] [37].
- Gamma scanning to determine the relative axial and transverse fuel-burnup profiles and fission product relocation to aid in evaluating the performance of the irradiated fuel plates.

After NDE, a non-destructive examination PIE report is issued and is used for updating the plan for destructive examinations (DE), including locations for performing the cutting of samples. The DE aims to evaluate fuel composition, fuel swelling, interaction layers, oxide growth, interdiffusion, impurities, and other relevant observations, and chemical burnup analysis for further confirmation of post-irradiation U-235 burnup analyses.

The general approach is to have representative samples from the top (T), middle (M), and bottom (B) of the plate or high, medium, and low burnup locations for examination in both the longitudinal and transverse directions. After samples are prepared, the examinations may include the following measurement/evaluation techniques:

- Scanning Electron Microscopy (SEM)
- Electron Probe Micro Analyzer (EPMA)
- Focused Ion Beam (FIB)/Transmission Electron Microscope (TEM)
- Radiochemistry burnup analysis.

4 Project-specific innovations

4.1 LEU-FOREvER project

Within the Euratom-funded LEU-FOREvER project, further development of all three fuel systems shown in Figure 2 has been achieved. Most of this project has been executed, and it is expected to be fully completed in late 2022. The fuel performance understanding and the fabrication equipment and processes of the UMo dispersion fuel system [8,10] have significantly matured during the project. The increased fuel performance understanding was primarily based on the FDEG review of the SEMPER-FIDELIS [28] experiment that was irradiated in ATR and examined in the previous Euratom project: HERACLES-CP [29].

A significant achievement was made in the demonstration of an alternative high-density fuel system: U_3Si_2 [5]. This was achieved through the successful irradiation of four (4) high-density/high-loaded (4.8–5.6 gU/cc) silicide fuel plates in the BR2 reactor, which subsequently received non-destructive PIE [14] to confirm the acceptable fuel performance at high heat flux (peak heat flux: 450 W/cm^2) and high U-235 burnup (peak U-235 burnup: 80%). This successful demonstration of fuel plates at representative high-performance conditions has opened

Table 2. LEU-FOREvER targeted fabrication technologies and verification experiments for specific fuel systems and gained verification of specific objectives.

Fuel system & technology	LEU-FOREvER experiment	*Gained* improvement/verification	References
HD U_3Si_2 fabrication	HiPROSIT	Fabrication demonstration of high-loading and high-density silicide fuel in full-size plates (4.8–5.6 gU/cc)	[32,33]
HD U_3Si_2 general fuel performance	HiPROSIT	Irradiation & PIE confirmation of high loading and HD silicide fuel behavior (4.8–5.6 gU/cc)	
		Development of the fuel performance modeling to include HD silicide	[5,11]
UMo dispersion fabrication	SEMPER-FIDELIS	Fabrication demonstration of fuel powder heat treatment process	
		Fabrication demonstration of the new design of a fuel particle coating device	
		Fabrication demonstration of UMo dispersion in full-size plates	[9,10,15]
UMo dispersed general fuel performance	SEMPER-FIDELIS	Confirmation of atomized, heat-treated, ZrN-coated U7Mo fuel with and without Si added to the pure Al matrix at high power and high burnup through analysis of PIE results and modeling	[5,10,13,14,17,31,34]
UMo monolithic fabrication	EMPIrE	Fabrication demonstration of the PVD Zr coating process and equipment on representative-size foils	
		Fabrication demonstration of the C2TWP EU cladding process on mini plates	[21]
UMo monolithic general fuel performance	EMPIrE	PIE confirmation of the PVD-coated U10Mo monolithic fuel with C2TWP process at moderate-high power and moderate-high burnup	[22]
U_3Si_2	4EVERTEST	Demonstration of a substitution element for European Reactor with original Russian design	[35,36]

a credible alternative pathway for LEU conversion of high-performance research reactors still using HEU.

Other notable accomplishments in the project include the further development of the equipment and processes of the monolithic UMo fuel system and the successful design, fabrication, and irradiation of a new fuel assembly design for the LVR-15 medium power research reactor. The confirmation of the monolithic UMo fuel system fabrication was demonstrated in a US Department of Energy-funded irradiation experiment called EMPIrE, with mini-plates tested in the ATR reactor (USA) [9]. The PIE of these monolithic plates was included in the scope for this LEU-FOREvER project, and these results are positive and sufficient to enable further irradiation testing in the next project. The new fuel assembly for LVR-15 [30] demonstrates an alternative fuel form and an alternative fuel supplier based in the EU for a medium power research reactor (the LVR-15 is a light water tank-type research reactor at the research organization Centrum Výzkumu Řež (CVŘ) in the Czech Republic). This demonstration enables a path of independence for historical research reactors which may currently be dependent on non-EU fuel fabricators for fuel supply by demonstrating that an EU-based fuel supplier can provide an alternative fuel design that can strengthen the reliability of fuel supply for EU-based research reactors.

Table 3. Fabrication technologies and the expected innovation outcomes from EU-QUALIFY targeted fuel systems. MRL = Manufacturing readiness level, TRL = Technology Readiness Level.

Fuel system & technology	EU-QUALIFY experiment	*Expected* innovations
HD U_3Si_2 fabrication	ME-DEUS, ME-CHARTREUSE	Increased TRL/MRL Fabrication demonstration of HD silicide fuel in full-size formed fuel plates swaged into an assembly (4.8–5.3 gU/cc)
HD U_3Si_2 general fuel performance	ME-DEUS, ME-CHARTREUSE	Irradiation & PIE demonstration of HD silicide fuel in full-size formed fuel plates swaged into an assembly (4.8–5.3 gU/cc) at high power and high burnup Development of the fuel performance modeling to include HD silicide assemblies
UMo dispersion fabrication	E-FUTURE-III	Increased TRL/MRL Fabrication demonstration of atomized powder fuel powder heat treatment process Fabrication demonstration of the new design of a fuel particle coating device with fuel powder
UMo dispersed general fuel performance	E-FUTURE-III	Irradiation & PIE confirmation of multiple plates of atomized, heat-treated, ZrN-coated U7Mo fuel with and without Si added to the pure Al matrix at high power and high burnup
UMo Monolithic fabrication	FUTURE-MONO-1	Increased TRL/MRL Fabrication demonstration of the EU LEU U10Mo foil rolling capability Fabrication demonstration of the PVD Zr coating process and equipment on full-size foils Fabrication demonstration of the C2TWP EU cladding process on full-size plates
UMo monolithic general fuel performance	FUTURE-MONO-1	Irradiation & PIE confirmation of the PVD coated U10Mo monolithic fuel with C2TWP process at high power and high burnup

Table 2 summarizes the innovations obtained from the irradiation tests conducted or examined within the project; namely: SEMPER-FIDELIS (in BR2), EMPIrE (in ATR), HIPROSIT (in BR2), and 4EVERTEST (in LVR-15).

4.2 EU-QUALIFY project

The recently started EU-QUALIFY project, funded by Euratom, builds on the experience acquired in HERACLES-CP, LEU-FOREvER, and the collaborative actions with the US across all three fuel systems. This project has completed the project planning phase and is well into the preparations to begin 3 different irradiations; one for each of the fuel systems. As the name of the project implies, the scope of this project is to begin the generic qualification of the high-density silicide and both UMo fuel systems.

The high density and highly loaded U_3Si_2 fuel qualification will be moving forward with the fabrication demonstration of full-size plates that are formed and swaged into full-size fuel assemblies. To enable this experiment, a BR2 driver fuel element design will be utilized where the outer ring of 3 fuel plates will be replaced by the LEU U_3Si_2 fuel plates. Two such assemblies will be produced: one with a fuel core consisting of U_3Si_2 4.8 gU/cc with thick meat and one with a 5.3 gU/cc fuel core. Both will be irradiated at high power (450–470 W/cm^2) and relatively high burnup (>60% U-235 burnup). These "mixed elements" (LEU fuel plates mixed together with the standard BR2 HEU driver fuel) will be tested as ME-DEUS and ME-CHARTREUSE at BR2 starting in 2023. Following irradiation and initial visual observations, the LEU plates will be disassembled/removed from the mixed element and then typical non-destructive PIE will follow in 2024.

The qualification of the UMo dispersion fuel system will begin with the irradiation of 4 nearly identical

Table 4. Summary of current state-of-the-art and next development steps for the fuel systems studied in this paper.

Fuel system	Uranium loading	Current status (LEU-FOREvER)	Next steps in EU QUALIFY
U_3Si_2 (standard) fuel	4.8 gU/cc	Readily used in research reactors	Verification in mixed elements *with thick meat* at high power (ME-CHARTREUSE)
U_3Si_2 HD fuel	5.3–5.6 gU/cc	Four (4) full-scale plates successfully tested in relevant irradiation conditions	Verification in mixed elements experiments with 5.3 gU/cc (ME-DEUS)
UMo dispersion fuel	~8 gU/cc	One (1) full-scale plate successfully tested in relevant irradiation conditions	Verification with four (4) full-scale plates (EF3 experiment)
UMo monolithic fuel	~16 gU/cc	Mini-plates successfully irradiation tested	Verification in full-scale plates (FM1 experiment)

plates: U7Mo heat-treated powder coated with ZrN. Two plates will be a pure aluminium matrix and 2 will include a 5% silicon addition. It was observed in SEMPER-FIDELIS that at the micro-scale, there is marked improvement by including the silicon. This test, the E-FUTURE-III (EF3) experiment, will put the silicon side-by-side with plates without silicon to determine if the addition of the material is necessary and warranted. Fabrication will mostly be performed at CERCA, utilizing commercial-scale equipment and processes. Due to timing constraints with fabrication scale-up, the ZrN powder will be coated with a commercial-scale system at SCK CEN. This experiment is planned to begin in 2023 and non-destructive examinations will follow in 2024.

The qualification for the UMo monolithic fuel system with EU fabrication technology will commence with the FUTURE-MONO-1 (FM1) experiment. This experiment is still in the planning stages but will include 2–4 monolithic fuel LEU plates designed prototypic to the LEU design of the FRM-II reactor. Significant investments in equipment by TUM at CERCA will enable the fabrication to mostly be performed at CERCA, utilizing commercial-scale equipment and processes. Only the Zr coating of the foils for FM1 is expected to be coated on a commercial-scale system at TUM. This experiment is planned to begin in 2023 and non-destructive examinations will follow in 2024.

In addition to the fabrication studies leading up to these experiments, the EU-QUALIFY project also includes innovative efforts to establish a fuel performance database and to further enhance the capability of the fuel performance modeling. These activities are also important for a generic fuel qualification and to enable the reactor-specific fuel qualifications.

Table 3 summarizes the innovations *expected* from the irradiation tests conducted or examined within the project; namely: ME-DEUS/ME-CHARTREUSE, E-FUTURE-III, and FUTURE-MONO-1.

5 Conclusions

Several milestones in developing suitable alternative fuels for research reactor LEU conversions have been accomplished to date and several more are expected to be accomplished in the ongoing actions. A short summary of the current European state-of-the-art of innovative research reactor fuel development is given in Table 4. It is envisaged that the dispersion silicide and UMo fuel systems will reach a technological readiness level sufficient to support further reactor-specific irradiation campaigns (see Fig. 1) with the ultimate objective of reactor conversions. The challenges that potentially remain for the monolithic fuel system (currently the least developed in Europe) after EU-QUALIFY are expected to be further tackled through bilateral TUM/CERCA activities and the HERACLES consortium is hopeful for continued financial support through a potentially new European project.

Conflict of interests

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

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Data availability statement

The data reported has been deposited in a data repository in accordance with the regulations of the project partner's organization.

Author contribution statement

The main authors were Stefan Holmström and Jared Wight. Stéphane Valance provided a detailed review.

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Review Article

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Towards an optimized management of accidents

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Abstract. Nuclear safety has been one of the main research domains in EURATOM programs for decades, and accident prevention and mitigation have drawn much of the attention paid over the years to this framework. In the essence of this interest are designs of reliable systems, accurate methods to estimate risk, and a permanent search for optimizing accident management. This is the focus of PIACE, MUSA, and AMHYCO projects. A fully passive system for decay heat removal in off-nominal conditions based on the concept of isolation condenser is the subject of PIACE. A harmonized approach for analyzing uncertainties and sensitivities associated with severe accidents, particularly with the source term to the environment, is the final aim of MUSA. And finally, AMHYCO is exploring the potential for enhancing the management of combustible gas risk. Despite the project's diversity, they all will converge on the same outcome: an optimization of nuclear safety from better safety systems, risk estimating methods, and in-accident guidelines. These projects have received funding from the H2020 EURATOM research and training program under grant agreements 847715 (PIACE), 847441 (MUSA), and 945057 (AMHYCO).

1 Introduction

Nuclear safety relies on several aspects, such as the Defence-in-Depth approach, which identifies Nuclear Power Plant (NPP) conditions progressively degraded from nominal to postulated severely deteriorated in five levels, and articulate means (standards, engineering safety features, and guidelines) to minimize risk to public and environment. For decades, Euratom has brought nuclear safety up as one of the key targets for research. With a broad scope, which ranges from testing more reliable and efficient systems to enhancing procedures, guidelines, and measures on robust knowledge and know-how, research nuclear safety projects have been awarded under the HORIZON 2020 framework. PIACE, MUSA, and AMHYCO are good examples of them.

The high standards set for NPPs get its top in nuclear safety systems that are supposed to operate in harsh conditions. Their performance needs to be demonstrated before being implemented in any reactor design, particularly if they are based on an innovative passive approach. The challenge is multiple. On one side, suitable facilities capable of setting representative initial and boundary conditions as well as being scalable to NPPs should be built and/or adapted, if already existing. On the other, the system should be properly modeled so that its effect is soundly assessed under any anticipated condition. PIACE integrates all these aspects for a specific proposal to remove decay heat based on the concept of isolation condenser.

Numerical simulation tools are widely used to assess the behavior of NPPs during postulated accidents, including Severe Accident (SA). In other words, they are a central element of the safety demonstration where the compliance of the main safety features of an NPP is checked against the actual safety requirements reflecting the state-of-the-art. In addition, the development and optimization of Accident Management (AM) measures aiming at preventing and mitigating the consequences of SA strictly rely on numerical simulations with SA codes. Since the SA tools predict important parameters such as the time of failure of safety barriers, on the one hand, and the potential radiological Source Term (ST) to be released to the environment if the safety barriers fail, on the other hand, it is of paramount importance to be aware of and enhance their accuracy. To do so, MUSA brings uncertainty quantification into SA analyses and provides insights that might change the perception of the current precision of SA codes and highlight areas where further research would be more beneficial.

One of the priority areas of SA research has been analyzing the risk of combustion of H_2 and CO, as it might

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jeopardize containment integrity. The Fukushima Daiichi accidents that occurred in Japan in 2011 just strengthened the need to properly manage such risk and practically eliminate the consequential dynamic phenomena. By keeping the containment integrity, the potential release of a significant amount of radioactive material to the environment would be prevented. Despite the numerous research projects and activities conducted in different frameworks, some of their outcomes have not been fully exploited in the form of actions to be taken for accident management, particularly in the ex-vessel phase of accidents when H_2 and CO coexist in a containment atmosphere. AMHYCO fills this gap by using a comprehensive approach involving analytical methods, systems testing, and SA management procedures.

Euratom has always paid due attention to communication and dissemination of the research results and outcomes of the projects sponsored in its frame. This aspect has been particularly emphasized in H2020. Consequently, in each of the above projects, a specific Work Package (WP) deals with these aspects. It is a common feature nowadays to host project websites for internal communication, as storing and share-points of the material produced or used as a background in the project. Newsletters, LinkedIn, and Facebook accounts are among the instruments used by these projects to reach the public. No less important, these WPs foster the education and training aspects by facilitating the participation of young researchers and engineers in scientific and technical events as well as financially supporting their mobility across European laboratories.

2 PIACE: an efficient system for decay heat removal

2.1 Project overview

The PIACE (Passive Isolation Condenser) project will provide a significant contribution to the safety improvement of the present and future technology of nuclear reactors. The project aims to demonstrate the feasibility, shortening the time to market, of an innovative Decay Heat Removal (DHR) system, based on an isolation condenser with non-condensable gases, to manage the variable decay heat in a passive way, verifying and validating the concept of a patented passively controlled safety system for decay heat removal [1]. The innovative concept has the important peculiarity of being completely passive by making use of simple physical phenomena, limiting the use of energy sources or movement of mechanical parts only at the actuation stage (category D of passivity according to IAEA [2]) without human intervention, and have the flexibility to be adapted both to the liquid metal and water-cooled reactors.

The project has received funding from the Euratom research and training program 2014–2018 under grant agreement No. 847715. The total cost is in the order of 3 M€ with human resources involved in the order of 400 person-months, over 3 years (2019–2022). It is an international collaboration involving 11 European partners, research centers, and private companies (ANN, EAI, ENEA, GEN ENERGIJA, JSI, RATEN, SCK-CEN, SIET, SINTEC, TRACTEBEL, and UPM), and is led by ENEA. In addition, an external advisory committee, specialized in different types of plants, as well as safety and licensing aspects, is supporting the project; and an exploitation manager is defined to guarantee the process of exploitation and dissemination of the results reducing the risks associated with technological innovation.

The ultimate goal of the PIACE project is the finalization of specific designs of the innovative DHR concept, ready for industrial implementation on several reactor technologies ranging from currently operating plants to innovative energy systems, namely: Lead-cooled Fast Reactor (LFR) Accelerator Driven System (ADS), Pressurized Water Reactor (PWR), Boiling Water Reactor (BWR) and Pressurized Heavy Water Reactor (PHWR).

Two main branches can be identified in the project, a design assessment, with the support of numerical codes, to analyze the applicability of the concept to the different reactor technologies of interest, and an experimental investigation to test the feasibility and the performance of the system during accident scenarios. The experimental tests will take advantage of the facility SIRIO located in Italy in the SIET laboratories [3]. The facility is conceived for feasibility testing on this new DHR system applied to LFR technology, and it will be easily adaptable for the tests in PIACE. A simplified scheme of the SIRIO facility, along with a photo of the steam generator, is reported in Figure 1. The system mainly consists of Steam Generator (SG), Isolation Condenser (IC), Non-condensable Gas Tank (GT), and By-pass Heat Exchanger (HX), each equipped with isolation valves.

The facility can simulate the transient operation of the IC starting from a steady state condition of the system. During the steady state condition, the valves (V3) and (V4) are open, and the water circulates, in two-phase flow and natural circulation, between the steam generator and the bypass heat exchanger. The valves (V1) and (V2) are closed, and the IC and the GT are filled with nitrogen at a lower pressure than the waterside. Later, the (V4) is closed, and the pressure of steam in the upper branch increases up to the automatic opening of the valve (V1). The steam enters the IC, "pushes" the non-condensable gas in the gas tank, and condenses along the IC tubes. After a certain delay with respect to (V1), the condensate isolation valve (V2) opens, and a natural circulation occurs, providing heat transfer from the SG to the water of the IC pool. Then, the electrical heater power in the SG is modulated to simulate the decay heat. When the power removal capacity of the IC exceeds the power generated in the SG, the condensation of steam in the IC increases, and consequently, the pressure of the system (SG+IC) decreases. In this condition, the non-condensable gas flows back from the GT into the IC tubes, decreasing its condensing capacity. Consequently, the pressure remains almost constant and the system can passively align the power removed from the isolation condenser with that produced by the steam generator.

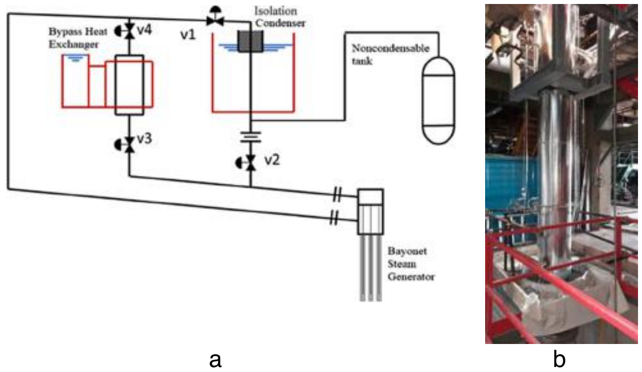

Fig. 1. The SIRIO facility. a. Schematics, b. Steam generator.

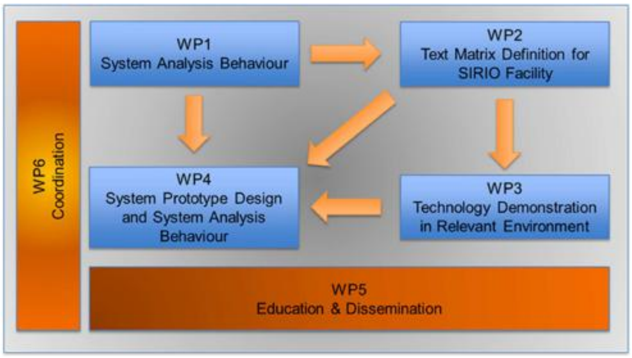

Fig. 2. PIACE Functional structure.

2.2 Project structure

The project is structured into 6 distinct work packages (WP), as reported in Figure 2.

WP1 is devoted to implementing the innovative system to the different reactor technologies and analyzing the plant response for a reference full-scale system through modeling and analyses by system codes. The result consists of a first feasibility study highlighting the potential benefit of the safety system applied to a specific reactor technology. The WP1 is concluded.

In WP2, the main phenomena controlling the system behavior are identified. Then, a pre-test phase with numerical models is used to analyze the scalability of the system to be tested on the SIRIO facility once the facility is adapted to reproduce the reactor technology under investigation. Finally, the test matrices are defined, for each reactor technology, to identify the minimum set of experimental runs necessary to catch the controlling phenomena. The WP2 is concluded.

The WP3 is devoted to the experimental campaigns on the SIRIO facility. The first run planned is relevant for LFR technology. Further tests will then be performed, considering the other two reference cases, with an upgrade of SIRIO. The WP3 is ongoing. The selection of the two reference cases is concluded. The test campaign for the LFR technology is ongoing, and the preparation of the SIRIO facility for the two further reference tests is started. Delays are accumulated on these text campaigns due to the forced long inactivity of the laboratories caused by the pandemic situation of Covid-19. An extension of the project of six months is indeed requested.

The WP4 activities will be devoted to the comparison of the experimental data with the pre-test analyses to understand any difference or scaling distortions, as well as to validate the computational tools and provide "best practices" guidance to capture the main underlying phenomena. Moreover, a technical specification of the safety system will be developed for each of the nuclear technologies under study, covering aspects like, but not limited to, system functions, system criteria, interface requirements, system performances, and validation basis. The activities outcome will represent a perspective improvement in Technology Readiness Level (TRL) and bring the innovation closer to the market. The preparation of the structure of the documentation is already done.

The WP5 deals with dissemination and training activities. In addition to the classic dissemination activities, webinars, workshops, and hands-on training on the SIRIO facility are planned during the project to inform young researchers and students about the issues of interest in passive safety systems.

As expected, one WP (WP6) deals with coordination activities related to both project management (quality plan, risk management, interface management, administrative matter, reporting) and technical coordination (project execution plan, technical interfaces, technical review). This can also be applied to MUSA (WP1) and AMHYCO (WP6).

2.3 Preliminary results

The WP1 relates to the selection of enveloping accidental transients, and the most representative results obtained through the system codes simulations for each of the reference technologies are reported in [4]. Just to illustrate the work done, a couple of examples are succinctly described next:

- in the liquid metal reactor technology, the activities are based on ALFRED design [5], a pool-type concept with all the components installed inside the reactor vessel. The analyzed operating condition of ALFRED is related to a thermal power of 200 MWth and a thermal cycle between 400 °C and 480 °C. On the secondary side, the water enters the steam generators at 335 °C and flows out as superheated steam at a temperature of 435 °C and 175 bar. The passive DHR interfaces with the secondary system through the feed water and the steam line, and each steam generator has its safety system loop. The accidental transient studied in the PIACE project was taken from the list of accidental events developed during the LEADER project [6]. The enveloping event that was identified for the numerical study is the Protected Loss Of Offsite Power (PLOOP) and accounts for the loss of electricity (resulting in loss of all pumps), containment isolation, SCRAM, and actuation of the safety system. The transient was analyzed by means of the system code RELAP5-3D [7]. Two main phases of the transient are identified. At first, the safety system operates

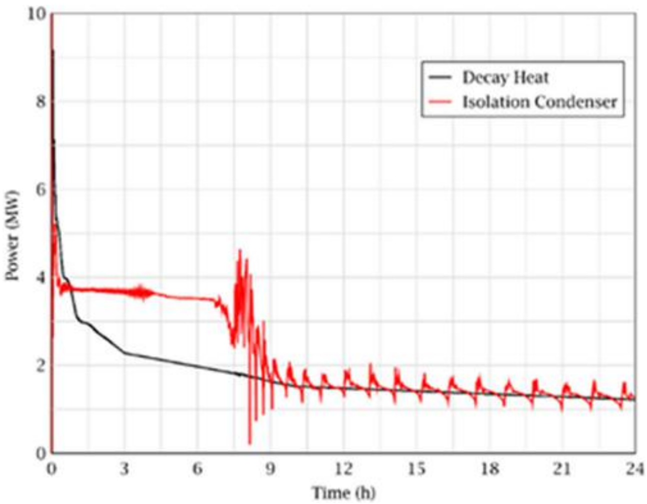

Fig. 3. IC power removal by IC in ALFRED during a PLOOP.

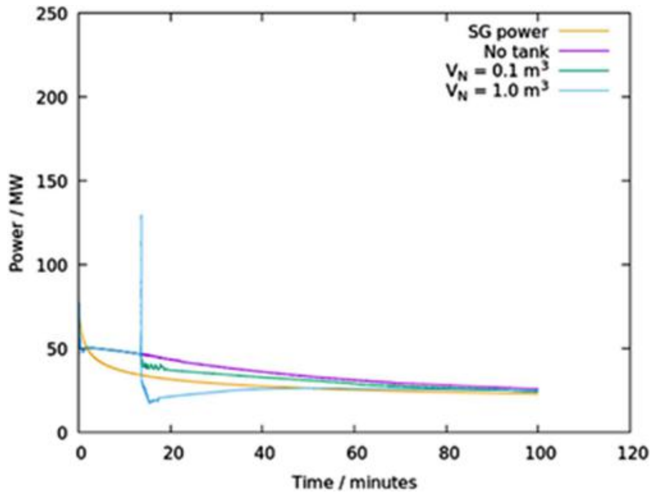

Fig. 4. Power removal by IC in a PWR configuration (effect of the N_2 tank).

at maximum power while maintaining the non-condensable gases trapped inside the tank, with a total power of around 4 MW. Over time, the temperatures of the reactor coolant system decrease, and once much of the heat capacity has been removed, non-condensable gases migrate from the tank to the isolation condenser, and the power balance is achieved. In parallel, the temperatures of the reactor coolant system stabilize to a value greater than 350 °C, about 20 °C above the freezing temperature. The system maintains this safe condition for the entire 24-hour period studied in this case. The results indicate an increase in the grace time against reactor coolant freezing (which would be otherwise reached in approximately 10 hours), and temperatures are kept within the safety conditions. Figure 3 shows the trend of power absorbed by the coolant and removed by the isolation condenser.

ADS transients and accidents based on MYRRHA design [8] have also been analyzed.

- On the water-cooled reactor technology, the considered plant, in the case of PWRs, was a two-loop Pressurized Water Reactor (PWR) with thermal power of 2000 MWth. The enveloping scenario assumed is a station blackout, where the electrically powered components are not available, and only passive components and systems remain functional. The proposed conceptual design of the passive isolation condenser consists of cylindrical headers and vertical tubes. The condenser was modeled as being part of a separate, closed loop that includes a heater, which simulated the heat flow due to the decay power. The transient involving the functioning of the condenser was simulated with the system code RELAP5/MOD3.3 [9]. A parametric analysis was performed with different values of the nitrogen tank volume and different initial decay power, highlighting their impact on transient behavior and the most suitable parameter selection for accident mitigation. Figure 4 shows the trend of power removed by the isolation condenser with different nitrogen tank volumes.

In addition, transient and accident analyses have also been conducted in BWR (particularly ESBWR) [10] and PHWR (particularly CANDU 600) [11].

The scalability of the systems under investigation has been analyzed, and the representativeness of the SIRIO facility has been delineated in terms of upgrading needs related to instrumentation, layout, volumes, main components, and logical controls. In addition, the test matrix of each reactor technology relevant for the experimental characterization of the SIRIO facility has been set (Tab. 1). The study provided the basis for selecting the experimental campaigns of the two additional reference cases.

The selection of the two further reference cases to be tested on the SIRIO facility is concluded. The choice made concerning BWR and PWR technologies has been made based on the scientific value of the test, technical feasibility, economic sustainability, and time needed for the modifications compared to the project time schedule. The test campaign on the LFR technology is started, and the first results are under analysis.

3 MUSA: empowering severe accidents predictability

3.1 Project overview

The MUSA (Management and Uncertainties of Severe Accidents) project aims to quantify the uncertainty in SA codes when modeling accident scenarios to predict the radiological ST [12]. Uncertainty Quantification (UQ) methodologies are being applied to initial and boundary conditions, model parameters, and even accident management measures. ST-related Figures Of Merit (FOMs) have been set for each scenario in which the Best Estimate Plus Uncertainties (BEPU) is being applied.

The project has received funding from the Euratom research and training program 2014–2018 under grant

Table 1. Tests conditions for SIRIO experimentation.

	LFR (SIRIO as it is)	ADS		PWR		BWR		PHWR	
		Proposal 1	Proposal 2	Proposal 1	Proposal 2	Proposal 1	Proposal 2	Proposal 1	Proposal 2
Layout & components modifications required	None	Direct connection of the non-condensable tank to the HX upper header		Heat transfer surface of HX increased by a factor 1.82	Heat transfer surface of HX increased by a factor 1.82 Gas Tank volume increased by a factor 1.2	Extra vessel on Steam line. 6″ × 5.86 m	None	Modification of the diameters of the most piping of the loop	
Operation parameters									
Power (kW)	55	28.3	3.25	55	55	55	110	30	55
Pressure primary circuit (bar)	180	16.0	16.0	60	60	72.52	72.52	46	46
Pressure gas tank (bar)	110	12	12	50	50	50	69	30	30
Water inventory (kg)	38	38	50.7	38	38	57.1	57.1	38	38

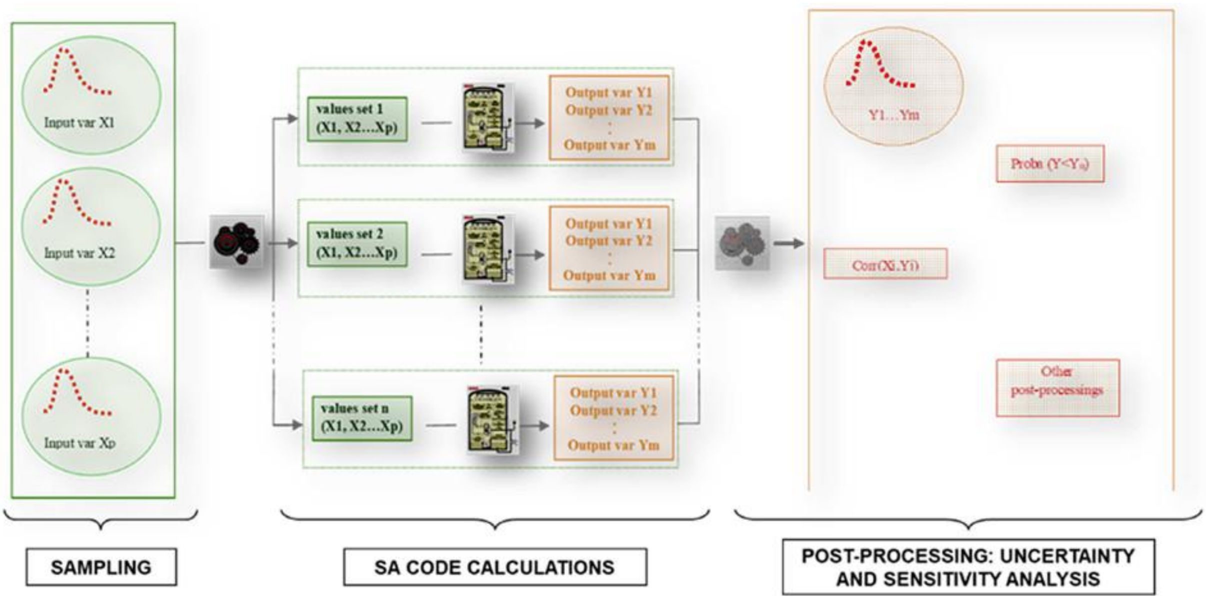

Fig. 5. Sketch of uncertainty propagation being applied in MUSA [13].

agreement No. 847441. The total cost is in the order of 5.9 M€, with human resources involved in the order of 625 person-months over 4 years (2019–2023). MUSA is an international collaboration that involves 28 partners led by CIEMAT. The rest of the partners are mostly European, but there are institutions from America and Asia as well (Bel V, CEA, CNPRI, CNSC, ENEA, Energorisk, EPRI, Framatome, GRS, INRNE, IRSN, JAEA, JACOBS, JRC, KAERI, KIT, LEI, LGI, NINE, PSI, SSTC, Tractebel, TUS, UNIPI, UNIRM1, USNRC, VMU, VTT). This large participation ensures the involvement of a wide range of competencies and approaches (i.e., Technical Support Organizations (TSO), utilities, research centers, and academia) and effective dissemination of major project outcomes worldwide.

Numerical simulation tools are a central element of the safety demonstration where the compliance of the main safety features of an NPP is checked against the actual safety requirements reflecting the state-of-the-art. In addition, the development and optimization of AM measures aiming at preventing and mitigating the consequences of SA heavily rely on numerical simulations with SA codes such as ASTEC, AC2, MAAP, MELCOR, etc. However, although statistical tools are available worldwide, few investigations have been focused on SA and UQ. Therefore, MUSA goes beyond the state-of-the-art regarding the predictive capability of SA analysis codes by combining them with the best available UQ tools. By doing so, not only the prediction of the timing for the failure of safety barriers and the radiological ST in the case of a SA in an NPP will be possible, but also the quantification of the uncertainty bands of selected analysis results, considering any relevant source of uncertainty, will be provided. A schematics of the uncertainty propagation is given in Figure 5 [13].

MUSA is not restricted to reactor accidents, including GEN II and GEN III designs (PWR and BWR ones). Spent Fuel Pool (SFP) accidents are also addressed. In addition to including AM in the uncertainty analyses, MUSA intends to develop some innovative AM strategies for SFP accidents. It is worth noting that the project has strong links with the communities dealing with Probabilistic Safety Assessment (PSA) level 2, emergency response, environmental consequence analysis, and AM, all of which have been undertaking deep reviews since the Fukushima Daiichi accident.

3.2 Project structure

As shown in Figure 6, the technical WPs (i.e., WP2-WP6) distribute in two blocks (WP1 and WP7 deal with coordination and dissemination, respectively). The first one, including WP2 and WP3, is meant to prepare everything necessary to conduct the second block, which can be referred to as the "application WP block" (i.e., WP4, WP5, and WP6). The "application block" represents roughly two-thirds of the total workforce anticipated in MUSA.

WP2 (Identification and Quantification of Uncertainty Sources, IQUS) identifies and partially quantifies the major sources of uncertainties of any type of processes and phenomena during SAs affecting the ST. This would entail both uncertainties in the existing models and uncertainties due to the lack of specific models in the codes. A preliminary "knowledge-based matrix" containing the selected variables, parameters, and models and their uncertainty ranges has been set. To do so, a list of FOMs was previously developed consistent with the focus of MUSA on ST.

WP3 (Review of Uncertainty Quantification Methodologies, RUQM) aims to review and assess methodologies and codes used for uncertainty quantification and sensitivity analyses and their applicability to the analysis of SA. In particular, the strengths and weaknesses of each methodology/code to be applied have been identified, and by the end of the project, a report on guidelines for the best use of UaSA (Uncertainty and Sensitivity Analysis) codes/methods in the SA domain is planned to be delivered. Among the uncertainty quantification tools, partners are using SUSA, DAKOTA, URANIE, RAVEN, and data assimilation tools (NEMM, MOCABA); additionally, the coupling and post-processing require PYTHON scripting.

WP4 (Application of UQ Methods against Integral Experiments, AUQMIE) was outlined to get some experience and insights into applying the RUQM methodologies against internationally recognized integral ST-experiments. Since its onset, it has become a drill for other application WPs (WP2 and WP3) and an opportunity to provide some early feedback to RUQM. The test PHEBUS FPT-1 was selected for this purpose. The work has already been practically finished and the main outcomes are gathered in [14].

WP5 (Uncertainty Quantification in Analysis and Management of Reactor Accidents, UQAMRA) aims at demonstrating the applicability and the level of readiness of uncertainty assessment in a broad range of set-ups. In addition to uncertainty bands affecting ST estimates, two other major outputs are to be produced: a best-practice protocol for applying UaSA methods to SA codes (as feedback to WP3) and identifying areas where further research would efficiently reduce ST estimates. Four subgroups have been set up according to the reactor technology (PWR Gen II; PWR Gen II; VVER/CANDU; BWR). The work is undergoing, and preliminary insights

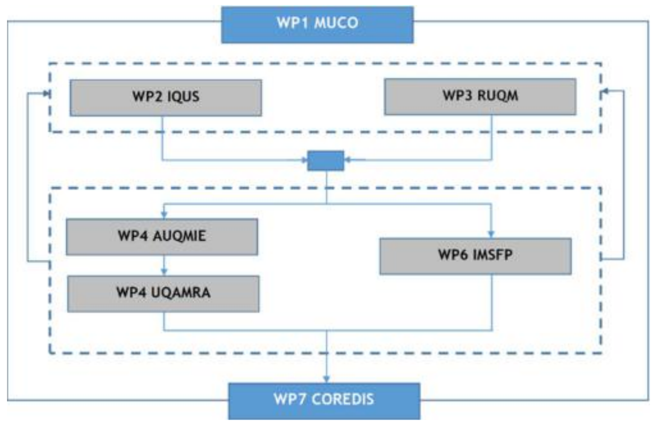

Fig. 6. MUSA Work Package interlink.

into BEPU application to SA have already been gained [15].

WP6 (Innovative Management of SFP Accidents, IMSFP) follows the same orientation as WP5 with respect to RUQM methodologies application to SFP SA scenarios, but a special emphasis has been placed on AM mitigation measures. The same scenario (a loss-of-cooling accident inspired in the SFP of Unit 4 of the Fukushima Dai-ichi NPP) is being simulated by all the partners. Given the differences with WP5, FOMs have been somewhat adapted. Preliminary results of the UaSA exercise are being obtained, and major observations have already been delivered [13].

3.3 Preliminary results

Once over the MUSA half-life time, some preliminary results, particularly from the application packages (WP4-WP6), are worth noting:

- identification and characterization of the input uncertain parameters has resulted/is resulting in a key and challenging task. On one side, the huge complexity of a SA scenario involves a tight phenomenological interlink that, even when just focused on a few FOMs, results in an overwhelming number of potentially influencing input variables subject to uncertainty (easily over hundreds or even further). On the other, the lack of characterization (lower and upper bounds, probability density function) data for many of those variables make their definition uncertain by itself.
- A review is ongoing to identify if input parameters are lacking. But the input uncertainty quantification, which has been identified as an important step in the UQ phase [13], is a long task that is out of the scope of this project.
- Highly demanding computation costs have been found in all the application WPs, although a noticeable variability among partners has been reported (from a few hours to several days per single run). Using multi-core processors or PC clusters might help overcome this challenge (particularly with UQ exercises over 100

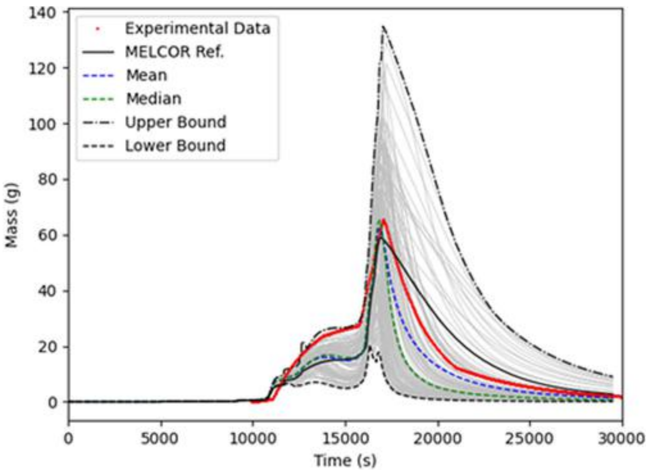

Fig. 7. Airborne particle mass in containment (FPT1) [14].

runs). Figure 7 shows an example of the type of results obtained within WP4.

- Code crashes look practically unavoidable when addressing "full-scope" scenarios for the first time, and there is no systematic way to handle them. Extending the number of runs with respect to the minimum required by the Wilks' formula to ensure having enough computations is an option but does not guarantee a proper FOM distribution without biases. All this said some codes appear to be more resilient to failures than others.
- Systematization of SA code/UQ-tool coupling, as well as post-processing through scripting, is an essential step to better accommodate the long time required by this application and to address the best way to analyze the huge numerical data resulting.
- The application of regression techniques entails no minor challenges. At this time, it seems unlikely to define an optimum correlation coefficient; what is considered essential is the accurate meaning of the chosen coefficient. This is an area where several project partners are working on. Using the physical understanding of the scenario to figure out the rationale behind the significance/non-significance of any sampled variable is indispensable.

4 AMHYCO: optimizing management of combustible gases

4.1 Project overview

The project AMHYCO (Towards an Enhanced Accident Management of the Hydrogen/CO Combustion Risk) will consider practical issues to reduce further (as much as possible) the threat posed by the combustion of gases generated during accidents on containment integrity [16]. Specifically, it will improve the Severe Accident Management Guidelines (SAMGs) for both in-vessel and ex-vessel phases using numerical and experimental results. It will also experimentally study the phenomena that are difficult to predict numerically (such as H_2/CO/H_2O distribution and combustion). A third goal will be to improve the predictability of the numerical tools used for explosion hazard evaluation.

The project has received funding from the Euratom research and training program 2019–2020 under grant agreement No 945057. The total cost is in the order of 4 M€ with a human resource involved in the order of 490 person-months, over 4 years (2020–2024). It is an international collaboration that involves 10 European partners, research centers, and private companies (CIEMAT, CNL, CNRS, ENERGORISK, FRAMATOME, FZJ, IJS, IRSN, LGI, NRG, RUHR U., UPM), and is led by UPM. In addition, an external advisory committee and an end-user group have been set up to count on some external consultancy and to ensure the optimum exploitation and dissemination of the results.

Appropriate management of the associated risk to combustible gases is paramount to avoid the potential release of radioactive material to the environment due to the containment loss of integrity. SAMGs must be regularly updated and include knowledge gained from international efforts, including recent and ongoing research projects. AMHYCO will contribute to this objective by improving the understanding of H_2/CO combustion and incorporating this knowledge into SAMGs. The AMHYCO project intends to respond to practical questions, such as the right timing and mode for actuation of containment safety systems (i.e., Filtered Containment Venting System (FCVS), sprays, fan coolers) to reduce as much as feasible the threat posed to containment integrity. To do so, all the available tools to enhance the present status (i.e., LP, 3D, and CFD codes, together with experimentation and the best use of engineering judgment) are to be applied.

The scope of this project is outlined by the most common reactor technology in the EU: PWRs. The three existing designs are being addressed: PWR-Western type (PWR-W), PWR-KWU type (PWR-K), and PWR-VVER type (PWR-V). When feasible, diversity in reactor size (power) is also being considered.

4.2 Project structure

In order to meet the above objectives, the project proposes a working method based on five different work packages (WPs), as illustrated in Figure 8, which are at the same time successive and interlinked.

The WP1 aims at reviewing the status of existing methodologies and practices related to gas combustion risk management in the late phase of severe accidents. As most of the mitigation strategies adopted in European countries to prevent this risk are based on the use of Passive Autocatalytic Recombiners (PARs), a critical assessment of the PAR behavior in the late phases of severe accidents is performed. Similarly, a survey of the available experimental data and engineering combustion models is provided. The lessons learned will help identify knowledge gaps related to hydrogen (H_2) and carbon monoxide (CO) recombination and combustion. In addition, a review of

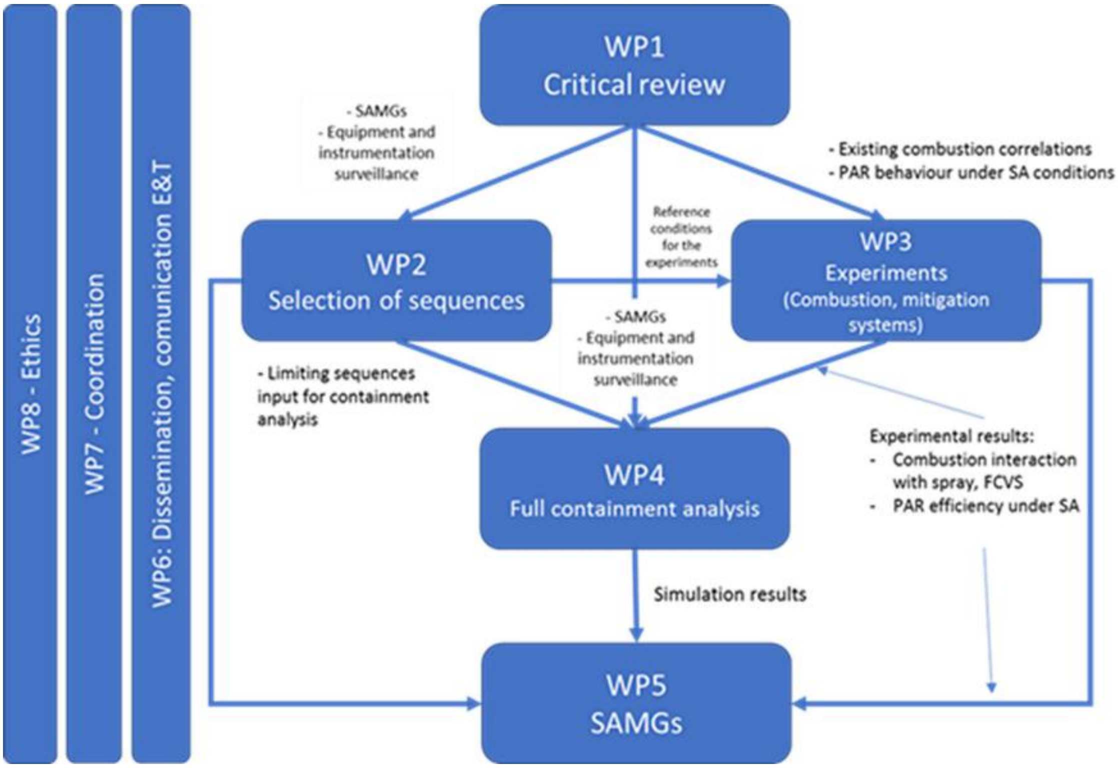

Fig. 8. AMHYCO project outline.

the safety equipment qualification criteria and gas monitoring systems, as well as the existing SAMGs, is established with the aim of paving the way toward SAMGs enhancement.

The intention of the WP2 is to identify accident sequences in which H_2 and CO combustion risk might jeopardize containment integrity. Given the current European nuclear reactor fleet, the three PWR reactor designs have been modeled (PWR-W; PWR-K; PWR-V), and the most relevant sequences have been chosen according to a set of agreed criteria: high molar fractions of combustible gases ($H_2 + CO$) in control volumes which conditions are within flammability limits; large total mass of combustible gas ($H_2 + CO$) within the containment; and, fast combustible gas ($H_2 + CO$) release rates. Besides, this WP includes a specific task to produce "Generic Containments (GC)" databases based on containment descriptions available and/or reachable by the AMHYCO team [17]; from the 3D description (CAD file), lumped-type nodalizations are agreed among partners to be later used in WP4.

The objective of WP3 is to experimentally investigate phenomena related to hydrogen and carbon monoxide combustion and mitigation, which are still not covered by existing numerical models. The focus is set on the combustion of hydrogen/carbon monoxide/steam mixtures as well as on the operational behavior of PARs under boundary conditions representative of the late phase of severe accidents. Hence, following the conclusions of the review performed in WP1 and the scenarios selected in WP2, WP3 will provide specific experimental data to assess and enhance the numerical tools used in WP4.

The most penalizing sequences identified in WP2 for the PWR containment designs will be further analyzed within WP4. The focus of the analysis will be to investigate the late phase containment response in terms of containment pressure build-up, H_2/CO combustion risk, efficiency, and options/timing of individual mitigation measures (in particular PARs, fan cooler or spray systems, and FCVS), and equipment and instrumentation surveillance. For this purpose, the sequences for each plant design will be generalized and harmonized as far as possible in WP2 to enable comparability, and the RCS is simply represented by source terms (energy and mass; fission products will be neglected).

Finally, WP5 aims to identify room for improvement of SAMGs with respect to the management of combustible gases within the containment. The basis for this evaluation is the experimental and computational efforts carried out in the above-mentioned WPs. Thereby, the insights from the calculations, including the late phase with CO present in the containment, will be transferred into SAMG considerations. Recommendations are foreseen for all large-dry PWRs containments explored in the project.

4.3 Preliminary results

For the time being, the results have come from the insights gained from WP1 reviews, the calculations conducted in the frame of WP2 and the GC databases built up, and the early phase of experimentation concerning PARs performance and combustion of combustible gas mixtures. All of them may be summarized as follows:

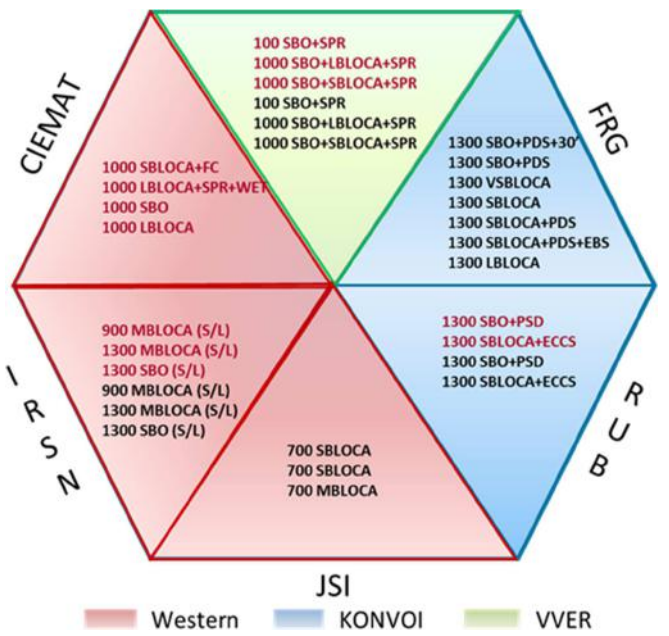

Fig. 9. Severe accidents sequences modeled.

- additional experimental and theoretical investigations are needed to fill the knowledge gaps regarding the PARs behavior in representative conditions of severe accidents in late phases. Given that the different nature of existing models (from engineering correlations to CFD models accounting for phenomena such as thermal radiation, superficial and bulk chemical reactions on the surface and in the gas) was validated on experiments dealing with H_2, data with gas combustible mixtures are necessary to extend the domain of the model's validation. WP3 will supply the data for such a purpose, and the resulting enhanced equations will be implemented in safety codes to simulate the containment of severe accident scenarios in WP4.
- The requirements for combustion risk management and mitigation measures address only in-vessel conditions and aim to preserve containment integrity; their extension to ex-vessel conditions needs to be established. In addition, most times, they have a qualitative nature. This focus on the in-vessel phase extends to monitoring systems, which are not designed to measure CO. Finally, just a few SAMGs instruct on how to use other safety systems (i.e., sprays, FCVS) to handle the combustion risk in the late phases.
- H_2/CO combustion in representative conditions has been poorly investigated. Few data are available in the open literature, and, consequently, the application of existing modeling is restricted to a limited validation. Part of the work underway in WP3 is dealing with this issue and will provide data on laminar and turbulent flame speed, flammability limits, and flame acceleration criteria. These data are expected to contribute to the enhancement of the existing engineering correlations and combustion models.
- A number of accident sequences have been modeled for each reactor type addressed (Fig. 9). The accident selection has been fundamentally based on the resulting Shapiro diagrams, samples of which for PWR-W are shown in Figure 10. In the case of PWR-KWU reactors, the sequence selected has been an SBLOCA ($80\,cm^2$). Despite the diversity of reactor size in PWR-W (i.e., 700 MW, 1000 MW, and 1300 MW), it was agreed that the selected sequences were an SBLOCA ($120\,cm^2$) and a double-ended guillotine break (LBLOCA). As for VVER reactors, the decision is still to be made.
- The flammability limits for a mixture of $\{50\%H_2 + 50\%CO\}$ in air ($O_2/N_2 = 0.264$) and in starvation conditions ($O_2/N_2 = 0.11$) for an initial pressure ranging from 1 to 3.5 bar were determined in the ENACEFF facility. The effect of CO_2 and H_2O is currently being investigated [18,19].
- Scoping tests were performed with different catalysts (platinum- and palladium-based) to define the boundary conditions of more complex experiments to be conducted in the REKO-3 facility [16]. Specific focus was set on identifying the conditions for catalyst poisoning, which could be highly significant for late-phase PAR operation. For Pt-based catalysts, the catalyst poisoning temperature (i.e., the threshold value of the catalyst temperature below which the catalyst gets poisoned) was shown to be independent of the gas temperature, while Pd-based catalysts were found to be less sensitive to poisoning at elevated gas temperature.

5 Final remarks

This paper illustrates the ongoing support from Euratom to further strengthen the nuclear safety of NPPs through investigating innovative, reliable safety systems (PIACE project), enhancing predictive analysis of SA scenarios (MUSA project), and optimizing guidelines to manage combustible gas risk in containment (AMHYCO project).

The PIACE project focuses on the designs of the innovative DHR concept, ready for industrial implementation on several reactor technologies ranging from currently operating plants (L- and H-WRs) to innovative energy systems (including FRs and ADSs). The innovation lies in the ability of the system to control passively the power exchanged with the heat sink by using non-condensable gases. The activity developed so far showed: the applicability of the system to the different reactor technologies, the scalability of the system to be tested on the SIRIO facility, the necessary testing of each reactor technology, and the selection of the reactor technologies as reference cases for the test campaign. The experimental campaign is ongoing.

The MUSA project is facing the challenge of bringing uncertainty and sensitivity analysis into the SA simulations as a means to better assess the potential source term to the environment, encompassing both Gen. II and Gen. III reactors and SFP accidents. So far, a database on input deck uncertainties has been built and applied to the simplified scenario of PHEBUS-FPT1, and the first challenges and difficulties of a systematic application of UaSA into SA analyses have been experienced, and ways

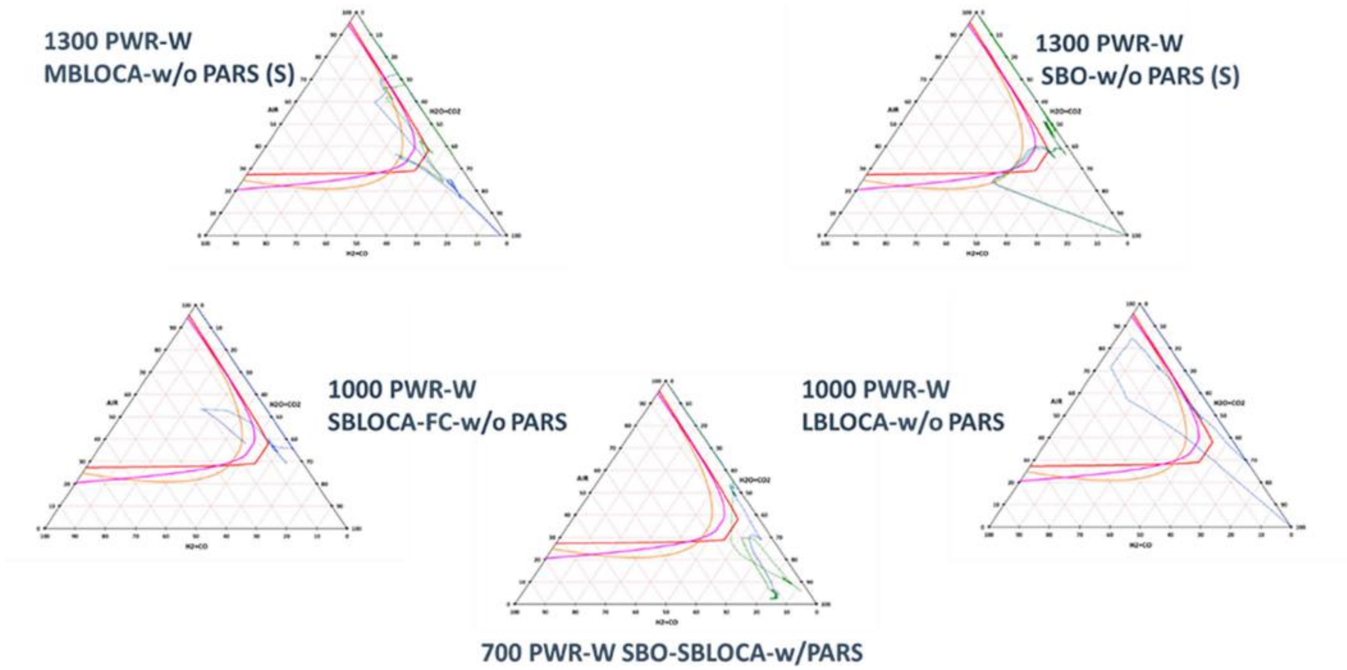

Fig. 10. Shapiro diagrams of the PWR-W accident sequences analyzed.

to overcome them are being proposed. Currently, the practical application to reactor and SFP scenarios is underway, and the lessons learned from the FPT1 training experience are being tested in these "full-scope" simulations. From these exercises, feedback on BEPU methodologies application in SA analyses is being settled.

The AMHYCO project is addressing practical issues to further reduce (as much as possible) the threat posed by the combustion of gases generated during accidents on containment integrity. Specifically, it will propose improvements to the SAMGs for both in-vessel and ex-vessel phases using numerical and experimental results. It will also experimentally study the phenomena that are difficult to predict numerically (such as $H_2/CO/H_2O$ combustion and recombination). The progress done so far has paved the road to the full containment simulations and SAMGs feedback that will take place in the second phase of the project; in addition, experimental investigations on PARs performance and gas combustion under conditions barely explored earlier are ongoing.

Finally, despite the harsh COVID conditions that have prevailed since early 2020, the three projects are deeply committed to young researchers' and engineers' education and training through powerful mobility programs already being executed.

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.

Author contribution statement

Each of the authors: coordinated the work presented in the article; contributed with specific sections of the authors (F. Saveiro for PIACE; G. Jiménez for AMHYCO; L.E. Herranz for MUSA); L.E. Herranz drafted the first version of the paper and polished the last one.

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Review Article

Open Access

Probabilistic Safety Assessment for internal and external events on nuclear power plants and on mitigation strategies/H2020 European projects NARSIS, R2CA and BESEP

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Abstract. The NARSIS project aimed at improving assessment methodologies to be integrated into "extended Probabilistic Safety Assessment" (PSA) procedures for nuclear plants in case of single, cascade and combined external natural events. An open-access framework tool has been released to build multi-hazard scenarios, and various risk integration approaches (e.g., Bayesian Networks) have been implemented and compared, identifying their advantages and limits for further collaborative research activities. The R2CA project aims at harmonizing the safety analysis methods for best estimate evaluations of the radiological consequences, in case of Design Basis Accidents and Design Extension Conditions without significant fuel melting. It is planned to improve models and upgrade existing simulation tools and calculation chains used in safety studies. Finally, the BESEP project is to support safety margin determination, by developing best practices for safety requirement verification against external hazards, using efficient and integrated set of Safety Engineering practices and PSA. The project is carried out in a benchmark exercise based on case studies previously performed by the consortium participants. All three projects aim to improve nuclear safety within the European research and development framework. The research objectives are achieved by the development and improvement of proven and justified safety assessment methodologies for the verification of stringent safety requirements of nuclear industry.

1 Introduction

The response to the 2011 Fukushima nuclear accident has led to stringent safety requirements in many EU countries. To verify the fulfilment of the stringent safety requirements, proven and justified safety analysis methods should be developed and applied in the nuclear industry. Such methods have been studied and developed for internal and external events and on mitigation strategies in three EU projects: NARSIS, R2CA and BESEP.

The NARSIS project (see Fig. 1a) aimed at improving assessment methodologies to be integrated into "extended Probabilistic Safety Assessment" (PSA) procedures for nuclear plants in case of single, cascade and combined external natural events. An open-access framework tool has been released to build multi-hazard scenarios, keeping only hazard parameters relevant for the safety assessment of the main critical plant structures, systems and components. Various risk integration approaches (e.g., Bayesian Networks) have been implemented and compared as well, identifying their advantages and limits. The project achievements have led to recommendations useful for further collaborative research activities.

The R2CA project (see Fig. 1b) aims at harmonizing the safety analysis methods for best estimate evaluations of the radiological consequences in case of Design Basis Accidents and Design Extension Conditions without significant fuel melting. It is planned to improve models and upgrade existing simulation tools and calculation chains used in safety studies. Among results, some guidelines to design and implement new Accident Management Procedures and safety devices are expected, as well as the development of innovative approaches (e.g., artificial intelligence) for anticipated accidental situation diagnosis.

The BESEP project (see Fig. 1c) aims to support safety margis determination, by developing best practices for safety requiremens verification against external hazards, using efficient and integrated set of Safety Engineering practices and PSA. The core of the project is a benchmark exercise based on case studies previously

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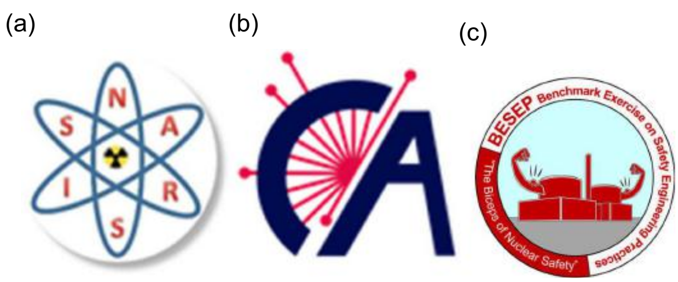

Fig. 1. The logo of (a) NARSIS; (b) R2CA; and (c) BESEP project.

performed by the consortium participants. In the benchmark, the performances of various safety analyses (i.e. Deterministic safety analysis, PSA and Human factors engineering) and Safety Engineering practices are compared to common safety requirements defined for the project. Expected project results are best practices and guidance for the verification of evolving and stringent safety requirements against external hazards.

A more detailed introduction to the NARSIS, R2CA and BESEP projects, their objectives, expected key results and dissemination activities are given in Chapters 2, 3 and 4 respectively. Finally, Chapter 5 is reserved for a short, general conclusion on the research projects.

2 The NARSIS project

2.1 Presentation of the project

In light of the Fukushima Daiichi nuclear accident in Japan (March 2011) and based on the FP7 ASAMPSA_E lessons and on the outcomes from other European FP7 projects (e.g., SYNER-G, MATRIX, INFRARISK), the NARSIS project (New Approach to Reactor Safety ImprovementS, 2017–2022) aimed at investigating the possible improvements to be integrated into existing PSA procedures for NPP related to single, cascade and combined external natural hazards.

Two main interconnected components were part of the NARSIS methodology, organized in 5 main scientific workpackages WP1 to 5 (Fig. 2):

- reviewing existing methodologies and proposing some scientific improvements for multiple natural hazard assessment and their impacts, including advance in evaluation of uncertainties and reduction of subjectivity related to expert judgments (addressed in WP1, 2 & 3);
- verification and testing of the applicability and effectiveness of the improvements w.r.t. safety assessment, as well as demonstration of an improved decision supporting tool for operational and severe accident management purposes (addressed in WP4 & 5).

Thirty-six technical reports and two software tools have been produced by project partners. Most of these reports are publicly available on the project website (www.narsis.eu).

In the following sections, we give an overview of the main objectives and related achievements of the project.

2.2 The Multi-Hazard (MH) framework

One of the main objectives of NARSIS was to develop an integrated Multi-Hazard (MH) framework for safety assessment on main critical NPP Systems, Structures & Components (SSC), accounting for single, cascade and combination events at different time scales, focusing on earthquakes, flooding, tsunamis and extreme weather, as these hazards were identified as priorities by the PSA End-Users community in the European ASAMPSA-E project. The MH framework implementation has been possible thanks to the works recalled hereafter:

- producing a complete state-of-the-art [1]:
  many data from various sources, for the key hazards identified to affect NPPs across Europe have been collected as well as examined: earthquakes, tsunami and waves, extreme weather effects (heat/cold wave, hail, precipitation, etc.), flooding. Various methodologies for single and multi-hazard characterization and assessment have been reviewed, and various definitions of natural external events have been provided (e.g., occurrence of either simultaneous-yet-independent hazards or cascading events). Part of the work involved determining which hazards are more suitable for probabilistic or deterministic analysis and where improvements could lie in the assessment. Key input parameters and metrics have been also examined for each of the main hazards, as well as uncertainty, which forms a major part of the analysis, given the large variability of past events and simply the random nature of natural hazards. From the many historical events reviewed, more than 60 of them were identified as affecting NPPs in Europe, but with no extensive damages in most cases. Secondary effects (e.g., earthquake-triggered tsunami or landslides, storm surge/heavy rainfalls during tropical cyclones) have also been examined, as often causing more damages and fatalities than the primary hazards.
- Performing stress tests' review [2]:
  the key design parameters for earthquake, flood, and precipitation have been derived from the review of the national and individual plant reports for each of the available NPP in Europe. This review has shown that the multi-hazard aspects (assessment for combined and/or cascading hazard events) were not addressed in most cases, thus comforting the need for a MH framework such as proposed by NARSIS.
- Improving Probabilistic Hazard Assessment (PHA) methodologies for tsunami, extreme weather and flooding hazards:
  - for tsunamis, contrary to the usual practice, NARSIS has implemented an accurate numerical tsunami propagation and inundation modelling approach, based on several nested bathymetric/topographic grids, characterized by a coarse resolution over deep-water regions and an increasingly fine resolution close to the shores and coastlines. Thus, specific

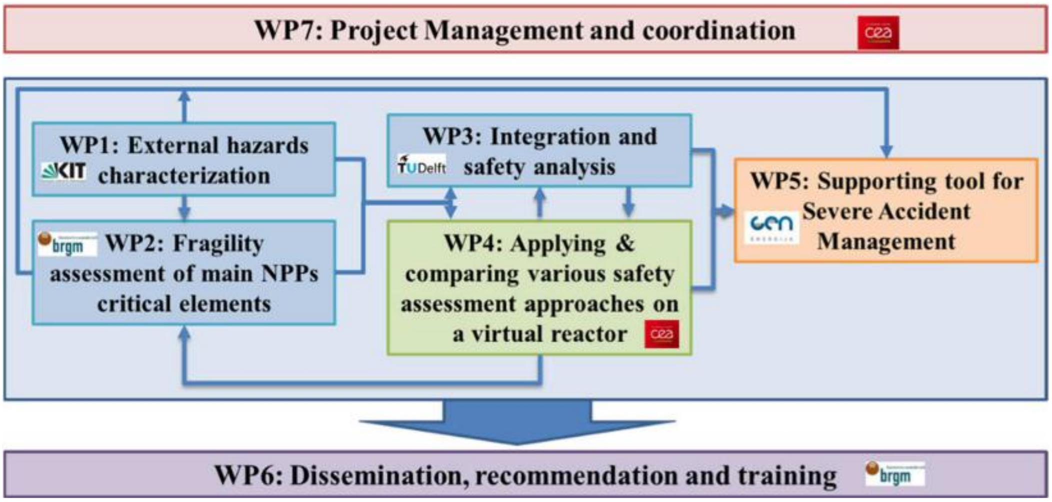

Fig. 2. NARSIS overall structure.

coastal responses, run-up and horizontal inundation could be assessed properly, together with the related uncertainties along the whole process (e.g., fault slip variability, in case of earthquakes, etc.). This approach has been applied to the French Riviera coastline and could be also applicable to other European regions, which are prone to tsunamis (e.g., Mediterranean, English Channel & South-Western Atlantic coastlines).

- For extreme weather and flooding, the current structural design codes are based on the assumption of stationary climate conditions, which are however no longer prevailing in the Climate Change context. Hence, the traditional reliability-based calibration approaches cannot be directly extended to non-stationary climate cases. For instance, the return period concept is no longer applicable due to a time distribution between event occurrences which is no longer invariant. Similarly, the annual failure probability is no longer constant in non-stationary climate conditions. These issues have been fully addressed in NARSIS using the stochastic processes and extreme value modelling-type approaches, as their sound mathematical framework allows to justify data extrapolations. In addition, some works have been dedicated to reviewing the different methods used for Uncertainty Quantification and Global Sensitivity Analysis in case of modelling input parameters considered as dependent, as most analyses rely on the assumption of independent variables of interest.

– Testing and refining the MH framework:
careful site selection around Europe was important, in order to test and demonstrate the capabilities of the NARSIS framework. As a real NPP would never be located anywhere, creating a generic set of locations has been considered outside of the scope of the project. It was hence decided to analyse all NPPs in Europe including decommissioned and research plants to examine potential sites for NARSIS analyses. Finally, three decommissioned and shutdown sites have been selected: Trino Vercellese in Italy, Mülheim-Kärlich and Biblis in Germany and their hazards' datasets have been fully examined and characterized, to produce single hazard curves. Station correlation analysis for extreme weather was undertaken as part of the study, as well as multivariate modelling, looking at correlations between various dependent parameters/station measurements.

The screening of the main NPP SSC was included in the analysis, in order to keep only relevant hazard parameters for each hazard in the final MHE software.

The final NARSIS methodology is derived from the FP7 MATRIX approach [3], which was based on 3 levels for analysis (qualitative, semi-quantitative, quantitative). In order to match the NPP specific nature, the NARSIS methodology implements five successive levels for assessment, which are part of the steps related to Initiating Events and Screening (deterministic or probabilistic) analyses in the extended PSA flowchart. Fig. 3 shows levels 1 to 4 related to the multi-hazard assessment loop. Level 0 (not shown) corresponds to a single hazard assessment through standard practice or improved methods.

This methodology has been implemented in an open-source open-access software tool, the NARSIS Multi-Hazard Explorer [4], suitable to assess not only multiple hazards but also independent single hazards. It is very plant specific, and although the methodology can screen all hazard types and scenarios, there are still some combinations, which may be missed due to specific fragility loops, and/or dynamic hazard loops.

2.3 Fragility assessment in a MH context

A second main objective in NARSIS was to develop refined fragility derivation methods in order to increase the accuracy of the estimation of SSC failure rates against external

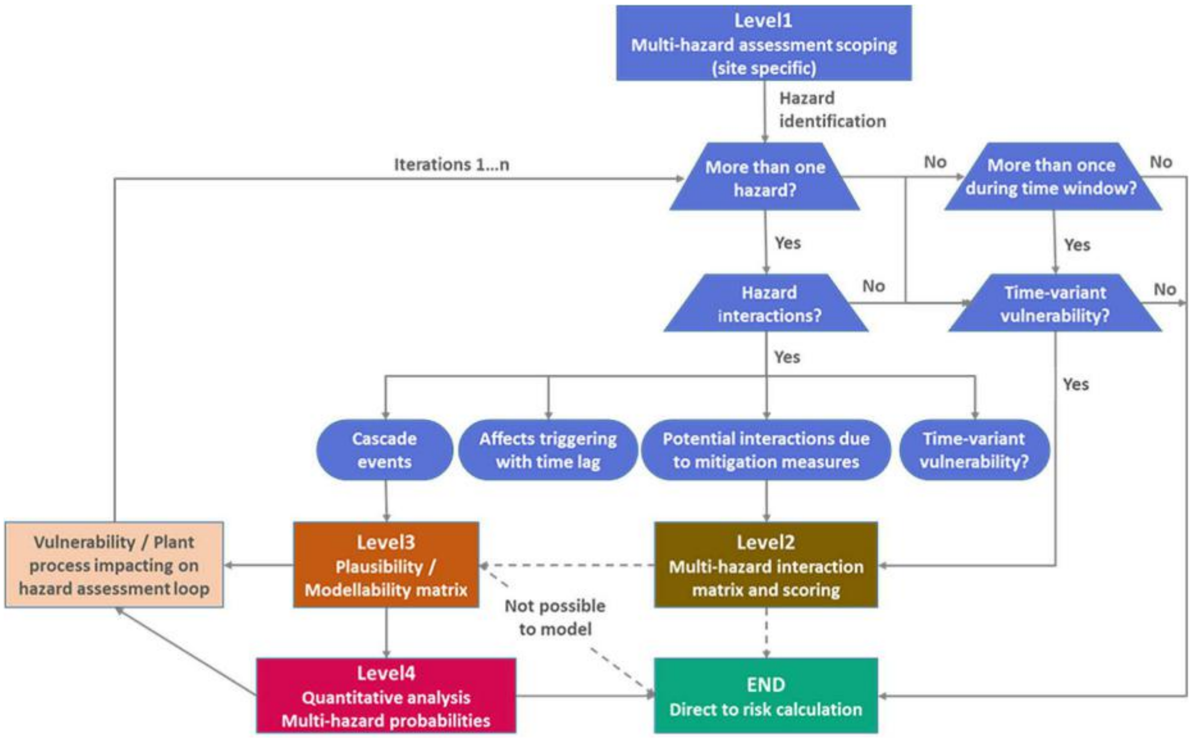

Fig. 3. The NARSIS MH framework scheme for scenarios to be used into multi-hazard PSA.

threats, thanks to current advances in quantitative hazard modelling and computational capacities.

Fragility or vulnerability curves are common in the nuclear industry as they are well suited for PSA applications, being at the interface between the probabilistic hazard assessment and event tree analyses, in order to estimate the occurrence rate of undesirable top events. They represent the probability of a given SSC to reach or exceed a predefined damage state as a function of an Intensity Measure (IM) representing the hazard loading. In the case of complex hazard loadings, a single scalar IM may not be sufficient to represent the severity of the aggression. As a result, conventional fragility curves using scalar IMs may come with a larger dispersion (i.e., uncertainty) in order to represent the imperfect relation between the IM and the loading actually applied. Such uncertainty then propagates through the PSA chain, potentially leading to unnecessary reliability margins.

In NARSIS, the concept of combining multiple IMs (also referred to as vector-valued IMs) in the formulation of fragility functions has been used, either for a single hazard event (essentially earthquakes), or for multiple hazard events (a volcanic eruption with deposit of tephra loads on a flood protection levee, followed by an earthquake), where each IM represents a loading level for a different hazard and the consideration of all IMs provides the means to quantify the probability of damage for multi-hazard scenarios. It has been shown that multiple IMs and physical failure modes can be combined in order to generate fragility models for a wide range of multi-hazard configurations. Provided that the required hazard-specific physical models are available, the following statistical tools are able to cover most of the multi-hazard cases:

- multivariate generalized linear model regression or maximum likelihood estimation are to be used for the estimation of fragility parameters given a set of conditioning variables.
- Algorithms and procedures based on the system reliability theory (e.g., [5]) are able to combine hazard-specific failure modes in order to model the functionality states of a given SSC. Either joint probabilistic of failure or damage-state-dependent fragility functions may be derived from this framework.

Parts of the works have been first dedicated to screening and selecting the most critical SSC deserving in-depth fragility assessment. Contrary to the usual Safety Factors approach, this was done by applying a Risk-Informed methodology (NRC 2004) in which the safety significance is quantified by risk importance measures. Based on different case studies, the following SSC and safety functions have hence been identified as critical elements for PSA:

- I&C and switchgear cabinets/devices;
- fuel assembly spacer grids and, more generally, reactor pressure vessel internals;
- distributed systems (HVAC, piping, cable raceways).
- primary circuit depressurization;
- active isolation of the reactor containment building;
- passive reactor building resistance and leak-tightness in severe accident conditions (pressure and temperature);
- depressurization of the reactor building (by a filtered containment venting system);

- annulus venting system for NPP with double wall containment, auxiliary buildings filtration and venting;
- hydrogen risk management provisions.

Some works have also aimed at investigating the impact on the fragility assessment of SSC, of Soil-Structure Interactions (SSI) and of cumulative effects by succession of seismic events combined with ageing mechanisms and/or lifetime fatigue.

Regarding ageing, structural degradations due to the accelerated flow corrosion, creep and time and/or temperature material properties degradation have been considered for analysis. A methodology for performance prediction has been set and a deterministic approach has been adopted, based on several thermo-mechanical and seismic finite-element simulations performed on the NARSIS virtual NPP, used as reference for this assessment.

Regarding fatigue and earthquake combinations, a unifying framework for characterizing the probabilistic behaviour of a critical SSC (piping) has been proposed, which rely on a loading sequence made of a preliminary High-Cycle Fatigue (HCF) thermo-mechanical loading followed by some damaging seismic loadings. The aim was to derive the vector-valued fragility curves, as a function of both the duration of the nominal HCF stage and the chosen seismic IM.

Finally, the integration of human factors in the reliability analysis, as a potential source of epistemic uncertainty in the PSA, has also been explored.

2.4 The Multi-risk integration framework for safety analysis

A third key objective within NARSIS has been to improve the integration of external hazards and their consequences with existing state-of-the-art risk assessment methodologies in the industry.

Parts of the activities have been dedicated to investigating, further developing and evaluating the Bayesian Networks (BN) approach, hence delineating the advantages and challenges as compared to more conventional probabilistic safety assessment techniques (e.g., fault trees). Vector-based fragility was used in order to use multiple IMs for hazards and a novel BN-based method for human error probability was developed and connected to technical BNs. In complex (sub-)systems, BNs were shown to be able to be used as surrogate models for advanced numerical methods, in order to substantially reduce computational effort and allow their inclusion into larger systems. In addition, a new approach to the analysis of common cause failures was developed showing several advantages over existing methods in both calculation of the impact and visualization.

In addition, the Extended Best Estimate Plus Uncertainties (E-BEPU) methodology, which combines deterministic and probabilistic approaches for safety assessment, has been implemented and its behaviour evaluated regarding defence-in-depth and design extension conditions, as well as Severe Accident Management Guidelines. E-BEPU is able to introduce stricter requirements on possible event sequences and avoid possible cliff-edge effects. It allows relaxation for extremely unlikely sequences under certain conditions, when these sequences can be treated as "practically eliminated". Its use has been demonstrated on the NARSIS reference plant model. However, it has required a huge computational effort.

Finally, some developments have been performed to constrain uncertainties when little data are available on failures. These developments have focused on the ability to identify the most influential sources of uncertainty and novel methods to prioritize and reduce them. In case of modelling of operator/human actions, the human failure probability for these actions can now be assessed and included in the study. Finally, a particular result is for the treatment of expert-based information using the tools of new uncertainty theories.

All these methodologies and developments can be used within a PSA. Each has advantages and disadvantages. Some methods (e.g., BNs) can be used as advanced versions of standard tools, whereas others can be used to investigate specific aspects and reduce uncertainties. Given the large variety of decision-making situations, finding a single appropriate framework appears to be debatable, and it is beneficial to take advantages of the strengths of multiple approaches to capture different types of information and knowledge important to inform decision-making.

2.5 Dissemination activities, potential impacts

Regarding education and training activities, apart from master trainings and postdocs proposed in the project, there have been 5 PhD theses covering a number of key research topics for NARSIS:

- extreme weather characterization,
- seismic fragility of ageing structures,
- vector-valued fragility functions for multi-hazard assessment,
- model reduction strategies for seismic response of structures,
- BN integration framework for probabilistic risk assessment.

Two international training workshops related to the Probabilistic Safety Assessment for Nuclear Facilities, have been held, one in Warsaw on September 2019 and the other in a fully digital format. A collaboration with the European Nuclear Education Network (ENEN), has enabled to invite 20 selected students and young researchers to participate in the first training workshop, where various lectures have been proposed in direct link with the project outcomes, as well as external invited talks on various topics.

At these occasions and all along the project duration, pedagogic materials (presentations, short videos, hands-on tutorials, notebooks) and lectures targeted towards students (e.g., masters) and young researchers or professionals have been produced.

Regarding dissemination activities, more than 20 journal papers have been published, as well as about 30 scientific conference papers (TINCE, NENE, SMIRT, FISA, EGU, COMPDYN, ...). In addition, the project results have been presented systematically to the nuclear community during the annual SNETP/NUGENIA Forums.

Finally, apart from newsletters and the aforementioned publications and participations, the project had interactions with its International Advisory Board members, through dedicated meetings. This has led to very profiting discussions and feedback as these members are all part of international organizations (SNETP, IAEA, JRC, ...) with close links to nuclear safety issues.

3 The R2CA project

3.1 R2CA general overview and motivation

The R2CA project (Reduction of Radiological Consequences of design basis and extension Accidents, 2019–2023) is intended to harmonize the safety analysis methods through the development of generic methodologies for best estimate evaluations of the radiological consequences. The project addresses a broad scope of light water reactor designs from Gen II, III and III+ through the analyses of bounding scenarios of loss-of-coolant and steam generator tube rupture transients. It explores both design basis accidents (DBA) and design extension conditions without significant fuel melting (DEC-A).

The idea of launching such a project comes directly from (1) the consolidated evaluations of nuclear power plant severe accident progression and their associated radiological consequences and (2) the improvements of severe accident management strategies both issued from the numerous R&D programs launched after the Fukushima Daiichi Nuclear Power Plant (FDNP) accident. The integration, thereafter, of all these outcomes in level 2 Probabilistic Safety Assessments (PSA2) indeed demonstrated the effective reduction of the risks of all main categories of severe accidents and, in turn, highlighted the too conservative evaluations of design basis accidents. In addition, the importance to still strengthen the nuclear power plant safety level by considering accidental situations more severe than those currently taken into account for the plant design (the so-called design extension conditions) resulting from additional events or combination of different events and for which provisions have to be designed, have also been evidenced at that time [6,7].

With the primary objective of better estimating the radiological consequences of accidents for design basis and design extension conditions, the work undertaken in this project is then fully in-line with the European directives [8] recommending to continuously review the methodologies to establish the nuclear power plant safety margins for especially considering the changes that might have occurred in the operation conditions (e.g., increase in fuel burn-up) and the potential higher risks exhibited by knowledge improvements (e.g., clad secondary hydriding, increased fission product releases from local restructured high-burn-up fuel zone and from MOx fuels).

During the project, main efforts will be paid on the upgrading of currently used simulation tools and calculation chains in safety studies through the improvements of their models. The updated methodologies/calculation chains will help to derive some rationales for the optimization of Emergency Preparedness & Response plan in order to lower down the impact of the population protection measures. Additionally, innovative actions will also be performed where their main goals will be to provide some guidelines for the design and implementation of new accident management procedures or safety devices (incl. dedicated instrumentation) or to develop innovative approaches based on artificial intelligence capabilities for anticipated accidental situation diagnosis. Finally, the project will also take benefits of the upgrading of simulation tools and calculation methodologies to quantify the pros and cons of some concepts of Accident Tolerant Fuels promoted worldwide.

3.2 R2CA overall approach

To address the project objectives, a step-by-step methodology (Fig. 4) was implemented including the following key milestones:

1. review of the existing methodologies for radiological consequence evaluations of loss-of-coolant and steam generator tube rupture scenarios, of available experiments and/or reactor measurements relevant for design basis and design extension conditions and of the simulation tools that will be used within the project;
2. identification of reactor accidental cases of interest covering all aspects (both conditions and scenarios, different light water reactor designs) and use of the available calculation chains and methodologies for the simulation of the selected scenarios;
3. developments and/or improvements of the calculation schemes used for the simulations of loss-of-coolant and steam generator tube rupture accident phenomena, when needed, and verification/validation of upgraded models against consolidated experimental databases. Model developments and/or improvements are expected from fuel behaviour up to the fission product releases to environment;
4. quantification of the obtained gains in terms of radiological consequence reduction for the selected scenarios with the improved simulation schemes and elaboration of guidelines for the development of harmonized evaluation methodologies;
5. demonstration of the safety gains that could be achieved from innovative accident management procedures, new safety devices (i.e., dedicated instrumentation and some Accident Tolerant Fuel concepts) and early diagnosis tools.

Both integral calculation chains (dealing globally with all the processes from the initiating events up to the environmental releases) and detailed/mechanistic simulation tools (addressing part on the phenomenology only) are used and will be upgraded within the project. These latter will support the re-assessment of the experimental database, will be used to inform low fidelity model of more integral simulation tools or, in some cases, to perform numerical experiments to investigate badly understood uncertainties.

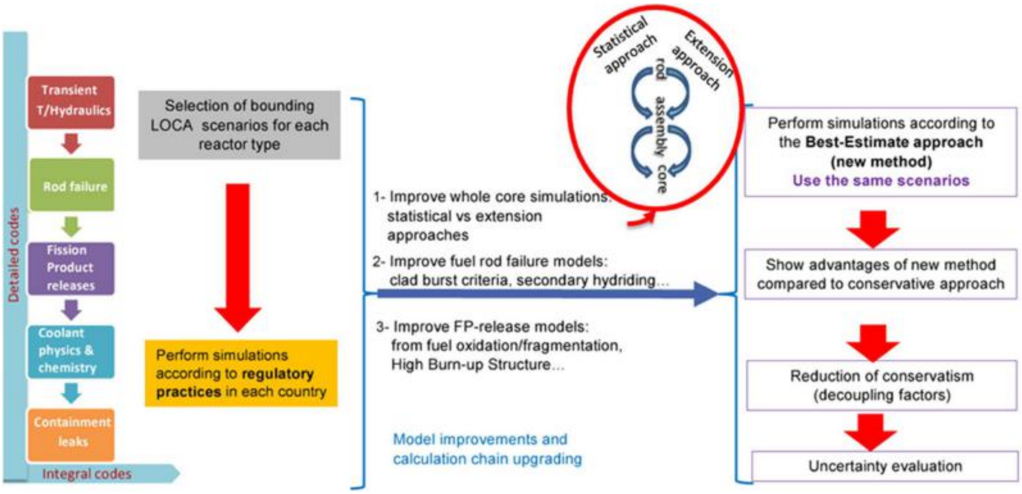

Fig. 4. R2CA methodology for best-estimate evaluation of releases during a LOCA transient.

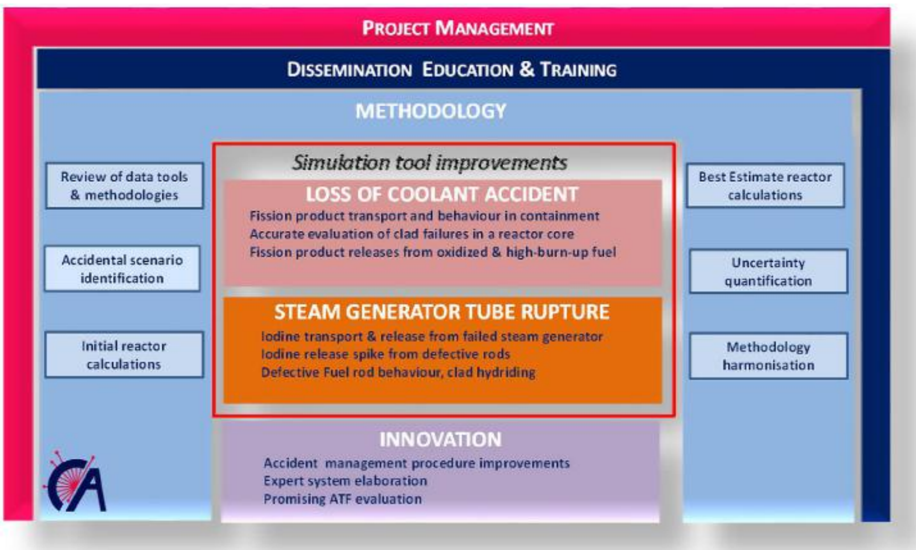

Fig. 5. R2CA overall structure.

The determination of radiological consequences to individual or group of populations will be evaluated from the fission product releases from the facility to the environment. Comparison and improvements of evaluation methodologies will be restricted to the source term from the facility whereas a simplified and unique tool for the source term dispersion in the biosphere and the associated doses to the population will be established and used by all the participants to quantify the obtained gains.

The achievement of the overall objectives is assured by a consistent and coherent work program, reflected in the four technical Work Packages (WP) defined as follows (Fig. 5) which are dedicated to:

- the reviews (methodologies, simulation tools, database) and performance of initial and upgraded reactor case simulations (WP2);
- the improvement of phenomenon modelling for loss-of-coolant (WP3) and steam generator tube rupture (WP4) transients;
- the development of new accident management actions (incl. proposals for new devices e.g., passive systems…) as well as of an accidental diagnosis tool prototype for steam generator tube rupture anticipation and the evaluation of the resistance to loss-of-coolant transients of some Accident Tolerant Fuel concepts (WP5).

The diversity of the 17 organizations included in the R2CA consortium, from industry (designers, utilities) to academic (universities, R&D centres) and including TSOs, favours the foreseen R&D work, the emergence of innovative ideas and the development of theoretical model whereas the demonstration of their effectiveness in lowering the radiological consequences will be tested on selected nuclear power plant case studies within the project. In addition, the consortium composed of 11 countries participating in the project, equally balanced between western and eastern Europe with different regulatory frameworks, offers the opportunity to cooperate on a wide variety of reactor designs from Gen II, III and III+

(BWR, PWR, VVER, EPR) and to share different safety approaches.

3.3 Main advances

Several milestones have already been reached by the project whose main ones can be summarized as follows:

1. the existing knowledge reviews have been completed. In particular, a specific database selecting past experimental data and power reactor measurements of interest for the project has been built [11]. Meanwhile, the methodology review has highlighted major differences leading for instance for loss-of-coolant transients to 1 to 2 orders of magnitude difference for some key isotopes (I and Cs). Finally, the review of simulation tools (more than 20) has helped not only characterizing their modelling capabilities but also pinpointing their required development needs and where the modelling effort should be focused on;
2. first set of reactor calculations have been performed (more than 40). A common template has been set-up for collecting the results of the reactor case simulations that will ease the comparison between initial and best-estimate calculations and the construction of the final calculation result database.

In parallel, a simple radiological tool was provided for evaluating the radiological consequences in a very generic way for the assessment or re-assessment of the safety margins. It basically consists in: (i) a Bi-Gaussian Plume dispersion model function with Briggs-equation for modelling the ambient air behaviour and (ii) the calculations of the effective doses (by inhalation & external exposure) and the equivalent thyroid dose based on formula originated from ICRP guides (e.g., ICRP 144 [9] & ICRP 71 [10]).

Finally, model revisions/developments for fission product transport/behaviour and for fuel/clad behaviour, as well as the coupling of simulation tools (e.g., fuel performance codes with fission product release ones) are ongoing and pave the path towards upgraded calculation chains that will be finalized very soon.

3.4 Key results expected and impacts

The derived guidelines to harmonize the methodologies for safety analysis of the radiological consequences for design basis and design extension condition accidents should be applicable to all existing European reactor designs (BWR, EPR, PWRs, VVERs) and foreseen concepts (incl. Small Module Reactors).

In addition, thanks to the knowledge, data provided to all participants during the project, and to the sharing of simulation tool improvements, it is foreseen to increase the competence of the contributing organizations in their evaluation of radiological consequences for loss-of-coolant and steam generator tube rupture transients. While being an opportunity for some of them to improve their safety studies, it is also expected that the upgraded simulation tools and calculation chains will be useful beyond the consortium to both Industry (utilities, vendors), National Authorities and their TSOs.

Finally, it is expected that by fostering the cooperation between a large diversity of participants and different countries in Europe and bringing together experts from fuel safety, source term and accident consequences, the nuclear power plant safety at European level will be re-enforced.

3.5 Dissemination and training activities

Dissemination of the project results is oriented towards the widest community as possible through several different media (publications in peer-reviewed journals, presentations in international conferences, periodic newsletters, public project deliverables, workshops or side-events open to a large audience...). A public website is also available (https://r2ca-H2020.eu). Since the beginning of the project, 15 papers have already been produced for journals, general and specialized conferences (ERMSAR, NENE, TOPFUEL, NURETH). A special edition of Annals of Nuclear Energy is also under preparation.

The dissemination is expected to be particularly efficient within the nuclear community and Europe, due to, respectively, the variety of participants spreading the information through their own networks (e.g., industrial partners through utility groups, TSO's through ETSON...) and the different countries involved.

The final dissemination of the project results is planned to be done through:

- an End-Users Group (with researchers not participating to R2CA and external stakeholders);
- international organizations (e.g., OECD or IAEA) with the sharing of a database collecting the best estimate reactor calculation results or the edition of dedicated documents (i.e., as State Of the Art Report or as part of "Safety Guides").

Training and education will be both part of the dissemination and exploitation of the results. An important objective of R2CA project is to contribute to the European effort on nuclear education and training activities by integrating the main outcomes of the project into the program of dedicated side-events to the main international workshops or of ad-hoc workshops. The project also favours the involvement of students (masters, PhDs) and postdoc fellows. Four students and one postdoc have already been involved covering the following research topics:

- fuel behaviour (re-structuring) and associated fission product releases during loss-of-coolant transients;
- defective fuel rod behaviour and accident management optimization during steam generator tube rupture transients;
- smart tools for early diagnosis of accidents.

Mobility of students and young researchers between different partner's organizations will be also funded to encourage the transfer of knowledge and expertise. Additionally, specific training sessions on computational tools

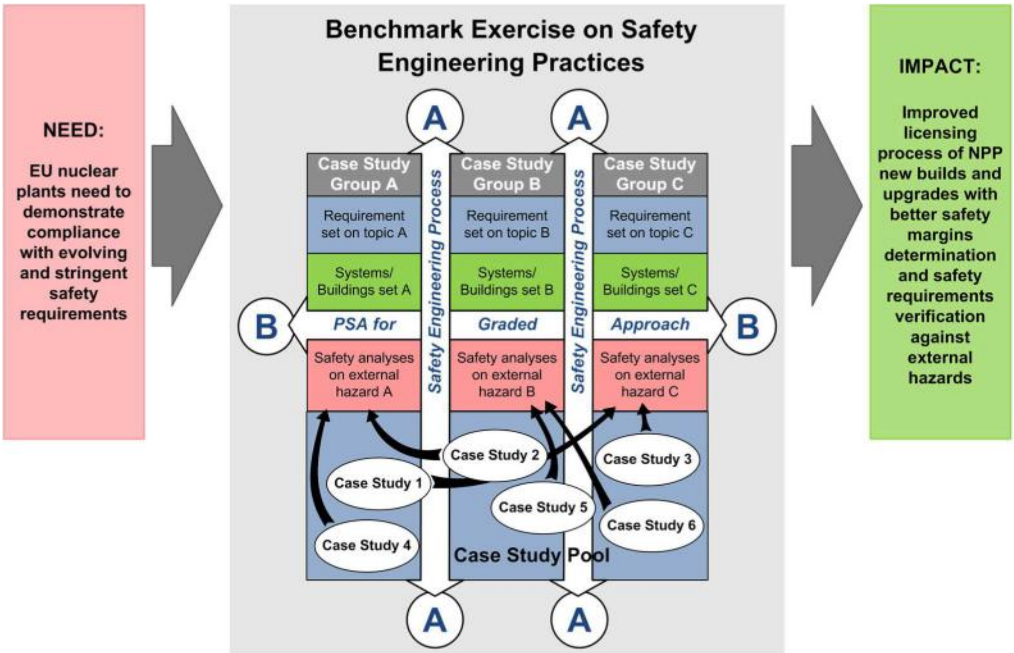

Fig. 6. The overall concept of BESEP project.

are planned to disseminate their use and their associated best-practices.

4 The BESEP project

4.1 BESEP overview

The objective of the BESEP project (Benchmark Exercise on Safety Engineering Practices, 2020−2024) is to support safety margin determination by developing best practices for safety requirement verification against external hazards, using efficient and integrated set of Safety Engineering practices and probabilistic safety assessment.

The overall concept of BESEP is illustrated in Fig. 6. The project is carried out as benchmark exercise (marked with grey background in the figure) between several EU member countries participating in the project. The benchmark exercise is based on case studies previously performed by the participants. The case studies will be further refined during the project to support the benchmarking.

The benchmark exercise focuses on the comparison of failure analyses performed in the case studies and on the inter-connections and inter-actions of different analysis methods involved in the safety assessment of different external hazards. The integration of safety analysis methods is typically handled in a Safety Engineering process.

For the selected case studies, a cross-case comparison for the case studies belonging to the same group and a cross-group comparison between generalized case studies representing each group are performed. The evaluation results of cross-case comparison focus on the safety margin determination and safety requirement verification (shown with letter A in Fig. 6). The evaluation results of cross-group comparison focus on the identification of benefits for increasing the level of detail in the applied safety analysis methods, e.g., the benefits of applying more detailed models or additional simulations. This helps in balancing the plant safety against different external hazards (shown with letter B in Fig. 6). Together, the results of both comparisons can be used to estimate the resilience of safety margins in case of design-basis exceeding external hazards.

As a result, BESEP will answer to the need for EU nuclear power plants to demonstrate compliance with evolving and stringent safety requirements. The impact of BESEP is the improved licensing process of nuclear power plant new builds and upgrades with better safety margin determination and safety requirement verification against external hazards.

4.2 Safety design and Safety Engineering process

In the licensing process of a nuclear power plant, the safety authority will review and assess the design basis of the plant, the requirement specifications, the analyses substantiating the fulfilment of safety criteria, the implementation of defence-in-depth concept in the design as well as the implementation of redundancy, physical separation, functional isolation and diversity principles in the design and implementation of safety functions. The licensing process is endorsed by a Safety Engineering process connecting together the main elements of safety design: safety requirements, safety analyses and plant design.

In a steady-state situation, the three main elements are in balance, and there is general consensus that, based on the safety analyses, the current plant design fulfils the given safety requirements. However, in case there is a change in one of the elements the change should be reflected in the two other elements. This is usually for the Safety Engineering process to take care of.

During the lifecycle of a plant, there can be various changes to the elements, for example:

- new design concepts and feasibility studies may give new ideas to refresh the plant design;
- international and national safety agencies may introduce new safety goals leading to changes in the safety requirements; or
- operational experience from internal and external hazards may challenge the existing safety analyses giving initiative for more stringent safety margins.

The main elements of safety design and the potential reasons to the changes in the main elements are illustrated in Fig. 7.

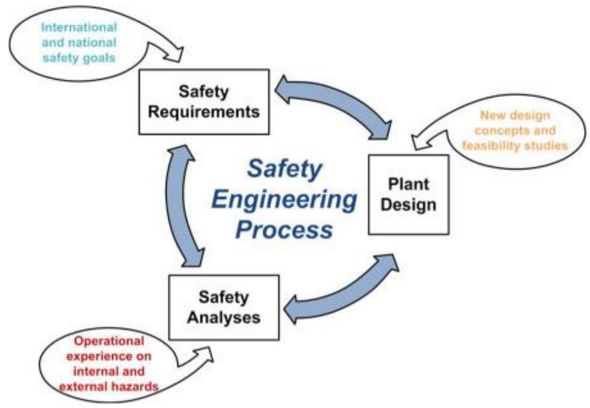

Fig. 7. Main elements of safety design and potential reasons to the changes.

4.3 Requirement baseline for BESEP

The BESEP partner countries have different nuclear safety requirements which lead to different safety engineering practices. Although, there are differences in practices, the goal is the same: Showing the fulfilment of the safety requirement in the nuclear power plant design and operation.

A requirement baseline for the benchmark exercise is created in Work Package 2. The requirement baseline is later used in Work Package 3 for cross-case comparison within case study groups and Work Package 4 for comparison between generalized case studies representing the different case study groups.

The following safety analyses and safety engineering practices are needed to ensure compliance with safety requirements for the plant:

1. deterministic safety analyses (DSA) – analyses of initiating events induced by external hazards, evaluating of plant response, plant performance or success criteria;
2. probabilistic safety analyses (PSA) – modelling of accident sequences, quantification of their risk significance;
3. human factors engineering (HFE) – scope of testing and maintenance, operator and emergency response actions on the basis of pre- and post-hazard procedures, SB EOPs and SAMGs;
4. safety engineering practices (SEP) – implementation of safety requirements to exiting plant design for fulfilling the Defence-in-Depth principle.

Based on the preliminary case studies and general experience of the BESEP partners the safety requirement topics have been defined for the above-mentioned safety analyses and safety engineering practices to be applied in the project. As an example, the topics and short descriptions on their focus in the category of safety engineering practices are listed below. The presented list is not trying to be a comprehensive representation of safety engineering practice topics. The purpose is to identify safety engineering practice topics of interest supporting the benchmark and the objectives of BESEP project.

1. safety engineering management, this topic concerns the processes and models regarding the general structured management of safety engineering activities of NPP license holders;
2. safety design and requirement management for external hazards, this topic concerns managing the balance between the plant safety design and the allocated safety requirements;
3. flow of information between safety analyses, this topic concern interactions and interconnections between the three analysis areas (DSA, PSA, HFE);
4. verification and validation (V&V) of design, this topic concerns interaction between the three main elements of safety engineering: safety requirements, plant design, and safety analyses;
5. system modification and configuration management, this topic concerns system modification configuration management;
6. validated modelling and simulation analysis tools, this topic concerns the validation and improvement of models and the tools used for the analysis of effects of external hazards.

For all these topics specific BESEP requirements were defined to support the upcoming benchmarking. The BESEP requirements were elaborated from the high-level requirements of IAEA and national requirements identified and selected by the BESEP partners. As an example, the BESEP requirements on the flow of information between safety analyses topic are shown in Table 1. The collection of BESEP requirements for all topics on safety analyses and safety engineering practices create the requirement baseline for the benchmark exercise [12].

4.4 Key results expected from BESEP

The expected key results from the benchmark exercise are:

1. best practices for the verification of evolving and stringent safety requirements against external hazards;
2. guidance on the closer connection of deterministic and probabilistic safety analysis and human factors

Table 1. BESEP requirements related to flow of information between safety analyses.

BESEP id	BESEP requirement text
BESEP_SEP_FISA_001	When several different types of safety analyses are used to provide evidence, the information flow between safety analyses shall be defined.
BESEP_SEP_FISA_002	The flow of information shall support reaching the comprehensive understanding on the issue analysed.

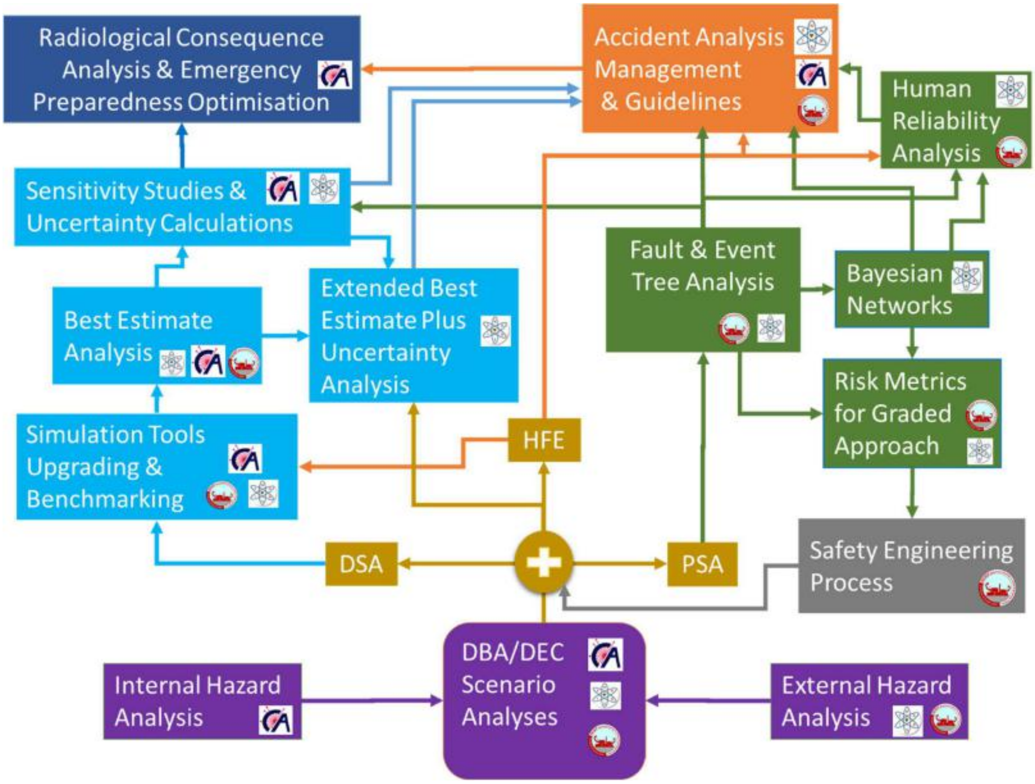

Fig. 8. Focuses and interaction areas of the three projects (marked with the project logos).

engineering for the determination and realistic quantification of safety margins;

3. guidance on the creation of graded approach for the deployment of more sophisticated safety analysis methods, such as upgrades of simulation tools, while maintaining the plant level risk balance originating from different external hazards.

The outcomes will help streamline the licensing process of nuclear power plant new builds and upgrades. The use of best practices will give maximum output for the amount of analysis work invested to the safety margin determination and safety requirement verification. At the same time, the amount of analysis work is optimized for a specific plant design and the plant level risk is balanced against different external hazards.

4.5 Dissemination and training activities in BESEP

An Industrial Advisory Board (IAB) has been established to ensure that the results of BESEP are practicable and the relevant stakeholders are reached. IAB is involved in reviewing and commenting the project results and to give guidance and feedback based on the project intermediate results. The members of IAB are used as dissemination agents to deliver information about BESEP and its achievements to their own organizations and the professional forums they are involved in. This will ensure that BESEP results have a higher impact at both national and international levels.

Currently, the IAB has five members from different European organizations with strong regulatory body representation. In the beginning of 2022, a joint workshop was arranged with IAB to discuss the requirement baseline and other results of Work Package 2. The IAB considered the BESEP requirements as a good, but not exhaustive, set of requirements. IAB considered it important to have Defence-in-Depth related topics well represented in the BESEP requirement topics, which they are.

In addition to the IAB, the results of BESEP are communicated though the BESEP web pages (https://www.besep.eu).

5 General conclusion

The focuses and interaction areas of NARSIS, R2CA and BESEP projects are illustrated in Fig. 8. As can be seen from the figure, the three projects cover a wide range of assessment methodologies in nuclear safety. The projects prove that the European research and development framework is the convenient environment for the improvement of safety assessment methodologies. The stringent safety requirements call for proven and justified safety assessment methodologies to be applied in the European nuclear industry. The European research and development programs bring together the different sides of nuclear industry, i.e. utilities, vendors, national safety authorities and technical support organisations, and benefits from their know-how and expertise.

The achieved and expected key results from the projects help improve the best practices for the safety assessment of internal and external events and for the planning of mitigation strategies. The results support the harmonization of safety assessment methodologies between European countries applicable to different existing NPP designs and foreseen concepts, such as Small Module Reactors. The projects help tighten cooperation between participants from different countries in Europe and bring together experts from the different areas of safety assessment, such as Deterministic safety analysis, Probabilistic safety analysis and Human factors engineering. Last, but not least, the projects foster new experts for the industry, who eventually take the responsibility of continuous development in nuclear safety.

Conflict of interests

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

Funding

The NARSIS, R2CA and BESEP projects have been cofunded by the European Commission and performed as part of the EURATOM Horizon 2020 Programmes respectively, under contract 755439 (NARSIS), 847656 (R2CA) and 945138 (BESEP).

Data availability statement

There are no special data nor any repository apart from what is provided on the projects or EU website.

Author contribution statement

This paper is an attempt to summarize the main elements regarding the three targeted projects, each author having contributed on behalf of his/her project consortium.

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FISA 2022
EURADWASTE'22

SESSION 2: ADVANCED NUCLEAR SYSTEMS AND FUEL CYCLES

Co-chair: Hamid AIT ABDERRAHIM (BE, SCK-CEN)

Co-chair: Jan PANEK (EC, DG ENER)

Rapporteur: Teodora RETEGAN-VOLLMER (RO, Expert)

SESSION 2- SUMMARY

Teodora RETEGAN VOLLMER

Objectives

The session was started by the introductions from the co-chairs Dr. Hamid Ait Abderrahim (SCK-CEN) and Mr. Jan Panek (European Commission – DG ENER). They presented the international background on advanced nuclear systems and fuel cycles and stressed the importance of further development of the emerging as well as current technologies.

After the brief introductions, presentations were held, in which numerous projects and results were presented. The interest and participation of the audience have been very high during this whole session. Some presented finished and on-going projects have clearly showed the success of the EURATOM funding programme. The presentations were grouped by topics and technologies, and they were largely discussed during the session. The main brief highlights are given below.

Brief Summary

In this session, some of the EURATOM Programme priorities were addressed, which are of paramount importance as these projects and activities are contributing directly to the criteria for taxonomy compliance of nuclear projects in line with the recommendations of the JRC report.

Making nuclear energy more sustainable and fitting the Net zero objective by 2050 will require innovative thinking and technology breakthroughs. It should allow the closing of the nuclear fuel cycle as well as advances in material science and the processing and disposal of nuclear waste, including HLW.

Realizing the potential of nuclear energy to contribute fully to the decarbonization of our energy system will require extending the portfolio of nuclear technologies, in large-scale installations as well as future SMRs, beyond electricity production towards other applications, such as heat and hydrogen production.

This needs to happen timely and at the same time with full respect of utmost priority on nuclear safety, transparency, and public acceptance.

Summary

In this session, several selected projects were presented, all of them being under the umbrella of the topic of advanced nuclear systems and nuclear fuel.

In order to give a good background for the whole session, a comprehensive keynote talk was held on global trends on nuclear power, where the main highlights of the state of the art in the world of advanced reactors was given, including the SMR and their integration in the hybrid technologies and how IAEA is currently working for this purpose was presented.

Also, the IAEA's new platform, SCORPION (Small Modular reactors Portal) was announced, and the aim was that the platform will be launched in July 2022. The portal is dedicated to coordination and resources for SMRs. As well, IAEA's Nuclear Harmonization & Standardization Initiative -NHSI was presented.

Further, the European Sustainable Nuclear Industrial Initiative (ESNII) was presented. Its main goals are supporting the demonstration of Generation IV Fast Neutron Reactor technologies. Its support to relevant research infrastructures, fuel facilities, research and development (R&D) work was highlighted.

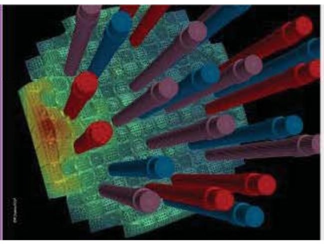
In order to emphasize the work performed on closing the fuel cycle with Gen IV reactors and research on in-pile behaviour and recycling of mixed oxide fuels, the European project PUMMA (Plutonium Management for More Agility) was presented. The project is dedicated to different Pu management options in the fourth-generation systems and to assess the impact on the entire fuel cycle and a throve of very relevant data were discussed. It was emphasized that PUMMA aims at being the link between Europe and other international organizations: fuel cycle studies at IAEA and OECD, GEN-IV systems at ESNII and GIF, and studies on fuel materials at OECD.

For the Partitioning and Transmutation and their contribution to an EU strategy for HLW management, three projects dedicated to the topic were presented highlighting their contribution to an EU strategy of HLM management. The projects were focusing on partitioning Am from PUREX raffinate, development, improvement, and validation of fuel performance codes for MA bearing fuel, the safety of the driver fuel of the MYRRHA ADS system and finally ADS system safety. Also, further another focus was on MYRRHA and ALFRED as the demonstrators of ADS and lead-cooled fast reactors (LFR) assessing the augmented safety of heavy liquid metal systems by addressing retention mechanisms of fission products in case of barrier failure within the fuel pin system, the coolant system, and the containment system. A newly approved project which will support ALFRED and MYRRHA pre-licensing and use maturity of design to take concrete steps towards PSAR was also mentioned.

For the innovative Gen-IV Fuels and Materials, EERA-JPNM, Fission and Fusion, the Organisation of the European Research Community on Nuclear Materials (ORIENT-NM) have been presented. The organization explores the possibility, and critically assesses the added value, of establishing a Co-Funded European Partnership (CEP) to support a coordinated European research and innovation programme on nuclear materials, according to the presentation and thus positively impacting Europe's competitiveness in the nuclear field at world scale.

For the Nuclear Cogeneration with High Temperature Reactors, the Nuclear Cogeneration Industrial Initiative (NC2I) was presented as one of the three pillars of the (European) Sustainable Nuclear Energy Technology Platform (SNETP).

Lastly, for the nuclear data activities, the Coordination and Support Action ARIEL (Accelerator and Research reactor Infrastructures for Education and Learning) and the Research and Innovation Action SANDA (*Solving Challenges in Nuclear Data for the Safety of European Nuclear facilities*) were briefly presented highlighting important results reached and despite some difficulties in scientific work and mobility of researchers.



FISA 2022

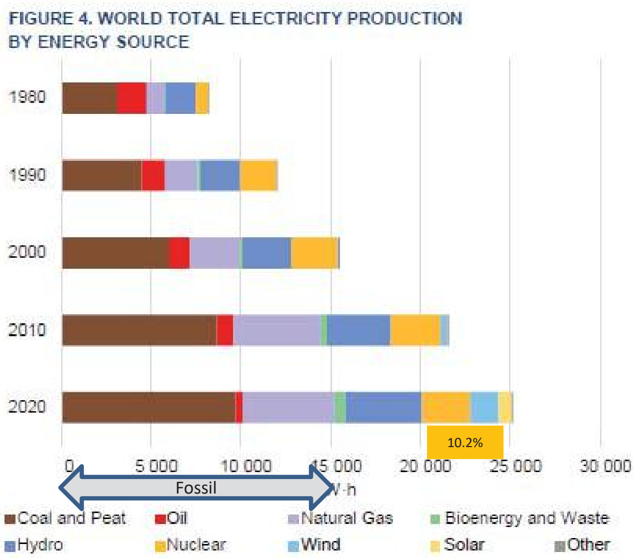
30 May - 3 June 2022
Lyon, France

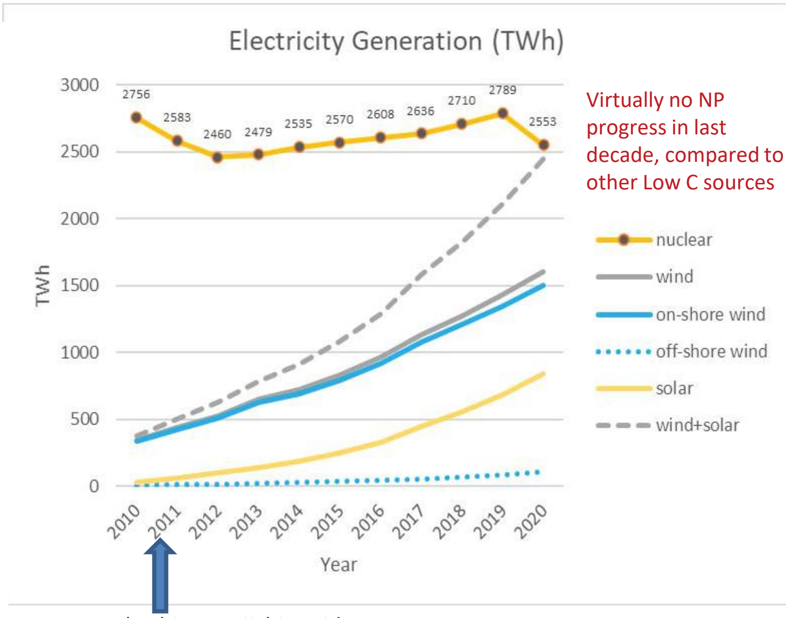
Global Trends in Nuclear Power:

Advanced Reactors Including SMRs: Challenges and Opportunities for Increased Sustainability

Stefano MONTI
Head of Nuclear Power Technology Development Section
International Atomic Energy Agency

Electricity generation still dominated by fossil fuels (>60%)





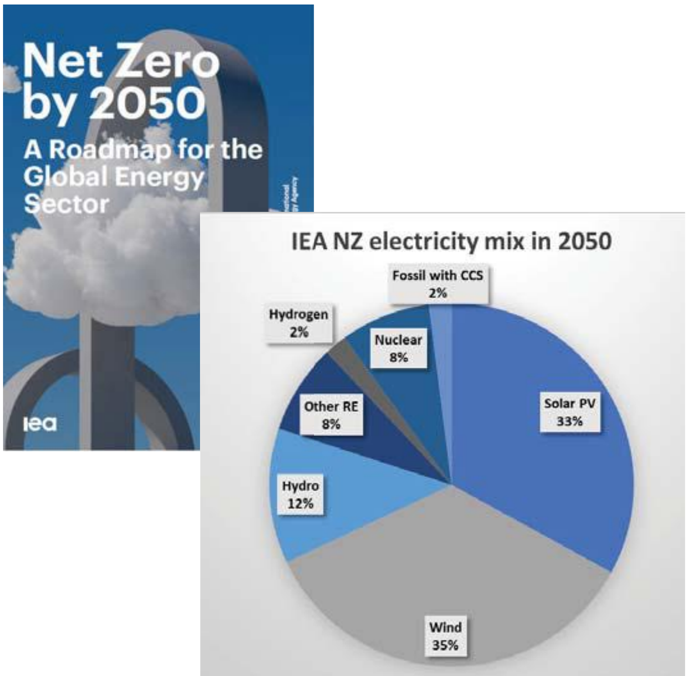
Virtually no NP progress in last decade, compared to other Low C sources

Fukushima Daiichi accident, 11 March 2011

IAEA and IEA data

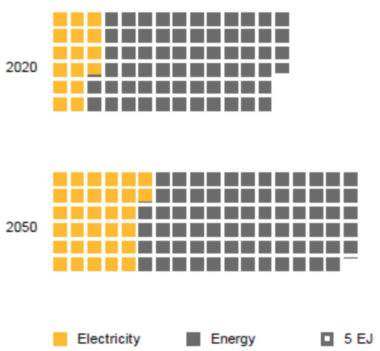
IEA Roadmap to Net Zero (May 2021)

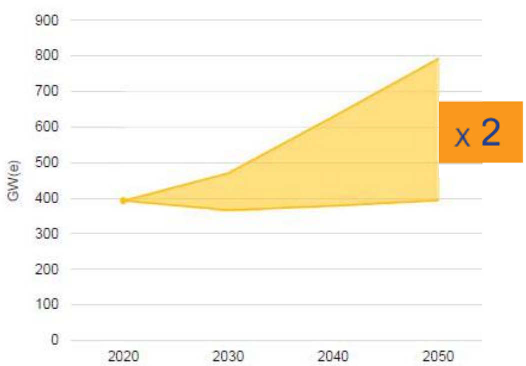
- Very little fossil in the mix → roadmap is massive deployment of renewables + **doubling of nuclear generation by 2050**
- High level of electrification (demand x 2.5)
- Nuclear generation (x 2) – share in electricity mix 10% to 8%
- Share of nuclear in heat 4%

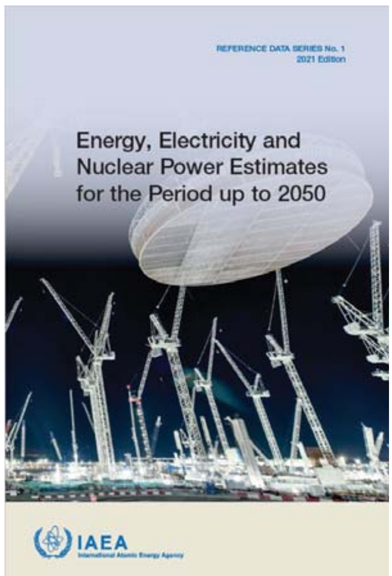


IAEA projections to 2050

- Energy, Electricity and Nuclear Power Estimates for the Period Up to 2050







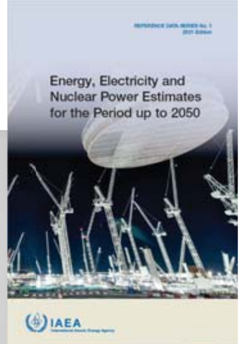
- Electricity consumption expected to double
- Share of electricity in energy consumption increases by 10 pts

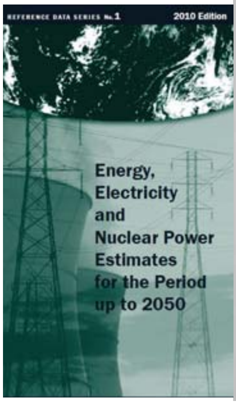
- High case: **More than doubling of nuclear capacity**, share slightly lower than 10%
- Low case: capacity by 2050 equal to 2020, share ~7.5%

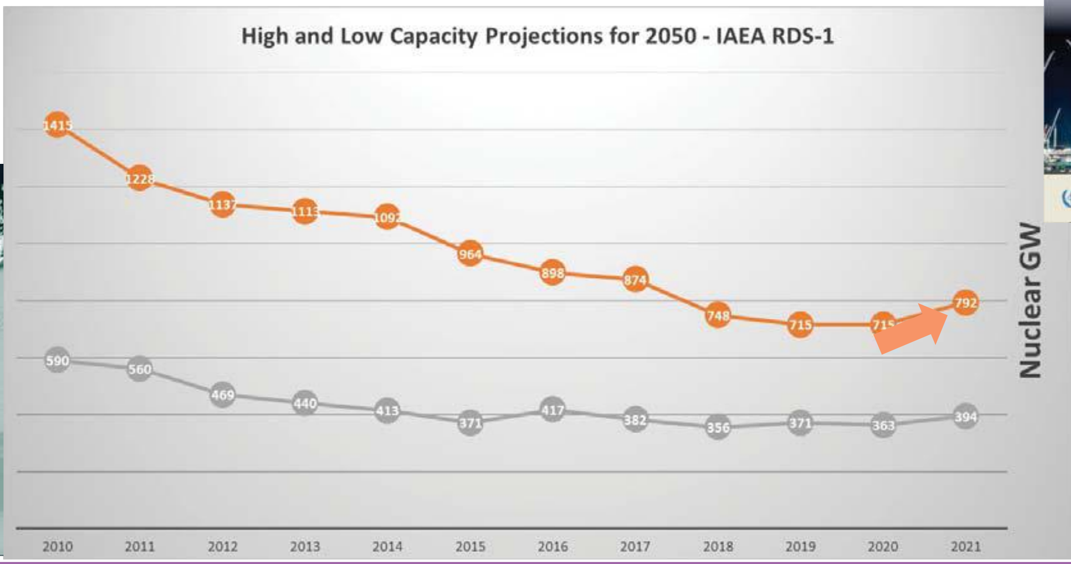
Released Sept. 2021

History of projections: 2021, one-off or the start of a trend?

[IAEA Increases Projections for Nuclear Power Use in 2050 | IAEA]



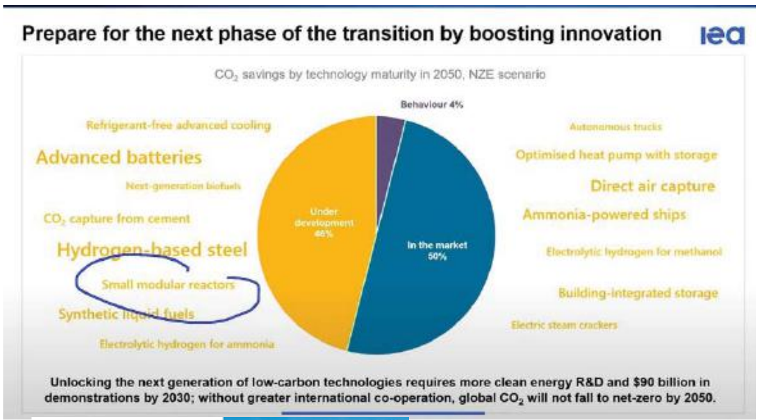


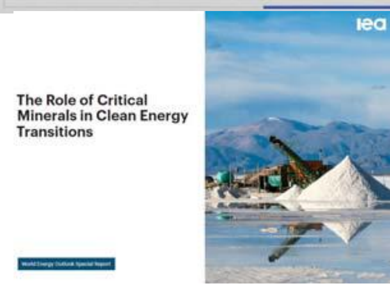


IEA Roadmap to Net Zero

2 important caveats:

1. Nearly half of the emissions reductions to 2050 come from **technologies that are not yet commercialized** → need to accelerate demonstration → market
   - For nuclear, this means the **demonstration & commercialisation of advanced reactor technologies (and fuel cycles)**
2. Issue of **supply of critical minerals**
   - More an issue for renewables (wind, solar) and grid and battery technologies than for nuclear power

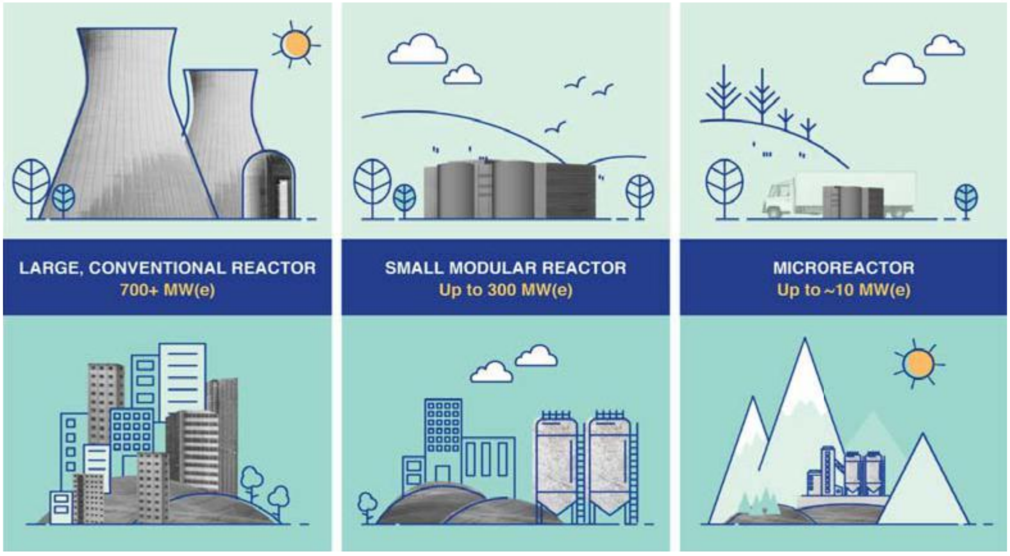




Nuclear energy is one of the low-C technologies with the lowest (critical) mineral intensity

Small Modular Reactor (SMR) Technology

Advanced Reactors that produce typically up to 300 MWe, built in factories and transported as Modules to sites for Installation as Demand arises



- Modular construction
- Ability to fabricate major components of the nuclear steam supply system in a factory environment and ship to the point of use
- Limited on-site preparation
- Substantially reduce the lengthy construction times
- Multi- module as per energy demand

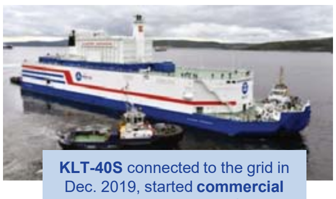
SMR – Deployment Horizon by 2030

SMRs at advanced stage:

1 in commercial operation
1 connected to grid
2 under construction
1 received SDA from U.S. NRC

HTR-PM first unit connected to grid on 20 Dec. 2021, commercial operation expected in **2022**

CAREM-25 construction halted in 2019, then restarted in 2019, expected to start **operation in 2023**



KLT-40S connected to the grid in Dec. 2019, started **commercial operation** at the end of **May 2020**

ACP100 construction officially started on 13 July 2021, at Changjiang NPP in Hainan province, scheduled commercial operation by the end of **2026**

NuScale received SDA issued by U.S.NRC in Sept. 2020. The first module is expected to be operational by **mid-2029**

10th European Commission Conference on EURATOM Research and Training in Safety of Reactor Systems
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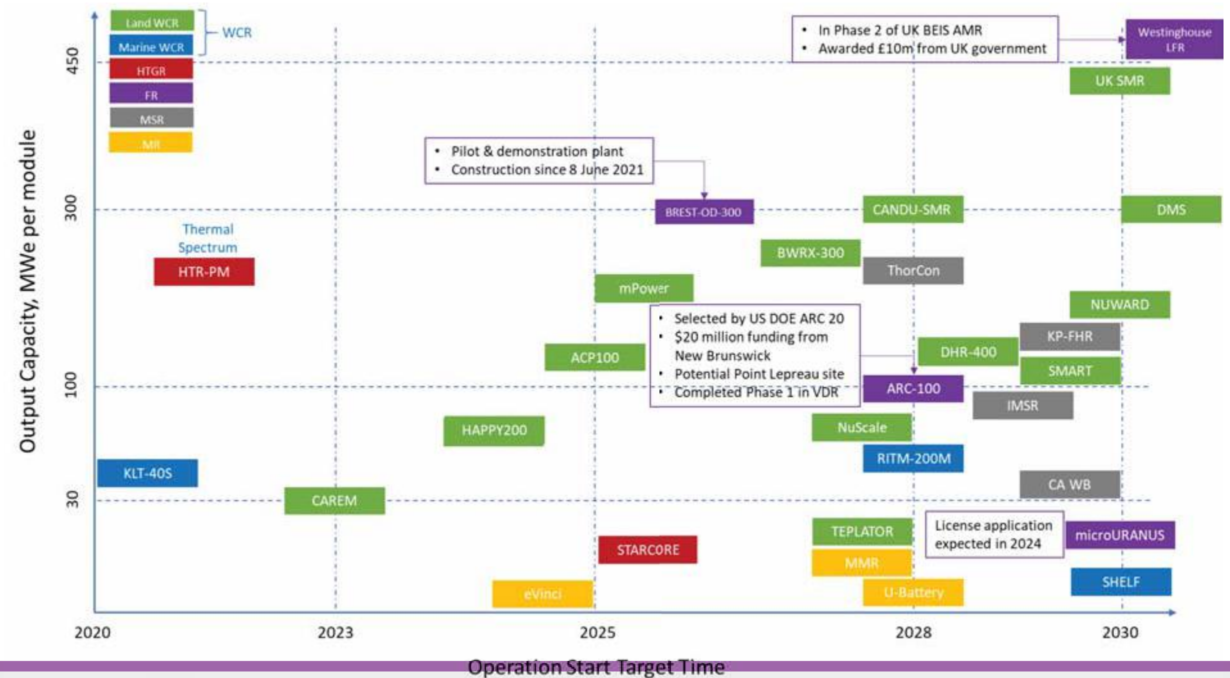
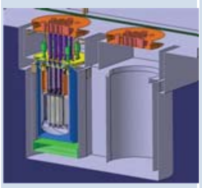
SMR – Deployment Horizon by 2030



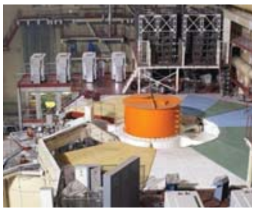
Microreactor – Designs

Six designs included in the IAEA SMR ARIS Booklet (2020 edition)

Energy Well	MoveluX	U-Battery	AURORA	eVinci	MMR
					
Design Status: Pre-conceptual design, neutronics, thermohydraulic and materials studies done	Design Status: Conceptual design, complete test without fuel, FOAK demo after 2030	Design Status: Conceptual design, VDR with CNSC	Design Status: Accepted combined license application by the US NRC	Design Status: Conceptual Design, vendor design review with CNSC	Design Status: Preliminary Design, vendor design review with CNSC
• Centrum výzkumu Řež, Czech Republic • Fluoride HTR, Pool type • Molten Salt FLiBe coolant • 20 MWt / 8 MWe • Forced circulation • TRISO fuel • Enrichment: ~ 15% • No onsite refueling • Refueling cycle: 84 months	• Toshiba, Japan • Heat-Pipe cooled • Calcium-hydride moderated reactor • 10 MWt / 4 MWe • Natural circulation • Silicide fuel, Hexagonal • Enrichment: < 5% • Continuous operation • 100 m² plant footprint	• URENCO, UK • HTGR • 10 MWt / 4 MWe • Forced helium circulation • TRISO fuel (17-20% U235) • Hexagonal FAs • Enrichment: < 20% • 5 EPFYs core life • 30 year design life	• OKLO Inc., USA • Liquid Metal Fast Reactor • Liquid metal coolant, no moderator • 4 MWt / 1.5 MWe • UZr metal fuel (<20% U235) • Refueling cycle: up to 20 years • Design life: 20 years per deployment	• Westinghouse, USA • Heat Pipe cooled • Metal hydride moderator • TRISO or another encapsulation • 7-12 MWt / 2-3.5 MWe per module • Enrichment: 5-19.75% • Refuel interval: 36+ months • No onsite refuelling, Replace reactor approach • Design life: 40 years	• USNC, USA, Canada • HTGR / micro-reactor / nuclear battery • 15 MWt / 5 MWe • Core Outlet Temp: 630°C • FCM TRISO graphite, Hexagonal fuel block • Enrichment: HALEU 19.75% • Refuel interval: fuelled once during lifetime

Fast Reactors in Operation & under Commissioning

Country	Name	Coolant	Purpose	Power (th/e) MW	Year (Op.)	Status
Russia	BOR-60	sodium	experimental	**60/10**	1969	operating
	BN-600	sodium	prototype	**1470/600**	1980	operating
	BN-800	sodium	commercial	**2100/880**	2015	operating
China	CEFR	sodium	experimental	**65/20**	2011	operating
India	FBTR	sodium	experimental	**40/13**	1985	operating
	PFBR	sodium	prototype	**1250/500**	(Est.) 2022	commissioning
Japan	JOYO	sodium	experimental	**150/--**	1978	license renew



BN-600
Russia, 1980

BN-800
Russia, 2015

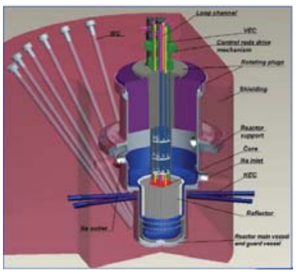
CEFR, 20 MW(e)
China, 2011

FBTR, 13 MW(e)
India, 1985

PFBR, 500 MW(e)
India, 2022

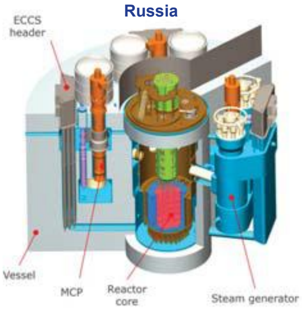
Fast Reactors under Construction

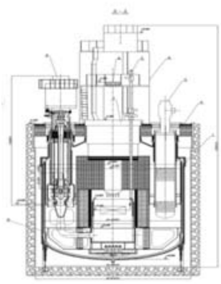
Country	Name	Coolant	Purpose	Power (th/e) MW	Year (Op.)	Status
Russia	MBIR	sodium	Experimental/MTR	**150/50**	~2028	construction
	BREST-OD-300	lead	demonstrator	**700/300**	~2026	construction
China	CFR600 x2	sodium	prototype	**1500/600**	~2023	construction (2 units)



MBIR, Russia

BREST-OD-300
Russia

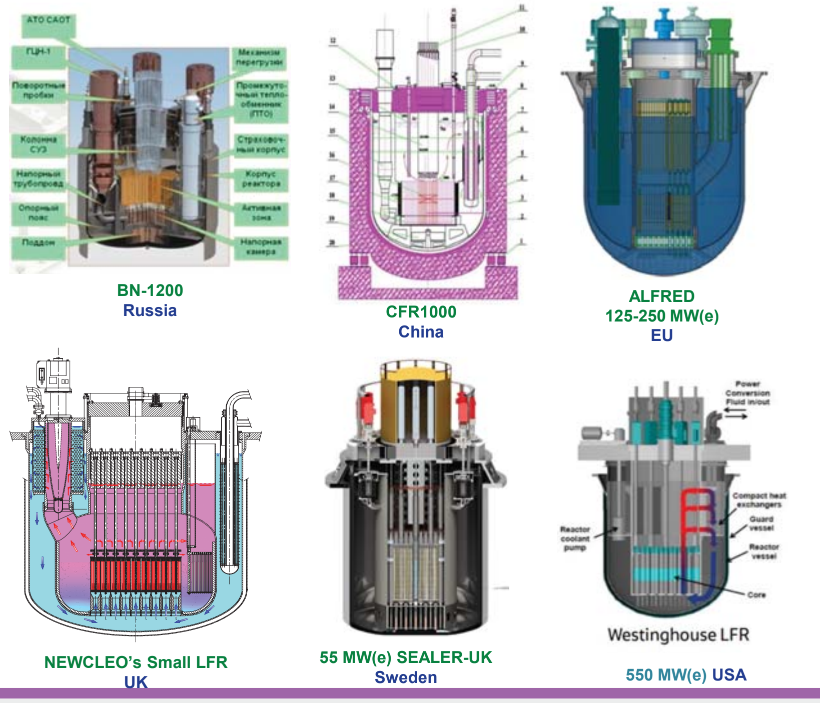




CFR600, China

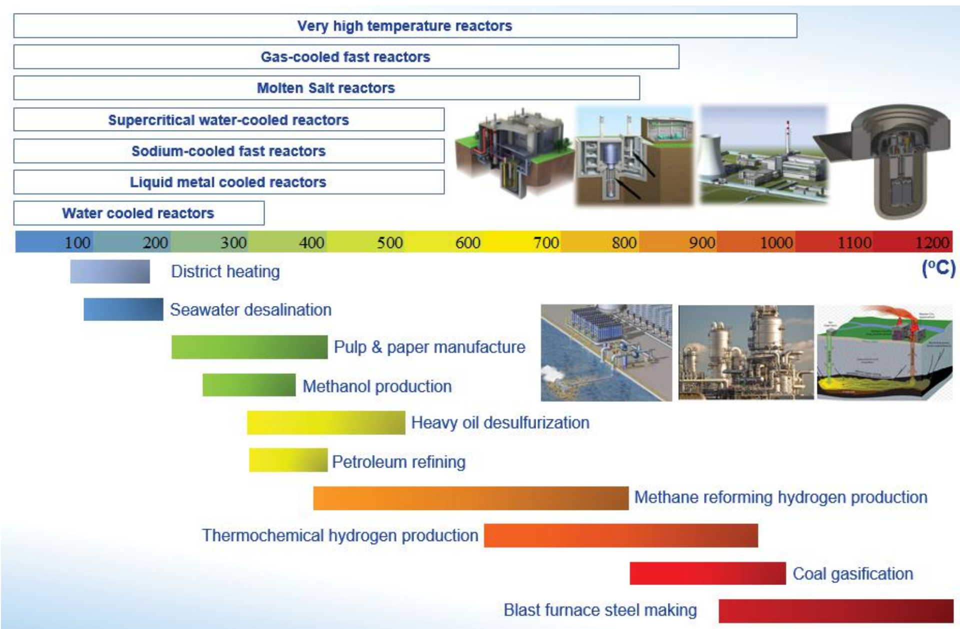
Fast Reactors under Development and Design

Country	Name	Type - Coolant
Russia	BN-1200	SFR sodium
	SVBR-100	LFR LBE
	MOSART	MSR molten salt
China	CFR1000	SFR sodium
	CLFR-300	LFR LBE/lead
	CLEAR-M10A	LFR LBE
	CLEAR-I	LFR LBE
	CLEAR-M10D	LFR lead
India	FBR1 & 2	SFR sodium
EU	ESFR	SFR sodium
	ALFRED	LFR lead
	ALLEGRO	GFR helium
	MSFR	MSR molten salt
Belgium	MYRRHA	LFR-ADS LBE
France	ASTRID	SFR sodium (suspended)
R. of Korea	KALIMER-600	SFR sodium
	PGSFR	SFR sodium (suspended)
UK/Italy	LFR-AS-200	LFR - Lead
UK/Sweden	SEALER-UK	LFR lead
USA	Westinghouse LFR	LFR lead
	NATRIUM	SFR sodium
	VTR (PRISM)	SFR sodium
	SSTAR	LFR lead (suspended)
	MCSFR	MSR chloride salt
	EM2	GFR helium
	KP-FHR	MSR fluoride salt
	LLC ARC-100	SFR sodium



ssion Conference on EURATOM Research and Training in Safety of Reactor Systems
Lyon, France

Reactor Technologies for Non-electric Applications



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Heat and H2: Prospects of using current fleet of NPPs

USA

US DOE commits $20M to create clean hydrogen from NP with Palo Verde project

China

Haiyang becomes first Chinese city to enjoy ‘zero-carbon’ heating with nuclear power

Russia

Kola nuclear power plant is building a hydrogen test facility

Canada

Bruce Power is exploring feasibility of using excess energy for hydrogen production

United Kingdom

UK Strategy lays out plans to use existing nuclear plants this decade for clean hydrogen production

India

Approved Nuclear Desalination Project at Madras Atomic Power Station (PHWR), Kalpakkam

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Heat and H2: Prospects of using advanced reactor technologies

Canada

- SMR Developers Focus on Process Heat
- Alberta’s oil sands producer considers capitalizing heat from SMRs

China

- HTR-PM: Feasibility study on the application and design of nuclear hydrogen and cogeneration in industrial sector
- Various SMRs designs (e.g. ACP100 SMR) for electricity production, heating, steam production or seawater

Finland

- Low-temperature District Heating and Desalination Reactor

Japan

- HTGR cogeneration plant for hydrogen production

Poland

- HTGR for district heating; MMR for hydrogen production

Republic of Korea

- SMR for desalination/ district heating

Russia

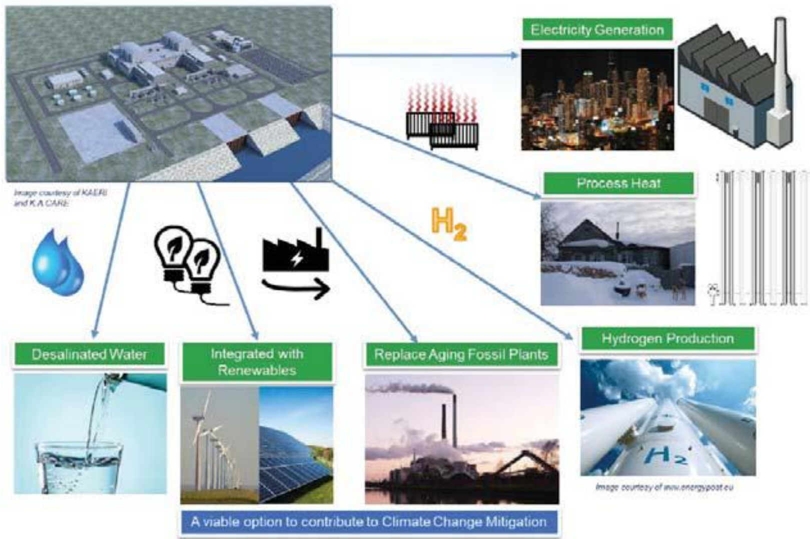
- Floating SMRs for cogeneration, HTGR for hydrogen production

United Kingdom

- SMRs, AMRs for cogeneration and hydrogen production

United States

- Various SMR designs for hydrogen production, water desalination, district heating



10th European Commission Conference on EURATOM Research and Training in Safety of Reactor Systems
30 May - 3 June 2022 | Lyon, France

Challenges Facing Successful Deployment of SMR & Innovative Reactor Technologies

- **Demonstration of Safety and Performance**
  - Above all as far as the most “revolutionary” designs
- **Demonstration of Economic Competitiveness**
  - Modularization
  - Economies of Serial Production
  - Integration with other clean energy sources
- **Harmonization and Standardization** *to enable the effective global deployment of standardized fleets of safe and secure advanced reactors*:
  - Common industrial approaches (e.g. codes & standards, supply chain, etc.) by technology holders and users’ requirements and criteria by operators
  - Harmonized regulatory approaches between national regulatory bodies, including a common set of internationally recognized requirements (*while maintaining national responsibilities*)
- **Development of nuclear infrastructure for deployment**
  - Embarking and expanding countries

IAEA Platform on SMRs and their Applications

Objective: Provide national governments, experts and regulators with integrated Agency-wide support on all aspects of SMR development, deployment and oversight

What?

- IAEA’s internal governance to coordinate activities consistently with MSs needs and requests
- Single access point for MSs and stakeholders

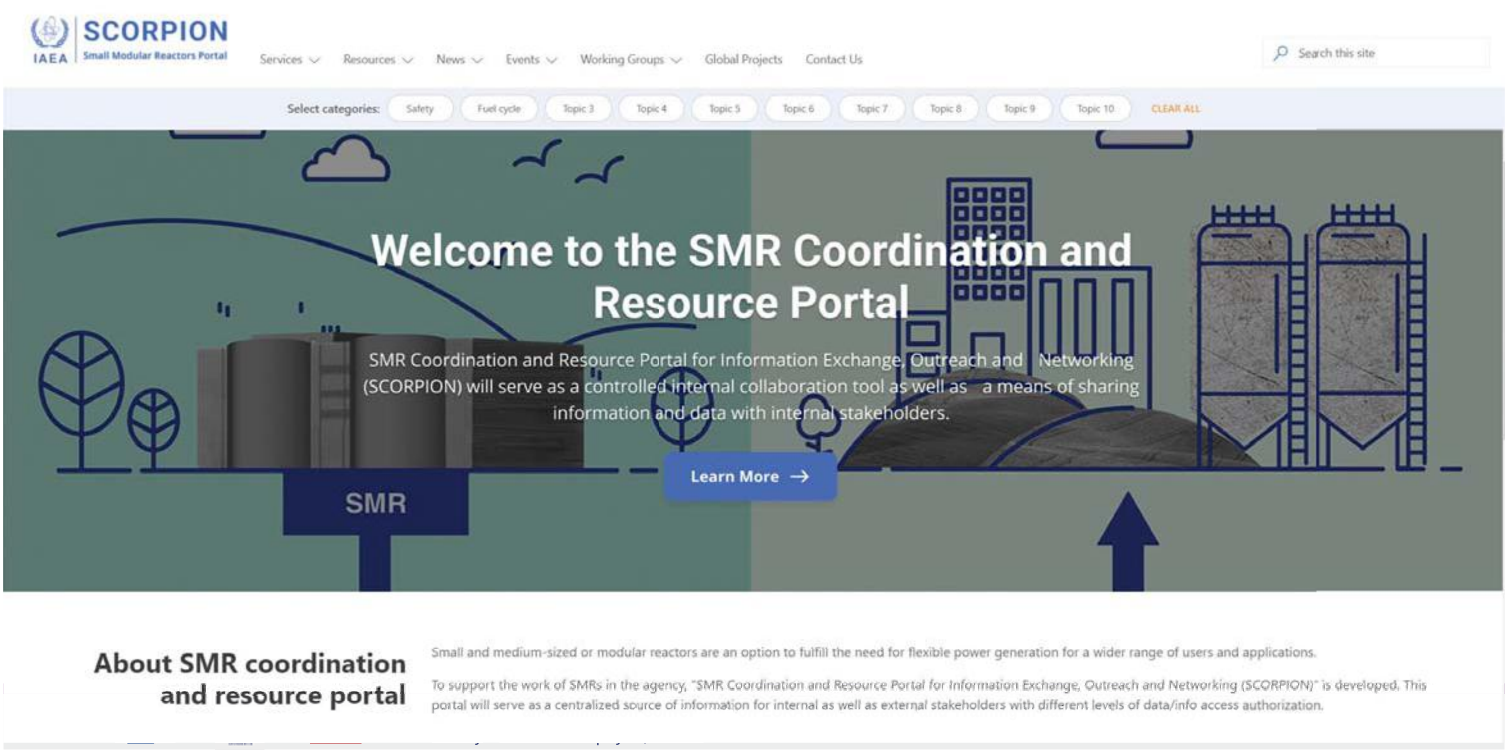
How?

- Develop medium-term strategy on SMR and its applications
- Create enabling environment and a portal to enhance internal as well as external communication

Why?

- Member Sates request for consistent, coordinated and optimized Agency support
- Effective and efficient support to Member States, International Organizations and stakeholders willing to cooperate with the IAEA

SCORPION: 1st Release in July



IAEA Nuclear Harmonization & Standardization Initiative - NHSI

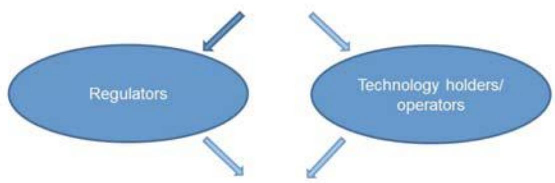
Regulatory Track

- Developing harmonized regulatory approaches between national regulatory bodies, including a common set of internationally recognized requirements, while maintaining national responsibilities for safety and security.

Industrial Track

- Developing common industrial approaches by technology holders and users' requirements and criteria by operators, consistent with fair global competition, intellectual property rights protection, and not hampering innovation and continuous improvement.

Two separate, complementary tracks



IAEA as facilitator and integrator

Take Aways

- Nuclear has unique attributes to play a major role in the **transition to Net Zero**:
  - Only technology that can provide **at scale low C electricity, heat and hydrogen**
  - **Reduced land footprint** and **use of critical minerals**, much **higher capacity factors**
- It can complement renewables – dispatchability, flexibility, **security of supply** - and support low carbon H_2 production.
  - It can **lower the costs of the transition** to carbon neutrality.
  - Offers a **less risky pathway** to net zero (*100% renewables would need extremely high deployment rates + massive storage capabilities + higher dependency on critical minerals*)
- For nuclear to fulfill its full role – *i.e. massive production of all major clean energy carriers* – consistently with net zero roadmap there is the **need to quickly advance design and demonstration of advanced reactor technologies, including SMRs and FRs**

Hotei-san: "focus on the moon and not on the finger pointing to the moon…"

IAEA International Atomic Energy Agency

IAEA intends to continue the conversation on nuclear energy's role in the energy transitions at the Ministerial Conference on Nuclear Power (October 2022) and COP27 (November 2022).


8 December 1953


1 to 23 October 1957


11 December 1957


1959


10 December 2005

1958 to 1979


23 August 1979

Thank you for your attention!

Contact:
Stefano MONTI
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Atoms for Peace and Development…

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REVIEW ARTICLE

OPEN ACCESS

Review of Euratom projects on design, safety assessment, R&D and licensing for ESNII/Gen-IV reactor systems

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Abstract. Five Euratom projects launched since 2017 in support of the development of ESNII/Generation-IV reactor systems are briefly presented in the paper in terms of key objectives, results, and recommendations for the future. These projects focus on various aspects of the following ESNII/Generation-IV systems: Sodium Fast Reactor, Gas Cooled Fast Reactor, Supercritical Water Cooled Reactor, and Molten Salt Fast Reactor. The paper does not consider EU projects focused on the Gen-IV reactor technologies based on the use of heavy metals as a coolant because these projects are reviewed in a different paper.

1 Introduction

The European Sustainable Nuclear Industrial Initiative (ESNII) aims at demonstrating Generation IV Fast Neutron Reactor technologies and supports relevant research infrastructures, fuel facilities, and research and development (R&D) work. ESNII was established in 2010 under the umbrella of the Sustainable Nuclear Energy Technology Platform (SNETP) to promote the European Union's (EU) contribution to Generation-IV reactors.

ESNII supports three technologies and related projects: Lead-cooled Fast Reactor (LFR) and the ALFRED project; Gas-cooled Fast Reactor (GFR) and the ALLEGRO project; Sodium-cooled Fast Reactor (SFR) [1].

The EU framework programs have supported a number of R&D activities on these systems as well as on other Generation-IV technologies, including a European Sodium Fast Reactor (ESFR) and The Molten Salt Fast Reactor (MSFR) as well as some cross-cutting activities. The EU projects focused on LFRs are reviewed in a different paper.

The paper briefly presents in terms of key objectives, results, and recommendations five Euratom projects started since late 2017 in support of the infrastructure and R&D of the four Generation-IV reactor systems (Fig. 1). Table 1 presents the list of the project acronyms, participants and coordinators. Figure 2 presents the budgets and time spans of the presented projects.

2 ESFR-SMART: European Sodium Fast Reactor Safety Measures Assessment and Research Tools

2.1 Key objectives

To improve the public acceptance of the future nuclear power in Europe we have to demonstrate that the new reactors have significantly higher safety levels compared to traditional reactors. The ESFR-SMART project [2] aims at enhancing further the safety of Generation-IV SFRs and in particular of the commercial-size European Sodium Fast Reactor (ESFR). The project aims at 5 specific objectives:

(1) produce new experimental data in order to support calibration and validation of the computational tools for each defence-in-depth level.
(2) Test and qualify new instrumentations in order to support their utilization in the reactor protection system.
(3) Perform further calibration and validation of the computational tools for each defence defense-in-depth level in order to support safety assessments of Generation-IV SFRs, using the data produced in the project as well as selected legacy data.

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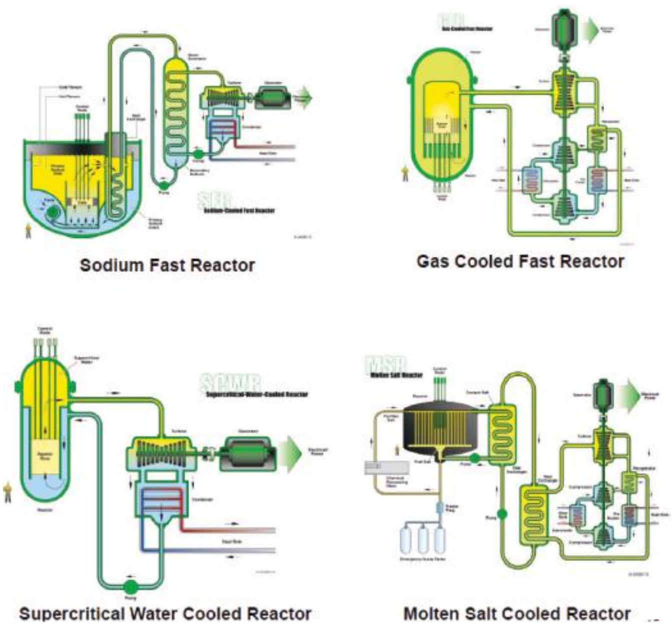


Fig. 1. Four Generation-IV systems supported by the considered EU projects.

(4) Select, implement and assess new safety measures for the commercial-size ESFR, using the GIF methodologies, the FP7 CP-ESFR project legacy, the calibrated and validated codes, and being in accordance with the update of the European and international safety frameworks taking into account the Fukushima accident.
(5) Strengthen and link together new networks, in particular, the network of the European sodium facilities and the network of the European students working on the SFR technology.

By addressing the industry, policymakers, and general public, the project is expected to make a meaningful impact on economics, EU policy, and society.

2.2 Key results

Originally scheduled for four years the project has been prolonged by one more year in order to accommodate the time delays mainly related to the COVID-19 impact on the experimental activities.

2.2.1 Experimental programs

Two specific objectives of the project address new experiments: (1) to produce new data to support calibration and validation of the computational tools for each defence-in-depth level; (2) to test and qualify new instrumentations in order to support their utilization in the reactor protection system. In particular:

– new tests on chugging boiling regime (CHUG) have been conducted to support the computational activities on analysis of the ESFR behaviour under sodium boiling conditions [3].
– New tests on corium jet impingement (HAnSoLO) have been conducted using a water-ice system as a model of the corium-catcher system [4].
– The first-ever test (JIMEC-I) on the ablation of a thick steel substrate with a high-temperature, high-velocity steel jet test was successfully performed [4]. With a jet diameter of 40 mm and jet temperature of about 2100 °C, the 40 cm substrate was ablated through the bottom in 31 s. The pooled effect was clearly detected during the course of the ablation.
– Eddy-current flow meters (ECFM) were qualified for positioning above the fuel assemblies in order to detect possible blockages of the sodium flow [5].

2.2.2 Benchmarking of codes

One of the specific objectives of the project is to perform further calibration and validation of the computational tools for each defence-in-depth level. In particular:

– a new calculational benchmark has been created for the startup core of the Superphénix (SPX) Sodium Fast Reactor based on open publications [6,7].
– A computational exercise on sodium boiling modelling was conducted based on a KNS-37 sodium loop experiment featuring sodium boiling in pin-bundle geometries [8].

2.2.3 Proposal of new safety measures

The key idea is to make the next step in developing the large-power (1500 MWe/3600 MWt) SFR concept, following up the “line” of the Superphénix 2 (SPX2), European Fast Reactor (EFR) and ESFR designs and using the set of the GIF objectives as a target. In particular:

– the ESFR core design modifications were aimed at improving the core map symmetry; optimizing the void effect, and facilitating the corium relocation toward the corium catcher [9].
– The ESFR system modifications were aimed at simplifying the overall design (see Fig. 3) and improving the safety functions: control of reactivity, heat removal from fuel, and confinement of the radioactive materials [10].

2.2.4 Evaluation of core performance

After the new core design was proposed studies were launched to check how this core design will influence the neutronics and fuel performance. In particular:

– six-batch burnup calculations were performed using a Monte Carlo code and the core state specification at the End of the Equilibrium Cycle was defined, including the 3D isotopic composition needed to calculate the reactivity coefficients and kinetics parameters as well as the 3D power distribution for the following-up thermal-hydraulic analysis [11].
– Fuel performance for a typical cycle was analysed with a number of fuel performance codes and the gap heat conductance correlation was derived for the subsequent steady-state and transient thermal-hydraulic analyses.

Table 1. Participants and coordinators of the considered EU projects (C = Coordinator, X = Partner).

	BE		CH	CZ					DE				ES		EU		FI	FR						HU		IT				LV	NL		PL	RO	SE		SK		SI		UA		UK					
	SCK-CEN	ENGIE LABORELEC	PSI	UJV REZ	EVALION	VSCT	CTU	CV REZ	GRS	KIT	HZDR	BGF	UPM	CIEMAT	JRC	ENEN	VTT	IRSN	CEA	FRAMATOME	EDF	LGI	UNI DE LORRAINE	EK-CER	BME	ENEA	POLITO	POLIMI	UNI PISA	IPUL	NRG	TU DELFT	NCBJ	RATEN	KTH	CHALMERS	VUJE	STU	IJS	ZAG	IPP CENTRE LLC	ENERGORISK	JACOBS	UNI CAMBRIDGE	UNI NOTTINGHAM	UNI SHEFFILD	NNL	SUM
ESFR-SMART			C						x	x	x		x	x	x			x	x	x	x	x	x			x				x						x							x	x			x	19
SAMOSAFER			x					x		x					x			x	x	x	x						x	x			x	C																12
ECC-SMART						x		C		x				x	x	x	x								x				x					x	x			x	x		x				x	x		16
ACES	x	x					x	x									C	x	x		x																			x		x						10
SafeG				x	x		x	x				x							x					x	x								x				C	x					x	x		x		14

2.3 Recommendations for the future

A list of recommendations for the research and development of ESFR was prepared and discussed and on this basis, a new European project ESFR-SIMPLE was submitted and approved by European Commission. The new project is planned to start at the end of 2022, providing therefore a continuity of research and development. ESFR-SIMPLE stands for "European Sodium Fast Reactor – Safety by Innovative Monitoring, Power Level flexibility and Experimental research" and aims at challenging the current ESFR design to improve its safety and economics through the implementation of innovative technologies in accordance with the ESNII roadmap. A small-power version of ESFR is planned to be developed in this project. A special focus of ESFR-SIMPLE on further improvement of safety and economics was set based on the conclusions derived in ESFR-SMART (in particular, such conceptual design simplifications as replacement of the safety vessel by the liner on the pit surface, integration of the decay heat removal systems in the secondary circuit and more compact design of the secondary system will be studied for the low-power option). The project has 5 specific objectives:

(1) rethink the ESFR design in order to simplify it and make it more cost-competitive, while still achieving resource sustainability and having safety reinforced by intrinsic behaviour. This can be accomplished by reducing the size of the reactor, which will also allow taking advantage of small modular reactor features such as transportability, modularisation, standardisation, and flexible operation, all ultimately leading to improved economics.
(2) Assess the impact of alternative technologies, such as metallic fuel and compact secondary system design, for the large-size ESFR on the economics and safety.
(3) Propose, develop and assess advanced methods of monitoring and processing operational data using Artificial Intelligence, e.g., to optimise fault detection in steam generators at an early stage.
(4) Produce new experimental data in order to assist in the qualification of innovative components, such as expansion bellows, core catchers and thermo-electric pumps.

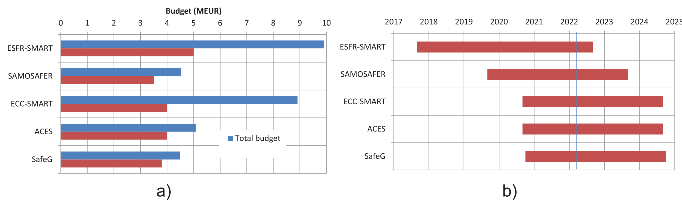


Fig. 2. Budget (a) and time span (b) of the considered EU project.

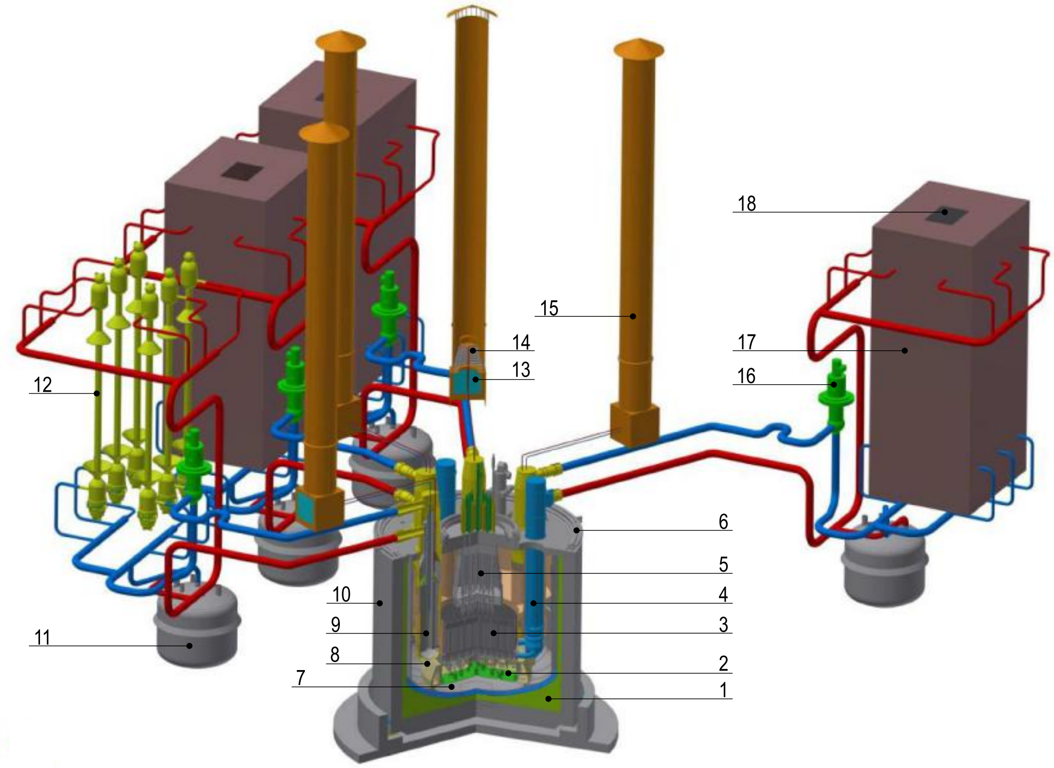
(5) Ensure that the knowledge generated in the project is shared not only among the project partner institutions but also with a wide range of stakeholders in Europe and internationally. The project activities will also be informed by the public and other stakeholders' perceptions of the risks and benefits of ESFR technology.

3 SAMOSAFER: Severe Accident Modeling and Safety Assessment for Fluid-fuel Energy Reactors

The ultimate aim of nuclear energy research is to develop a nuclear reactor that is inherently safe and that produces no nuclear waste other than fission products. The Molten Salt Fast Reactor (MSFR) has the potential to reach these goals. The most characteristic property of the EU MSFR design is the liquid fuel, which provides excellent options for reactivity feedback and decay heat removal. Furthermore, the continuous recycling of the fuel salt enables one to design a reactor either as a breeder reactor with in-situ recycling of all actinides or as a burner capable of incinerating the actinide waste from other reactor types. For these reasons, the SNETP has emphasized in its strategic research agenda of 2012 (Annexes on Thorium and Molten Salt Reactors) the merits of the MSR as the long-term option for safe and sustainable nuclear power.

3.1 Key objectives

The goal of SAMOSAFER is to develop and demonstrate new passive safety barriers for more controlled behaviour



1: Insulation with steel liner
2: Core catcher
3: Core
4: Primary pump
5: Above-core structure
6: Pit cooling system (DHRS-3)
7: Main vessel
8: Strongback
9: IHX
10: Reactor pit
11: Secondary sodium tank
12: Steam generator
13: Window for air circulation (DHRS-1)
14: Sodium-air HX (DHRS-1)
15: Air chimney (DHRS-1)
16: Secondary pump
17: Casing of SGs (DHRS-2)
18: Window for air circulation (DHRS-2)

Fig. 3. General view of ESFR-SMART reactor.

of MSR in severe accidents, based on new simulation models and tools validated with experiments. The grand objective of SAMOSAFER is to ensure that the MSR can comply with all regulations expected in 30 years' time.

After the successful completion of the project, the simulation models and tools can be used by the nuclear industry, and the innovative safety barriers can be implemented in new MSR designs like the MSFR (Fig. 4). This will lead to increased safety margins in future Gen-IV reactors to ensure they will comply with future more stringent safety standards. The grand objective has been divided into the following specific sub-objectives:

(1) investigating and translating the existing defence-in-depth safety approach to MSR.
(2) Developing a rigorous and well-established simulation code suite through:
  (a) developing theoretical models of physics and thermo-chemical phenomena relevant to the safety assessment and severe accident analysis in MSR, such as salt solidification and melting models;
  (b) developing simulation models and tools to be included in cutting-edge computation codes;
  (c) coupling existing computation codes to deliver an integrated simulation approach to complex phenomena, such as neutronics-CFD coupled to thermo-chemistry;
  (d) simulation models for the computation of multi-physics phenomena in existing codes.
(3) Developing and applying experimental setups for the validation of simulation models and tools through:
  (a) developing new experimental facilities for the validation of new theories and new models as well as for the validation of existing codes to new applications;
  (b) modifying and applying existing experimental facilities to generate data for validation purposes;
  (c) using experimental setups and computational schemes to generate data for the extension of user databases, such as the molten salt database at JRC-Karlsruhe.
(4) Design of advanced barriers for severe accidents in MSR, such as freeze plugs, drain tanks, and fission product extraction/immobilization methods, as well as the demonstration of the effectiveness of these barriers.
(5) Update of the MSFR design with all improvements and recommendations from aforementioned studies.

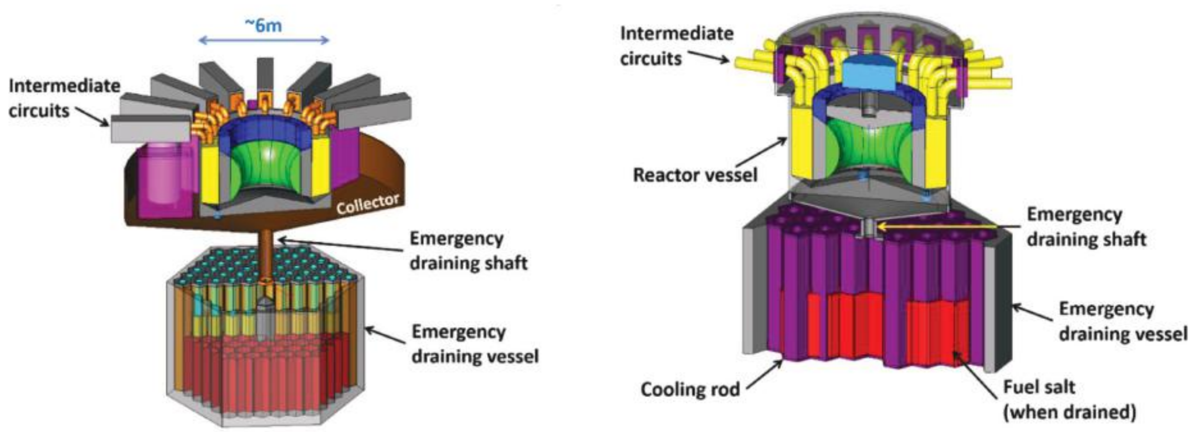


Fig. 4. Schematic design of the primary circuit of the MSFR showing the reactor vessel and Emergency Draining System for the fuel salt.

(6) Attracting and educating students, postdoctoral researchers and trainees in the exciting field of MSR and advanced Gen-IV nuclear energy.
(7) Develop and train a software user community and deliver the results of our project to future users to speed up the development of the MSR value chain.

Besides the Work Package (WP) on project management (WP8), the SAMOSAFER project contains seven specialized parts.

WP1 lays the foundation for the safety approaches applied in WPs 2–6. It compares the EU nuclear safety standards with the MSR safety case and extrapolates these to future requirements, identifies the risks, and the postulated initiating events for the Fuel Treatment Unit (FTU) like was done for the core and the Emergency Draining System (EDS) in the SAMOFAR project. This WP also explores and gives guidelines for the safety approaches to be taken for the nuclide retention in WP2, the source term redistribution in WP3, the radionuclide confinement in WP4, the decay heat removal in WP5, and the reactivity control in WP6. Furthermore, a global overview of integral experiments will be made to provide benchmark cases and to identify the needs for integral experiments. This WP is carried out with the strong involvement of the nuclear industry and TSO.

The aim of WP2 is to provide tools and data necessary to control the fuel salt behavior in the MSR and to assess the influence of fission products and corrosion products on the fuel salt properties. To this end, we extend our current code systems (DG-FLOW and OpenFoam) developed in SAMOFAR with a new thermochemistry module and perform extensive experimental validation and modelling. We perform Post Irradiation Examination (PIE) on the SALIENT-01 samples irradiated in the High Flux Reactor (HFR) in the Netherlands to study fuel salt behavior (fission product production, speciation, and relocation), the particle size distribution of noble metals, etc, of the irradiated fuel salt. Other properties will be measured as well, complemented with molecular dynamics simulations.

In WP3 we evaluate the nuclide inventory through the whole reactor including the FTU. The equilibrium nuclide concentrations in the core depend on the treatment scheme, therefore a new coupled code system simulating fuel burnup and chemical extraction methods will be developed for a complete and accurate safety assessment. Simulation tools will be used to assess the extraction efficiencies of the gaseous fission products and microparticles (noble metals) via helium bubbling. The chemical extraction processes in the FTU will be evaluated experimentally and assessed with the new simulation codes.

Essential for resistance against severe accidents is the ability of fuel salt to flow freely to redistribute the decay heat and to bring the reactor to a safe condition under abnormal operating conditions. Because heat conduction in the fuel salt is generally poor compared to heat convection (high Prandtl number), the fuel salt may easily solidify against cold walls or in cold regions. In WP4 we develop cutting-edge simulation tools to evaluate the melting and solidification phenomena of the fuel salt. We use these to optimize the Emergency Draining System (EDS) and other barriers including the freeze plugs and valves. The software will be validated using the experimental facilities SWATH-S and ESPRESSO.

In WP5 we develop simulation models and tools for the safe removal of decay heat from the fuel salt in the reactor core and the EDS. Because the fuel salt is partially transparent to infrared radiation, radiation heat transfer is more important for decay heat removal than in solid fuel reactors. On the other hand, natural convection is less effective, due to the internal heat production in the fuel salt, which leads to smaller density differences. We study both the natural convection phenomena, the effects of turbulence on heat transfer, and the radiation heat transfer mechanisms including experimental validation using SWATH-S and DYNASTY. The resulting models will be used to optimize the fuel circuit and the EDS with regard to decay heat removal.

In WP6 we integrate the results of our project by applying our simulation models and tools to new safety barriers. First, we define the MSFR operational states as well as the emergency operating procedures. Subsequently, we investigate advanced monitoring and predictive control strategies to prevent severe accidents. By control of the redox potential of the fuel salt, e.g., by controlling the ratio of UF_4 and UF_3, corrosion can be reduced, increasing the long-term mechanical strength of the fuel circuit. The barrier designs from WP3–5 will be incorporated to show their effectiveness with regard to risk reduction and severe accident prevention including uncertainty quantification. The effects of scaling laws on the occurrence and effects of severe accidents will be investigated to find generic relations for the design of MSRs. This knowledge will be transferable to other reactor designs as well.

WP7 focuses on the education and training of doctoral students and postdoctoral researchers in the project, and on the activities to maximize dissemination and exploitation. We organize a summer school and a Young-MSR conference for students, trainees, postdocs, scientists and engineers, and address an even wider community via webinars and other means such as a software simulator. To widen the skillset of our students, we support and stimulate the exchange of students and trainees. To build a software user community for our simulation tools, we will organize an exploitation workshop with hands-on lessons using the software. The exploitation of our results will be targeted at strategic stakeholders needed for the further development of the MSR.

3.2 Key results

In WP1 we defined the notion of severe accidents in Molten Salt Reactors (MSR) based on the methodologies from the Risk and Safety Working Group of GIF leading to so-called severe plant conditions. Based on this evaluation a specific MSR-oriented defence in-depth approach has been set up by analysing the safety functions of all fuel salt locations in the reactor and by defining the number of containment barriers.

A list of MSR-specific Postulated Initiating Events (PIE's) with a focus on reactivity insertion events have been established and a simulation tool for the reactor has been developed treating slow and fast dynamics. To establish the list of PIE's for the Fuel Treatment Unit (FTU) the process diagram has been reorganized to provide input to the Functional Failure and Mode Effect Analysis (FFMEA) methodology, which will be executed in the second half of the project.

The review of (integral) experiments for the validation of MSR code systems has started as well as an analysis to arrive at Process Identification and Ranking Tables (PIRT) to prioritize various phenomena important for the validation and demonstration of MSR.

In WP2, the Thermochimica software has been coupled to the JRC-Molten Salt Data Base for thermodynamic assessments of various salts. At a later stage, Thermochimica will be coupled to multi-physics codes as well. In the fuel salt, noble metals appear as solid precipitates. A single-phase Eulerian approach has been applied to model the transport and extraction of these particles. For better results, more accurate estimates of the noble metal particle size distribution are needed.

A thermodynamic assessment of various salt compositions has been performed by the Calphad method. Validation was performed by experimental studies on CrF_3. After irradiation of the LiF-ThF_4 samples in the High Flux Reactor (NL), the post-irradiation experiments started. The graphite crucibles have been punctured and the plenum gas evaluated. Further evaluation of the irradiated samples will be done in hot cells at NRG and JRC-Karlsruhe.

Furthermore, molecular dynamics studies were done on LiF-ThF_4 using a new forced-field model. They turned out to be capable of reproducing the experimentally observed viscosity. Other studies use the JRC database to predict properties like the density and viscosity of multi-component fuel salts. A computational tool has been developed to interpolate and extrapolate density and viscosity data, which can be used in thermal hydraulics codes.

Preliminary results of the benchmark calculations show that a substantial part of the decay heat can be generated in the off-gas system. The benchmark calculations simulating the fission product inventory with various processing schemes show good agreement. Multiphysics solvers have been extended for the simulation of gaseous fission products. Experimental studies on metallic particle extraction via bubble flotation are still ongoing.

Thermodynamical calculations resulted in a preliminary scheme for reprocessing chloride salts, and literature studies on the immobilization of fluoride and chloride salts were done. Several issues in the treatment of chloride salts by electrolysis were identified. The assessment of the fused salts volatilization method was limited to corrosion tests on selected nickel alloys and the fabrication of some apparatus. Simulations have been executed to evaluate fission product releases from the fuel salt under accident conditions.

Modelling freezing and re-melting of the salt is challenging because of the displacement of the solid–liquid interface. Several enthalpy approaches have been tested in multiple codes. Benchmarking of convection models with literature was successful, but the further implementation of phase change models needs to be done. Experimental data on phase change phenomena in a forced or mixed convection flow regime are not as abundantly available as data on phase change phenomena in conduction or in natural convection mode. In the near future, we expect to generate new experimental data for validation.

The SIMMER code has been extended and input has been prepared for the simulation of the Castillejos experiment for validation. Also, the secondary circuit and the heat exchanger have been included in the SIMMER model. Calculations with SYRTHES on conductive heat transfer showed good agreement with the literature. Studies showed that residual heat extraction by airflow only might not be sufficient and that other means should be sought.

The SWATH-S experimental facility has been extended to study radiation heat phenomena in salt. Two extensions, one closed and one open channel, have been designed and the closed channel has been built and installed. The experimental campaign has just started. Numerical models to study radiative heat transfer have been developed and will be validated when experimental data becomes available. DYNASTY will soon be used to measure natural convection and heat transfer phenomena which will be used to validate numerical models. The natural convection stability analyses performed in SAMOFAR will be extended in SAMOSAFER to provide more insight into the stability analysis of MSR.

In WP6, design drawings of the core and passive decay heat removal system and enclosing building structures have been made to get a clear view of these structures. The normal operating transients (startup/shutdown/etc) of the MSFR and the main plant parameters have been identified. These are inputs to the design of the MSR simulator needed to investigate predictive control strategies. The experimental protocol to analyse all elements at once in the fuel salt composition has been defined, but the experimental work as well as the measurement of the fertile and fissile components in the salt via electrochemical methods have been delayed due to Covid.

The summer school was held online in the second half of 2021 and will be finalized jointly with the Young MSR conference in June 2022. It attracted more than 200 students from over 30 nationalities.

The publications of the SAMOSAFER project published in the open literature till now can be found in references [12–21].

3.3 Recommendations for the future

The EU MSFR is a reactor design at a low TR level with many remaining points for improvement. We made significant progress in the design and safety analysis of this reactor using a newly developed MSR-specific safety approach, but for a more detailed design, we need to extend our knowledge of materials data (structural materials, fuel salt properties, corrosion data, etc), extended code packages with improved validation in extreme situations, nonproliferation issues, modularization and maintenance of the design, safety by design, the location and chemical form of the fuel inventory (both in the reactor core and the Fuel Treatment Unit), etc.

4 ECC-SMART: Joint European Canadian Chinese Development of Small Modular Reactor Technology

The ECC-SMART project is supported by Horizon 2020 Euratom call and focuses on a small modular reactor cooled by supercritical water (SCW-SMR) with the aim to support and help to solve the issues relating to structural materials, heat transfer, neutron physics and safety. The results will be used for assessing the feasibility and identification of safety features of SCW-SMR, considering specific knowledge gaps related to the future licensing process and implementation of this technology.

The project is divided into four technical work packages (material testing, thermal-hydraulics and safety, neutronics and reactor physics, and guideline synthesis and pre-licensing studies) and two administrative work packages, including nuclear education and training activities. Altogether, they aim to achieve the main objectives to define the design requirements for the future SCW-SMR technology, developing the pre-licensing study and guidelines for the demonstration of the safety in the further development stages of the SCW-SMR concept including the methodologies and tools to be used and to identify the key obstacles for the future SMR licencing and propose a strategy for this process.

The project consortium has 20 partners and consists of 15 European institutions from 12 member states and is supplemented by an important international collaboration with the Canadian, Chinese, and Ukraine supercritical water research programs. The project consortium and project scope were created according to the joint research activities under the International Atomic Energy Agency, Generation-IV International Forum, SNETP and NUGENIA umbrella. Hence, ECC-SMART maximizes international synergy between the national programs of the European member states on the one hand and the international programs on the other hand.

4.1 Key objectives

In general, the objective of the project is to provide science-based recommendations, methodologies for performing safety evaluations and safety improvements fostering the safety standards, including the experimental validation of essential items for safety demonstrations related to the SCW-SMR.

The activities of the project will lead to deriving the most economical safety-driven supercritical water-cooled small modular reactor (SCW-SMR) design requirements by identifying adequate solutions to key technical issues which drive cost and safety and their influence on the future licencing process. An important feature of the project is also the ambition to increase the level of knowledge as well as the interest of the industrial partners and demonstrate the benefits of the SCW-SMR concept.

However, the key objectives represent the main structure of the project:

(1) complete the understanding of the corrosion behaviour of the most promising candidate materials at different conditions to support the qualification procedure of the future SCW-SMR constructional materials and assess the relation to the existing standards and guidelines.
(2) Define the design requirements for future SCW-SMR technology. Verify, validate and further develop the selected thermo-hydraulic system-, subchannel-, safety-, and CFD-codes and assessment of the proposed SCW-SMR concepts by applying these codes.
(3) Provide reactor physics analysis of preliminary core layout based on a design proposed in the project including selection of proper neutron/reactor physics code.
(4) Develop pre-licensing studies and guidelines for the demonstration of safety in the further development stages of the SCW-SMR concept. Identify the key obstacles to the future SMR licencing and propose a

strategy for this process based on the findings on the multinational level.

In addition, the project wants to progress education and training and help increase interest in the nuclear field among young scientists. For this purpose, events, and workshops on variable topics from the nuclear field are and will be organized under ECC-SMART.

4.2 Key results

The project reached the first third of its duration, thus, most activities and corresponding results are expected in the next months. However, the overview of the project's main activities, relating to progress and results is described below.

The biggest work package is focused on material testing (WP2). For this purpose, the test matrix was established including more than 700 specimens. The focus is devoted to stainless steel 310S and alloy 800H, which have been selected as the most perspective material for fuel cladding for SCWR. In addition, experimental material such as AFA (alumina forming austenitic alloy) was supplied by colleagues from China (USTB). Most of the tested specimens have been manufactured from the tubes to get closer to the real conditions and to support the progress in the SCWR and SCW-SMR fields. The first planned experiments have been started and the results are being evaluated.

Within the work package, 3 on thermal hydraulics and safety of the SCW-SMR, an innovative design concept of a small modular reactor cooled by SCW (see Fig. 5) has been proposed based on HPLWR (high-pressure light water reactor) including the experiences from Canadian and Chinese designs. The first corresponding results have been published at the ISSCWR-10 conference [22]. The main design of the core is more complex as 6 heat-up stages of the moderator have been proposed. Accompanied sketches in Figure 5 show some basics of design such as the horizontal placement of fuel assemblies and the different heat-up stages achieved by horizontal plates welded with the tube sheet (Fig. 5b). On top of the core is a steam plenum above the reflector room, from where the superheated steam is leaving via two outlet flanges (Fig. 5a) [22]. Thus, the coolant flows inside the reactor core are always horizontal or upwards. However, further tests focused on thermo-hydraulic data and supporting the innovative design were proposed and started [23,24]. A conceptual investigation of passive safety aspects is prepared and will be performed.

Based on the proposed innovative design by the WP3, the first calculations relating to the reactor physics have been carried out as part of work package 4 (neutron physics of SCW-SMR). A few modifications have been proposed and they are under discussion to achieve a satisfactory design including economical and feasibility aspects. In addition, a computational benchmark was developed and used for the comparison of different neutronic codes.

The review report on safety criteria and requirements for the SCW-SMR concept was completed within work package 5 (synthesis and guidelines for safety standards). A compilation of the SSS (safety, security and safeguards) features implemented in the SMR is already being in advanced design and especially licensing stages will be further developed during the ECC SMART project including the progress performed in relevant work packages 2–4 and would propose a consistent set of the main safety-related findings and conclusions.

4.3 Recommendations for the future

The ECC-SMART project is at the beginning and key results are ahead of us. The actual geo-political situation uncovered the lack of appropriate sources of energy supporting its diversification and the independency of countries. In this light the importance of relevant research oriented on the future supplement of energy is necessary. Hopefully, the achievement of expected results would not be significantly affected.

5 ACES: Towards Improved Assessment of Safety Performance for Long-Term Operation of Nuclear Civil Engineering Structures

5.1 Key objectives

ACES addresses the EURATOM Work Programme 2019–2020, dedicated to Nuclear Fission and Radiation Protection Research regarding nuclear safety namely through ageing phenomena of components and structures and operational issues.

The main objective of ACES is to advance the assessment of the safety performance of civil engineering structures by solving the remaining scientific and technological problems that currently hinder the safe and long-term operation of nuclear power plants reliant on safety-critical concrete infrastructure [25–29]. A proper understanding of deterioration and ageing mechanisms requires a research strategy based on combined experimental and theoretical studies, following a multidisciplinary approach, and utilizing state-of-the-art experimental and modelling techniques. Material characterization at different length scales is necessary, focusing on the physical understanding of the degradation processes (e.g. neutron and gamma radiation, internal swelling reactions, liner corrosion, etc.) as well as physical phenomena (drying, creep, shrinkage, etc.), and their influence on macroscopic mechanical properties and structural/functional integrity of the components.

Although the ACES project states that the focus is on Gen-II and III reactors, in reality since the R&D development is on the ageing of reinforced concrete it can be applicable to most reactor designs that contain reinforced concrete structures in normal loading conditions (normal ageing and effect of radiation), so also applicable to GIF. Therefore, the ACES project aims at having a significant impact on the safety of operational Gen-II and III NPPs and impacting the design of next-generation

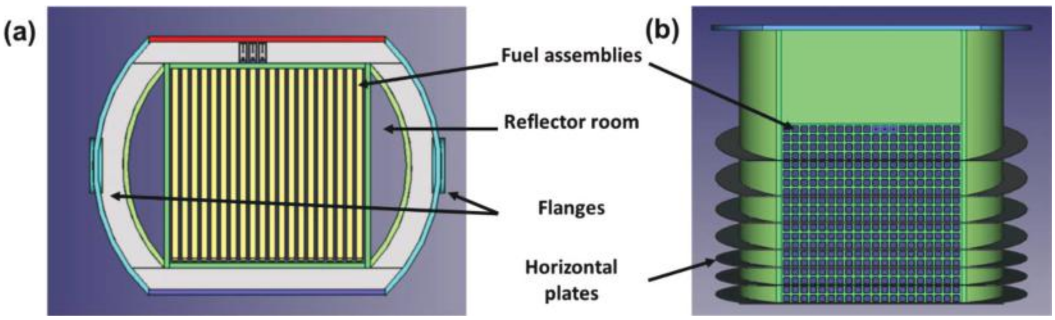


Fig. 5. A sketch to illustrate some basic design principles of reactor core of SCW-SMR: (a) top view of the reactor core; top cover removed; (b) side view onto the head end of the reactor core; front plate and outer cylinder of the reflector removed [22].

plants. ACES will improve the understanding of the ageing/deterioration of concrete and will demonstrate and quantify inherent safety margins introduced by the conservative approaches used during design and defined by codes and standards employed throughout the life of the plant. The outcomes from ACES will therefore support the long-term operation of NPPs. This will be achieved by using more advanced and realistic scientific methods to assess the integrity of NPP concrete infrastructure. ACES provides evidence to support the methods by carrying out various tests, including large-scale tests based on replicated scenarios of NPPs. This is being achieved by the development and validation of [30]:

– critical review of ageing management practice across EU nuclear power plants focusing on deterioration and ageing mechanisms of reinforced concrete, linked to decision-based assessment criteria.
– Improved engineering methods to assess components under long-term operation taking into account specific operational demands.
– Integrated probabilistic assessment methods to account for uncertainties and improve inspection capabilities.
– Innovative quantitative methodologies to transfer laboratory material properties to assess the structural integrity of large concrete components.
– Advanced simulation tools based on nonlinear finite element method, lattice-based models, FFT-based simulation, and combined empirical and mathematical material models reflecting the latest finding related to the combined effect of various loading (e.g. environment, radiation, internal swelling reactions) on concrete performance, i.e., the creation and evolution of deterioration areas in concrete structures.
– Improved understanding of internal swelling reactions and temperature/moisture effects on the delayed strains of containment buildings; improved prediction of the evolution of moisture, strain and stress of prestressed concrete containment buildings, during operational and accidental phases.
– Improved assessment of the effects of prolonged irradiation of the concrete biological shield using a holistic approach combining operating conditions, materials degradation and structural significance.
– Improved understanding of corrosion phenomena focusing on embedded liners, predicting the occurrence of corrosion and developing an innovative inspection tool for early detection of corrosion.

Furthermore, an important goal of ACES is the dissemination and education of the nuclear engineering and research community. This will improve and harmonise knowledge about NPPs ageing and thereby ensure a high impact on project results. The education will be carried out through workshops and training organised during the project. ACES results will be disseminated to the main European and international stakeholders.

The ACES project consists of seven work packages. Figure 6 illustrates the overall structure of the ACES work plan. The ACES work packages are WP1 – state-of-the-art of quantitative assessment of ageing of concrete SSC in NPPs; WP2 – corrosion assessment of embedded liners in concrete; WP3 – characterization, prediction and monitoring of internal swelling reactions in concrete; WP4 – delayed strains of containment buildings in operational and accidental conditions; WP5 – assessing the performance of irradiated concrete; WP6 – dissemination, communication and training; and, WP7 – project management.

WP1 provides an overview of existing approaches for quantitative assessment of concrete performance and identifies major gaps in technical competencies and scientific knowledge for new approaches. WP2–WP5 are dealing with technical aspects (experimental and modelling) and aim at answering industrial key issues as described before. WP6 addresses activities for dissemination and exploitation of results and training as well as End-User engagement. WP7 is dedicated to project strategic and operational management. WP7 provides the overall internal management of ACES, and the administrative control including liaison with the EC.

ACES engages 11 partners from five EU Member States (VTT, SCK CEN, ZAG, IRSN, EDF, CTU, CVR, ENGIE LAB and CEA) and two non-EU countries (ENERGORISK, ORNL). The core consortium was born within the ICIC (International Committee on Irradiated Concrete), but then grew with the need to address several different ageing mechanisms. Specific partners were invited to join and contribute to the project in their field of expertise to complement the competence of the consortium. An American partner was added due to the world-leading excellence brought by this partner (came with its

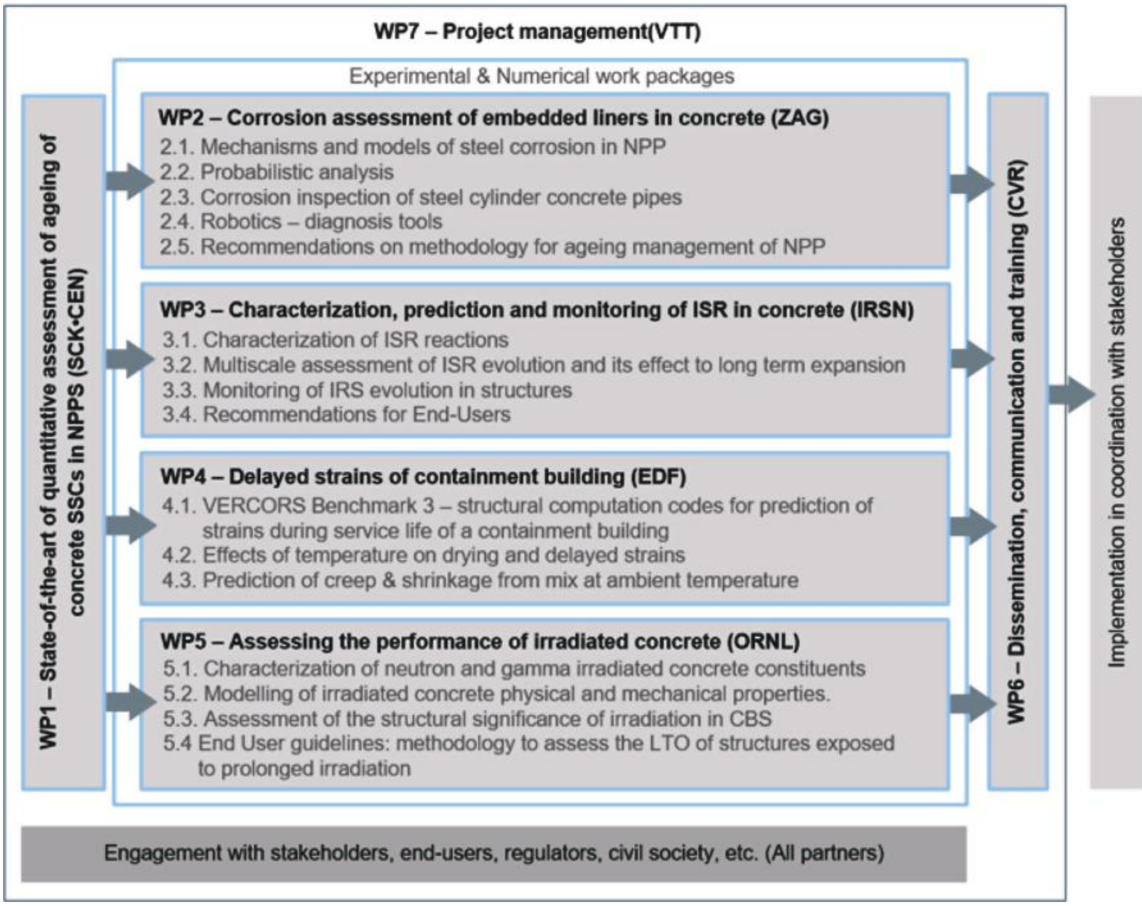


Fig. 6. Overall structure of the ACES work plan.

own funding). Many additional organizations could have joined but unfortunately, the size of the budget limited its numbers. However, most of these interested partners have joined the End Users Group to contribute through collaboration.

5.2 Key results

The key results of the ACES project include:

- a focused review of the current state-of-the-art of ageing processes of reinforced concrete SSCs in the framework of long-term operation of NPPs, including the effect of long-term climate change on environmental loading with the potential impact on concrete performance, and the synergetic effects of ageing processes under single and multiple loading conditions [31]. ACES will identify how the integration of monitoring techniques, experimental data, ageing models and modelling techniques can help to establish quantitative criteria for concrete performance in terms of the current condition, the evolution of the concrete condition, and consequences for safety.
- An improvement of phenomenological understanding and optimization of earlier detection of corrosion degradation, specifically related to the special conditions leading to chloride-induced corrosion of steel cylinder concrete pipes and crevice corrosion of steel liner embedded in the concrete of containment building (Fig. 7). Furthermore, a robotic platform will be developed with the ability to handle and applied suitable NDT and electrochemical techniques for corrosion inspection on the internal side of steel cylinder concrete pipes will be performed (Fig. 8).
- A contribution to the assessment of concrete structures affected by internal swelling reactions by investigating the interaction mechanisms between internal swelling reactions and other ageing phenomena such as creep and shrinkage. Furthermore, ACES will develop methodologies for extrapolating the long-term concrete degradation based on common civil engineering practices and in-situ monitoring, and also by developing robust and advanced prediction tools allowing the simulation of the long-term behaviour of NPP affected by internal swelling reactions based on a multi-scale approach.
- A validation of existing constitutive laws and structural modelling approaches regarding the simulation of containment behaviour during operational phases. Furthermore, contributed to the largest database on a single concrete mix with drying, creep and shrinkage behaviour at ambient and elevated temperatures (up to 150 °C). Also, a new empirical model for concrete

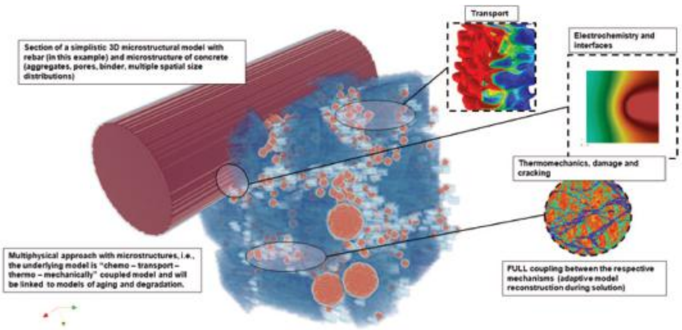


Fig. 7. Phenomenological modelling concept of steel corrosion.

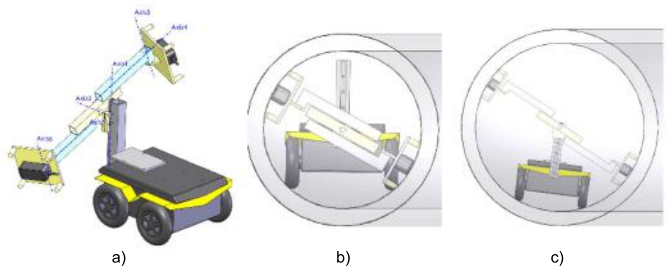


Fig. 8. (a) Concept of robotic solution design, (b) and (c) its deployment in a pipe with regard to the diameter.

behaviour up to 150 °C is proposed as well as evolutions of the FIB Code Model to better account for multiaxial effects on creep at moderate temperatures (up to 40 °C). Finally, the validation of existing models for the prediction of concrete delayed strains based on concrete composition.

– Generating critical data currently missing from the open literature on the neutron-irradiation-induced degradation of concrete aggregates relevant for European NPPs. Collecting data from in-service and accelerated irradiated concrete is key to understanding the significance of accelerated irradiation conditions against LWRs operating conditions. Furthermore, a rigorous benchmark of a large variety of modelling approaches, the capabilities and limitations of each model will be assessed and lead to thoroughly validated irradiated concrete models that are expected to serve as references for future uses by industry, regulatory bodies and code activities. The main advance of this research will be to establish a rigorous structural assessment based on operation data, materials consideration and validated materials and structural models.

5.3 Recommendations for the future

ACES will have a significant impact on the safety of nuclear power plants by demonstrating and revealing inherent safety margins being introduced by the conservative approaches used during design and being dictated by codes and standards used through the lifetime of the plant. The outcome of ACES will support the long-term operation of nuclear power plants, by using more realistic approaches for the integrity assessment of reinforced concrete SCC's and provide evidence by large-scale tests. The results of ACES will be disseminated in key industry circles. The results will be presented to key industry players such as UR NRC which also chairs the ACI 349, and therefore can bridge the integration of the new knowledge into standardization committees and initiate discuss how to integrate it.

Through the innovative methods and tools developed and the integration of knowledge carried out in ACES, the project results will allow companies to increase the reliability of safety measurements in nuclear power plants. ACES will contribute to the safe operation of nuclear power plants and to maintaining high safety standards that can be realised because of more accurate assessment methods resulting in the demonstration of an increased margin of safety. Through proactive management of NPPs ageing and long-term operation, the NPP operators will decrease costs related to better planning of the suspension of NPP activity for maintenance and to the reduction of the inspection time. This will in turn strengthen their competitiveness in the global energy market by replying in a cost-effective way to the increasing demand for nuclear power, foreseen by the International Energy Agency for 2050.

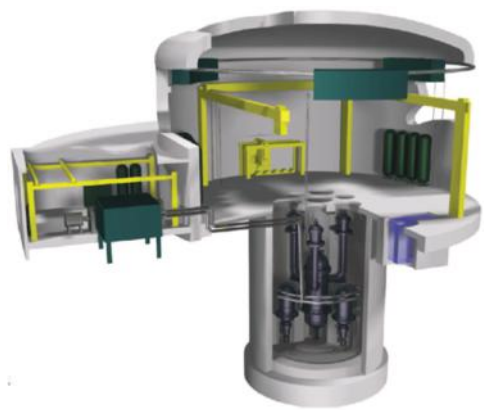


Fig. 9. ALLEGRO reactor system.

6 SafeG: Safety of GFR Through Innovative Materials, Technologies and Processes

6.1 Key objectives

The safety of the GFR demonstrator ALLEGRO (see Fig. 9) is to be enhanced through the use of innovative technologies, and materials and using unique know-how that has been built both inside and outside Europe over the last 20 years. The most important areas of ALLEGRO safety improvements tackled by the SafeG project are:

To solve remaining open questions in residual heat removal in accident conditions, leading to practical elimination of severe accidents, through the innovative design of the reactor core, diversified ways of passive reactor shutdown, passive decay heat removal systems, and instrumentation.

To strengthen the inherent safety of the key reactor components by review of obsolete material and technologies reference options, selection of innovative options, and designs based on these innovative options.

Review the GFR reference options [32] in materials and technologies, using experience gained in national research programs, the know-how of the consortium and stakeholders, and experience from the operation of various research facilities and high-temperature nuclear reactors. The aim is to increase the inherent safety of GFRs.

Adapting GFR safety to changing needs in electricity consumption worldwide with an increased and decentralized portion of nuclear electricity by the study of various fuel cycles and their suitability from the safety and proliferation resistance points of view.

Boosting interest in GFR research by wide involvement of universities, promotion of GFR-oriented topics of master theses and dissertations, organizing topical workshops including hands-on training and on-job training connected with staff exchange.

Deepen collaboration with international non-EU research teams (Kyoto University, University of Cambridge, University of Sheffield), relevant European and international bodies (GIF, standardization bodies) and partners with experience/interest in GFR.

6.2 Key results

The project is currently in its initial phase. The global objective of the SafeG project is to develop the gas-cooled fast reactor technology and strengthen its safety by solving open issues concerning the GFR technology and its demonstrator ALLEGRO. The project is divided into 7 Work Packages, four of them dealing with open research and development problems of GFRs, namely the core safety and proliferation resistance (WP1), advanced materials and technologies (WP2), decay heat removal (WP3), standardization and codes (WP4). Much of the effort is dedicated to education and training activities sheltered by WP5. Dissemination and outreach activities are included in WP6 while WP7 ensures smooth management and execution of the s project.

The main goal of WP1 is to determine the driver and refractory cores satisfying both the performance and safety requirements. In order to achieve this double goal in parallel, the necessary multi-discipline approach will be applied in an iterative way. Namely, neutronics, thermal-hydraulics, and thermal mechanics codes are to be used in the analyses. The normal operation power limitations – both global and local, the maximum burnup, and the core size are the key parameters of the above multi-discipline core design. The main goal of these activities is to optimize the existing designs of the driver and refractory cores from the point of view of safety, related mostly to core designs with more favourable behaviour in unprotected transient scenarios.

One of the main goals of WP2 is to implement materials with better performance for the primary circuit. The process of selection and evaluation of materials for internals will begin with the identification of potential candidate materials based on desired material properties. In general, materials that have been used in High-Temperature Reactors (HTR), and new materials such as SiC-based composites and High Entropy Alloys (HEA) will be researched. This activity will generate unique experimental data of material properties of these advanced materials in various GFR-specific conditions like exposing them to He-N2 mixture at very high temperatures, which will be beneficial not only for the project and GFR research, but will be included in the existing codes for reactor development.

Concerning WP3 the various phenomena of decay heat removal in GFRs will be simulated both numerically and experimentally. For numerical simulations, existing, but correspondingly upgraded models of DHR systems for the CATHARE, RELAP5 and MELCOR codes will be used, with support of CFD simulation for selected separated effects study. Multiple codes are used for detailed analysis of decay heat removal phenomena in the proposed concept. The ambition is to finish the fully passive decay heat removal strategy for ALLEGRO. To achieve this goal, detailed studies of thermal-hydraulics phenomena affecting the decay heat removal will be performed, complemented by designing the fully passive decay heat removal systems, and experiments studying decay heat removal performed at state-of-the-art GFR-dedicated facility S-ALLEGRO.

The results and experience from WP1 to WP3 will be collected in WP4 and evaluated, with emphasis on areas where an insufficient amount of solid data will be identified. The qualification options, and options for qualification of new fuels for GFRs will be explored, finishing with a proposal of a fuel qualification plan.

The reference GFR core should employ the high-temperature resistant cladding materials (SiC) as well as the UPuC (or UC) fuel pellet matrix with the possibility to close the fuel cycle. It was envisaged that such fuel assemblies will be qualified also in the ALLEGRO cores specified in the present project (UO2 and MOX, refractory cores). All the mentioned cores will be important for the fuel qualification process. However, recent advances introduced new variables, which must be considered. The rapid development of the Accident Tolerant Claddings for LWRs increased the knowledge base significantly, mainly with respect to the manufacturing a joining of the SiC–SiC tubes. The advanced multiscale modelling and PIE techniques may allow, to some extent relevant to GFR technology, to leverage the experimental results which will be produced in the next few years in the thermal neutron spectrum.

The fuel qualification plan will be done by taking into account all the above-mentioned variables and using the broad experience of the consortium members in fuel development, qualification and safety assessment.

The main driving force for research and development within this project will be the students and early career researchers employed directly through the project funds or contributing indirectly through complementary research activities in participating institutions. It is envisaged that a PhD. students involved in the project will spend a significant proportion of their research time in other than their home institutions, learning state-of-the-art methods and acquiring skills from other institutions participating in the project.

Participating universities will share their experience in teaching advanced nuclear technology curricula in their respective institutions with subsequent implementation of best practices. It is also envisaged that senior academics and post-doctoral researchers engaged in the project will offer and supervise a number of master-level theses on topics relevant to GFR technology development, therefore vastly amplifying the amount and value of research conducted within the project which is directly sponsored by the EC.

Dissemination of knowledge amongst the project participants will also be accomplished through regular face-to-face project meetings, dedicated thematic workshops and a summer school – all aiming at creating a self-sustainable and robust international network of experts and researchers at different stages of their careers engaged in the development of GFR technology, exchange of ideas to promote technological innovation, and information exchange to accelerate the development and eventual deployment of GFRs.

6.3 Recommendations for the future

The SafeG project focuses on the introduction of the GFR technology as a commercial, industrial source of both electricity and high-temperature heat for industrial applications. Nuclear power technology is a sustainable, low-carbon technology. It is an efficient alternative to fossil energy sources with a significant reduction of CO_2 emissions. Moreover, GFR technology can become a source of high-potential heat for the industry. One of its promising applications is to produce hydrogen, being considered the fuel of the future, reducing, even more, the carbon footprint of human activities.

ALLEGRO, as a demonstrator of Generation-IV GFR technology, will use a fast neutron spectrum, which enables re-using of already available fissile and fertile materials (including depleted uranium from enrichment plants). Through the combination of a fast-neutron spectrum and full recycling of actinides, the GFR reactors will minimize the production of long-lived radioactive waste isotopes, with a significant positive environmental impact.

7 Conclusion

The paper briefly presents five Euratom projects started since late 2017 in support of the R&D of four Generation-IV reactor systems: Sodium Fast Reactor, Molten Salt Fast Reactor, Supercritical Water Cooled Reactor and Gas Cooled Fast Reactor as well as cross-cutting activities on safety-critical concrete infrastructure.

On one hand, the **ESFR-SMART** project continues the development of the European Sodium Fast Reactor concept following up the EFR and CP ESFR projects, especially in terms of safety enhancement and design simplification. On the other hand, R&D activities in support of the Sodium Fast Reactors, in general, are performed in terms of codes validation and calibration, new experiments and new instrumentation, support of sodium facilities and measurements of MOX fuel properties. The project is ongoing and scheduled to finish in August 2022.

The **SAMOSAFER** project aims at the modelling of MSR including as many of the MSR-specific physics and chemistry as possible and at the experimental validation of these models. We build upon the expertise and experience generated in the SAMOFAR project and extend these to ensure the MSR will comply with all future regulations. The SAMOSAFER project is well on track and is expected to finish in 2023.

The **ECC-SMART** project benefiting from the European, Chinese, Canadian and Ukraine synergies helps to move forward the development of the nuclear supercritical water-cooled technology by preparing the design requirements and recommendations for the licensing of the future small modular reactor cooled supercritical water (SCW-SMR). The project started in September 2020 and is close to half with a scheduled end in August 2024. Most of the planned experiments have been started and the first results are evaluated and continuously published. Based on the preliminary results from neutronic physics and core layout, some modifications have been proposed and they should be included in the design concept. Despite the pandemic restrictions and inability to hold face-to-face meetings, the project is progressing well and the work activities in each work package are properly performed.

The research approach undertaken in the **ACES** project supports the development of a physical understanding of concrete degradation processes and their influence on macroscopic mechanical properties and structural/functional integrity of concrete structures. The research addresses important knowledge gaps such as (i) the corrosion of liners embedded in concrete; (ii) internal swelling reactions of concrete; (iii) the drying, creep and shrinkage of the containment structure; and (iv) the effects of prolonged irradiation of CBS. When completed in 2024, the ACES project will have developed industry guidelines enabling End Users to assess the susceptibility and structural assessment of their structures subject to the different deterioration and ageing mechanisms under consideration.

The **SafeG** project is a part of initiatives leading to the construction of the Gas-cooled Fast Reactor (GFR) experimental reactor ALLEGRO. The project's approach is based on the long-term and extensive experience of the project consortium partners in nuclear R&D, development and application of various simulation tools, licensing of nuclear installations, material science and reactor safety in general. The global objective of the SafeG project is to further develop the gas-cooled fast reactor technology and strengthen its safety by solving open issues concerning the GFR technology and its demonstrator ALLEGRO.

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 are disclosed according to the Consortium Agreements of every project.

Author contribution statement

Sections 1 and 2 was written by K. Mikityuk, and Section 3 by J.-L Kloosterman, Section 4 by M. Šípová, Section 5 by M. Ferreira, Section 6 by B. Hatala, and Section 7 was written by all co-authors.

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REVIEW ARTICLE

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Towards a single European strategic research and innovation agenda on materials for all reactor generations through dedicated projects

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Abstract. The goal of the ORIENT-NM action is to produce a single European strategic vision on research and innovation concerning nuclear materials in the EU, serving all reactor generations and nuclear systems. The key in this endeavour is to focus on advanced materials science practices that, combined with digital techniques, will enable acceleration in materials development, manufacturing, supply, qualification, and monitoring, in support of nuclear energy safety, efficiency, economy and sustainability. The research agenda will be rooted in existing virtuous examples of nuclear materials science projects. Here the results of three of them are summarised, thereby covering different reactor applications and families of materials, as well as a range of advanced material research approaches. GEMMA addressed a number of key areas concerning the development and qualification of metallic structural materials for GenIV reactor conditions, focusing on austenitic steels and their compatibility with several non-aqueous coolants, their welds and the modelling of their stability under irradiation. INSPYRE was an integrated project applying a basic science approach to (U,Pu)O_2 fuels, to develop physics-based models for the behaviour of nuclear fuels under irradiation and improve fuel performance codes. Modelling was also the focus of the M4F project, which brought together the fission and fusion materials communities to study the effects of localised deformation under irradiation in ferritic/martensitic steels and to develop good practices to use ion irradiation as a tool to evaluate radiation effects on materials.

1 Introduction

The ORIENT-NM project is elaborating a single European strategic research and innovation agenda (SRIA) that should set the path for future activities on nuclear materials in the EU until 2040, serving all reactor generations. The key in this endeavour is to focus on advanced materials science practices that, combined with modern digital techniques, will enable acceleration in materials development, manufacturing, supply, qualification, and monitoring, in support of nuclear energy safety, efficiency, economy and sustainability. This research agenda, which pursues five transversal research lines, is rooted in existing virtuous examples of materials science projects that target nuclear energy innovation. The objectives and key results of three of them, which cover different reactor applications and families of materials, are presented in this paper, illustrating the advances brought by the various research lines considered in ORIENT-NM. GEMMA addresses a number of key areas concerning the development and qualification of metallic structural materials for Gen IV reactor conditions: (1) corrosion-resistance of austenitic steels for application in heavy-liquid metal-cooled systems; (2) production of welds of available austenitic steels and their characterization in terms of internal stresses; (3) testing of these materials (baseline, welds and advanced) under representative conditions in contact with heavy liquid metals and helium; (4) development of physical models for the prediction of the behaviour of austenitic alloys under long term irradiation. The INSPYRE project applied a basic science approach to (U,Pu)O_2 fuels to get further insight into the mechanisms underlying their changes under irradiation, and accordingly develop physics-based models that describe the behaviour of nuclear fuels under irradiation and improve European fuel performance codes. Finally, the M4F project created a bridge between fission and fusion materials communities by applying physical modelling techniques to target two objectives: (1) understand and predict the origin and effects of localised deformation under irradiation in ferritic/martensitic steels,

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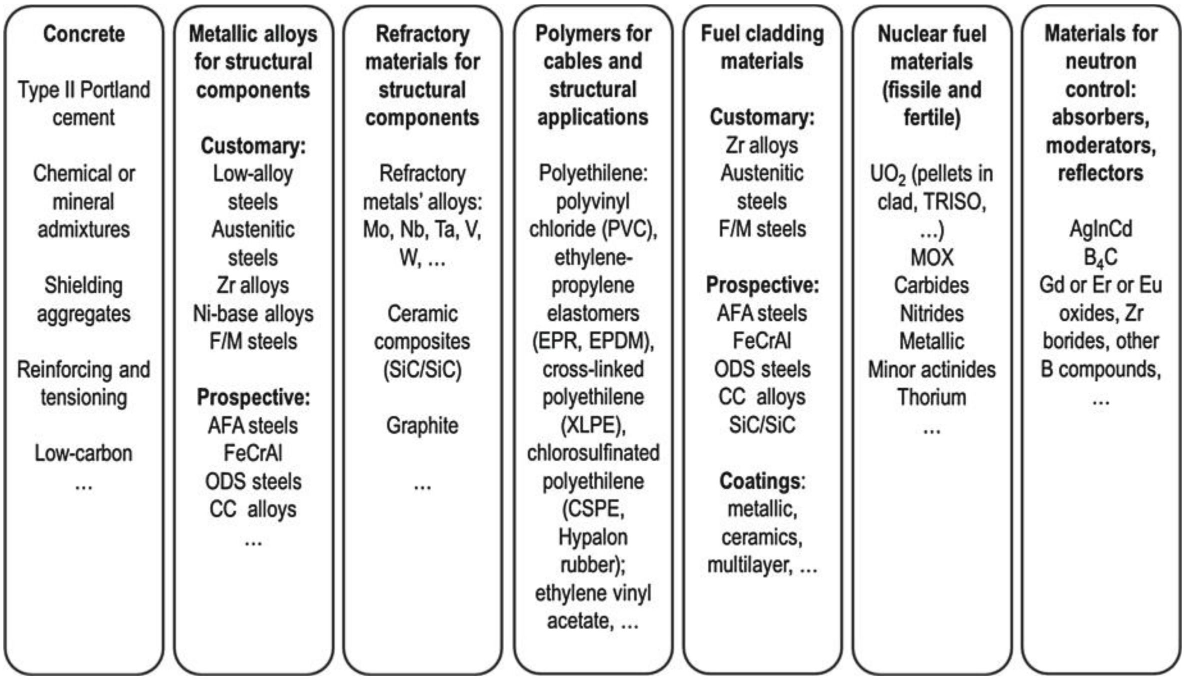

Fig. 1. Classes of nuclear materials and their variety.

which affect the mechanical behaviour of components for future fission and fusion reactors, to enable their design based on robust standards; (2) to develop good practices to use ion irradiation as a tool for the evaluation of radiation effects on materials, also applied to ferritic-martensitic alloys. The objectives and structures of these projects are described in [1]. All the projects described in this article are part of the activities of the Joint Programme on Nuclear Materials of the European Energy Research Alliance [2].

2 ORIENT-NM: a single vision on nuclear materials research for all reactor generations until 2040

ORIENT-NM (Organisation of the European Research Community on Nuclear Materials) is a Coordination and Support Action (CSA) partially funded by the Euratom research and training work programme 2019–2020. It was launched to explore the opportunity of setting up a European partnership on nuclear materials, establishing the relevant Strategic Research Agenda (SRA) and governing structure, while defining its interactions with external stakeholders. The starting point for this was the analysis of the national energy and climate plans (NECP) [3], as well as other documents that are available online, such as the IAEA and WNA country nuclear power profiles [4,5]. This enabled the different national priorities to be identified, in connection with nuclear energy and materials in the EU member states. This analysis [6] revealed, among other things, that a significant number of EU member states intend to maintain or even expand their nuclear-installed power through long-term operation (LTO), power uprates and new builds, from now to 2040. In addition, game-changers such as small modular reactors and advanced designs of interest throughout the continent may lead nuclear energy to be even more widespread in 2040 than currently foreseeable. Recent dramatic geopolitical events might also have an impact on this.

In this framework, materials research plays a crucial role to enhance the safety, efficiency, economy, and overall sustainability of current reactors and enabling the commissioning and deployment of next-generation reactors, as well as fusion. The nuclear materials science community in Europe is therefore called to provide the tools, knowledge and skills to enable each European country to maintain the wished and needed nuclear capacity and/or, depending on national policies and interests, to develop advanced nuclear systems, within the time horizon of 2040. Specifically, it should contribute to enabling EU member states to:

- ensure safe and affordable LTO of current generation reactors;
- design, license and construct Gen III+ new builds over the next two decades;
- deploy light water SMRs within the next decade;
- facilitate and reduce the time and costs for design, licensing, and construction of competitive next-generation nuclear reactors, including advanced SMRs, within the 2040 horizon.

The materials involved a priori range from concrete and metallic structural alloys, to polymers, fuel and compounds for neutron control, as is shown in Figure 1. In order to enable progress towards enhanced safety, efficiency and economy, the development, manufacturing and qualification of innovative materials must be accelerated,

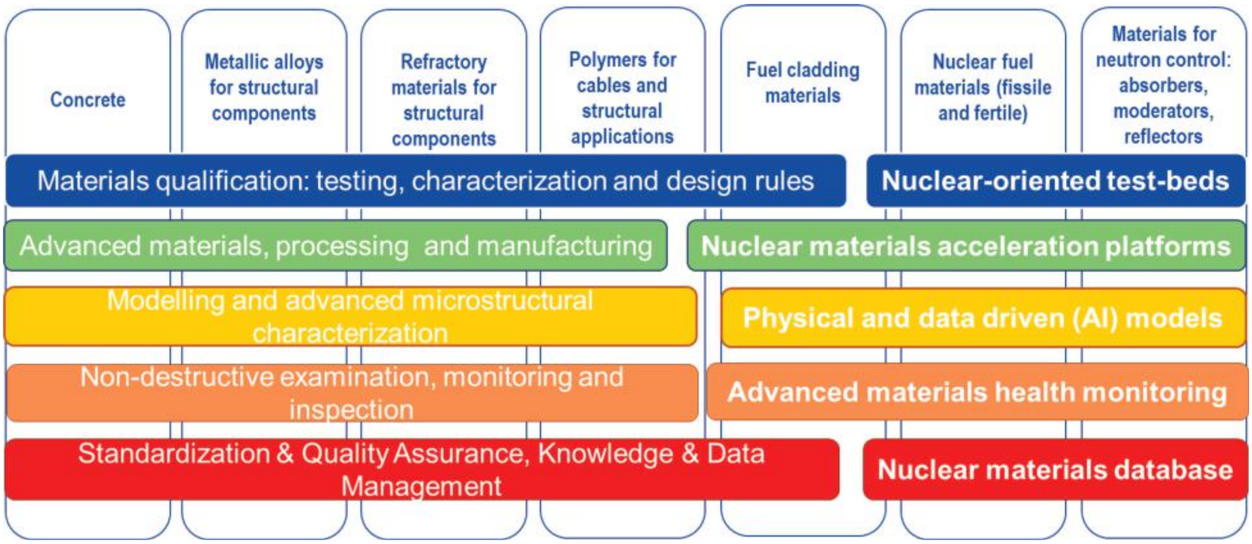

Fig. 2. The five transversal research lines and Grand Goals proposed in ORIENT-NM.

thus reducing their time to market. Accurate health monitoring while operating is also needed. This implies a shift from the traditional "observe and qualify" to the modern "design and control" materials science approach. Advanced digital techniques and suitable models are the enablers of this shift.

Five materials science practices and relevant research lines constitute accordingly the Grand Goals to be pursued within the next decade:

(a) establishment of an integrated European system for the efficient application of advanced and suitably standardized experimental procedures and methodologies for nuclear materials characterization, testing and qualification, be they destructive, non-destructive or microstructural; i.e., nuclear test-beds;
(b) development of methodologies for accelerated, targeted and systematic nuclear materials improvement, or even discovery, including the whole range of variables of relevance; i.e., nuclear materials acceleration platforms (MAPs), which promise to be key to reducing the time to market of innovation;
(c) development of combined physical and data-driven models and predictive methodologies of direct application for industrial needs;
(d) development of advanced methods for materials and component health monitoring through non-destructive examination and testing, coupled with diagnostics and simulation tools, to enable the implementation of digital twins;
(e) establishment and use of efficient platforms and procedures for data collection, storage and management (European nuclear materials FAIR[1] database).

Nuclear test beds and MAPs inherently require coordinated use of (present and future) European facilities and infrastructures and exploitation of available schemes and roadmaps for access to and use of major infrastructures (chiefly materials testing reactors and ion irradiation facilities, but also facilities for the exposure to fluids and the subsequent characterization). The transversal nature of the above five research lines and Grand Goals is illustrated in Figure 2. The first corresponding proposal of the Strategic Research Agenda has been published in [7].

[1] Findable, Accessible, Interoperable, Reusable.

3 GEMMA: qualification of austenitic steels for application in GenIV prototypes and demonstrators

The GEMMA project (GenIV Materials Maturity), which ended in November 2021, was partially funded by the Euratom research and training work programme 2014–2018. It mainly addressed the following areas: (1) production and characterization of advanced alumina forming corrosion-resistant austenitic steels for application in heavy-liquid metal-cooled systems; (2) characterization of welds on available austenitic steels in terms of internal stresses; (3) testing under representative conditions in contact with heavy liquid metals and helium; (4) development of physical models for the prediction of the behaviour of austenitic alloys under long term irradiation. The results on these topics are summarised below.

3.1 Advanced alumina forming corrosion-resistant austenitic steels for application in heavy-liquid metal-cooled systems

Alumina-forming austenitic stainless steels (AFA) and Al-based diffusion coatings are candidates for application in heavy liquid metals at high temperatures, to replace conventional stainless steels, which exhibit poor performance in these environments [8]. In the GEMMA Project, more than 20 AFA model alloys were produced by the industrial partner SANDVIK and compared.

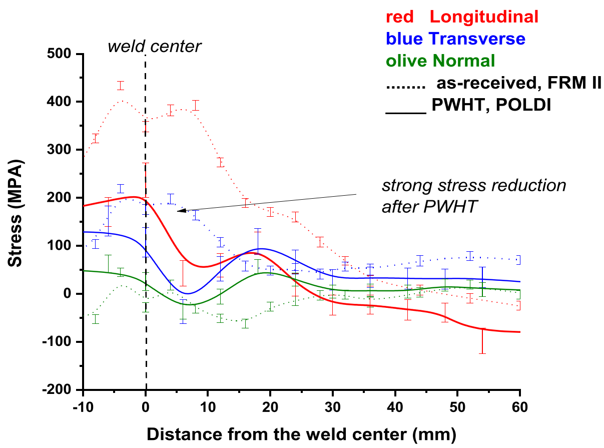

Fig. 3. Diffractometric measurements of internal stresses, before and after PWHT.

They were all exposed to liquid Pb under various conditions. Selected AFA alloys were also exposed to steam at 1200 °C to explore their potential use in a steam environment. Their microstructure was then analysed to investigate their corrosion resistance. The AFA model alloys with the composition formulas Fe–(15.2–16.6)Cr–(3.8–4.3)Al–(22.9–28.5)Ni (wt.%) and Fe–16Cr–(23–25.5)Ni–(3–4.5)Al–C(N)–(Y) have all shown corrosion resistance to oxygen-containing molten Pb at 600 °C. By increasing the exposure temperature to 650 °C, only the alloy of the first family, with the lower Ni content (∼23 wt.%), and with minor additions of Nb and Y, forms a protective oxide scale. Higher Ni contents increase the susceptibility to corrosion attack at 650 °C in Pb. The passivating scale was based on $(AlCr)_2O_3$ at both temperatures and formed a homogeneously alloyed coating with the expected composition. To evaluate the microstructural stability of AFA alloys at elevated temperatures, thermal ageing experiments were performed at 600 °C for 1000 and 2000 h and 650 °C for 3550 h. The austenitic phase was preserved, but all the alloys exhibited secondary phases and precipitations [9].

3.2 Characterization of welds on available austenitic steels in terms of internal stresses

High-resolution neutron diffraction residual stress measurements on a welded coupon after Post-Weld Heat Treatment (PWHT) were carried out at the spallation neutron source SINQ in Villigen (CH). An identical coupon had been studied by high-resolution neutron diffraction stress measurements in the as-welded state at FRM-II in Garching. The PWHT consisted of a dwelling temperature of 700 °C for 24 h with limited heating and cooling rates: these relatively high temperatures and long dwelling time were chosen to ensure tangible relaxation of residual stresses, but bore no connection with the heat treatment process prescribed by the RCC-MRx code. Diffractometric measurements were carried out on both coupons at the POLDI instrument (Pulsed Over-Lap DIffractometer). Figure 3 shows that the PWHT was effective to reduce the stresses inside the weld and the heat-affected zone, as well as to reduce the width of the stress gradient, particularly in the longitudinal direction. The maximum stress values are more than halved and stress lower than 100 MPa are found already at a 10 mm distance from the weld centre.

3.3 Testing under representative conditions in contact with heavy liquid metals and helium

An extensive experimental campaign was carried out to obtain data on the compatibility of base materials (austenitic alloys 316L and 15-15Ti), their welds, AFA, and coated specimens (alumina forming diffusion coatings, ceramic coatings by pulsed laser deposition and by detonation gun spray) with heavy liquid metals (HLM) and He gas. The goal was to clarify the degradation mechanisms and to establish correlations for the design of MYRRHA [10], ALFRED [11] and ALLEGRO [12]. For the first time, a large amount of data has been collected on the compatibility of steels and their welds in contact with these fluids. Thermodynamic simulations with the CALPHAD method and with atomistic modelling have supported the experimental work, to gather information on the relevant part of the phase diagrams of the complex oxide systems and the mass transport properties of the compounds that form.

Contrary to common perception, the corrosion in molten lead and lead-bismuth eutectic (LBE) differed both for the severity of the attack and the mechanisms, the dissolutive attack in LBE being more severe. Furthermore, while the lead dissolving process mainly concerns nickel, in LBE both chromium and nickel are dissolved. In particular, the corrosion campaign in flowing Pb in the testing loop MATLOO at CV-Rez showed that, after 16 000 to 18 000 h at 480 °C, with oxygen concentration 10^{-7} wt.% and 1.6 m/s flow velocity, corrosion was negligible in all the exposed materials [13]. The ENEA corrosion campaign, carried out in the BID1 facility, in liquid Pb at 550 °C with low oxygen concentration (10^{-8}–$10^{-7\%}$ wt.%) up to 8000 h, led to the interesting observation that the magnitude of the corrosion of welds in terms of the depth of penetration was low compared to the corrosion observed in base materials under the same conditions. The microstructural investigations have not unambiguously clarified the relevant mechanisms, but the results suggest precipitation of the δ ferrite at grain boundaries and triple joints, which limits or prevents the rapid diffusion of nickel there. Moreover, pulsed-laser deposited alumina coatings confirmed their superior protective action on 15-15Ti, while both selected AFA alloys showed low yearly corrosion [14,15].

Opposite results were obtained in tests in LBE, with the poorer performance of welded joints versus the base material. The unacceptable corrosive attack on welded joints calls for additional measures for their protection in LBE. Investigations aimed at studying the corrosion mechanisms highlighted that the initiating process of the attack in HLM is the dissolution of iron from the

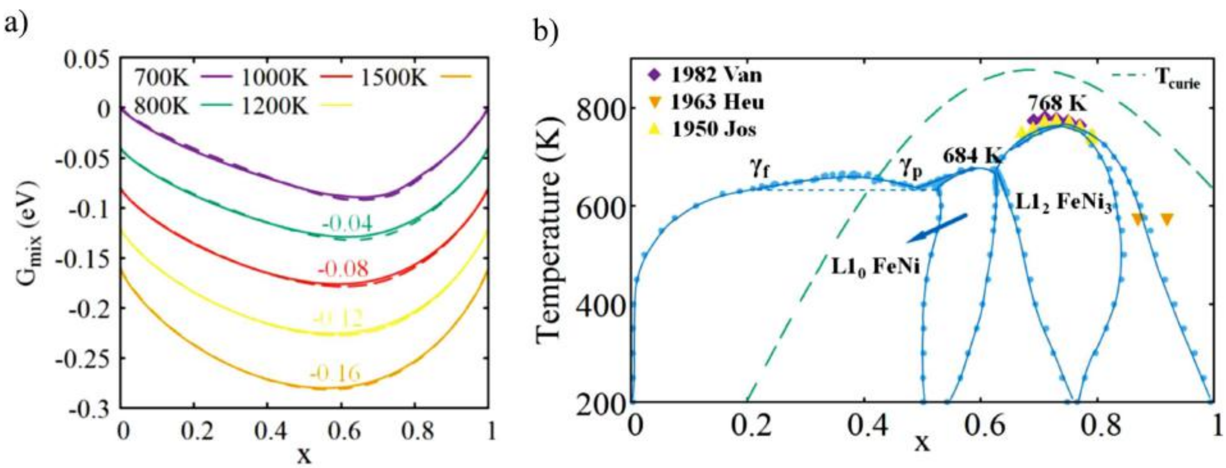

Fig. 4. (a) Gibbs free energy of mixing of the Fe–Ni solid solution of the pair interaction model (full lines) and CALPHAD (dotted lines), at different temperatures. For the sake of clarity, each curve (except at 700 K) is shifted downwards by the value given in the figure. (b) the Fe–Ni FCC phase diagram: comparison between the pair interaction model and experiments.

native iron-chromium oxide that protects the stainless steel in many environments. This dissolution leads then to the formation of a porous structure with interconnected channels along the grain boundaries, which is permeable to oxygen and the components of the steel. The inner Fe-Cr oxide provides channels for oxygen entering and iron leaching. Investigations have also shown that the subsequently formed layer of magnetite in turn loses its protective capability, due to the onset of wetting processes of the grain boundaries by the liquid metal, above temperatures around 450 °C. These results set limits on the applicability of oxygen control for corrosion control of HLM; on the other hand, they set a limit below which steels can be used safely in lead [14,16].

Finally, the mechanical testing campaign in HLM confirmed the absence of liquid metal embrittlement in the austenitic steels 316L and 15-15Ti. Yet, the intensity of the corrosion processes strongly depends on the microstructure of the steel. The presence of extended defects with negligible effects on the mechanical properties in the air could lead to deep corrosive attacks in HLM, with mechanical degradation that is solely linked to the reduction of the resistant section [17].

3.4 Development of physical models for the prediction of the behaviour of austenitic alloys under long-term irradiation

In the temperature range of interest for operation (300–700 °C), irradiation produces in austenitic alloys new microstructural features, such as new families of precipitates, solute segregations at structural defects, point defect clusters and voids, leading to dimensional changes (swelling) and worsening the mechanical properties (loss of ductility, hardening). These microstructural features induce adverse effects and limit the lifetime of the materials. Predictive models for microstructure evolution under irradiation are therefore useful tools in support of assessing the component lifetime. With this aim in mind, as the first step kinetic models were developed to describe the phase diagrams of Fe–Ni–Cr model alloys, their diffusion properties and the kinetics of segregation and ordering. The composition range of the ternary model alloy has been chosen to encompass those of 316L(N) and AIM1 steels, targeting temperatures around 500 °C. Interdiffusion experiments in Fe–Ni–Cr multi-layers during isothermal annealing and under ion irradiation have been performed to assess the validity of the atomistic kinetic models. Two thermodynamic descriptions were developed, one based on an implicit treatment of magnetism and a second one explicitly treating the magnetic interactions between Fe and Ni atoms. Relying on the former, a rigid lattice pair interaction diffusion model was developed and used for Atomic Kinetic Monte Carlo (AKMC) simulations in binary Fe–Ni alloys. The pair interactions were fitted to 0 K ab initio calculations of formation enthalpies of ordered and disordered structures and also systematically fitted on the Gibbs free energy of the γ Fe–Ni solid solution, as described in a CALPHAD (CALculation of PHAse Diagrams) study [18]. The model reproduces well the data for the solid solution (Fig. 4a) and the $FeNi_3$–$L1_2$ ordered phase in a large domain of composition and temperature, using first and second neighbour pair interactions which depend on temperature and local Ni concentration. The FCC phase diagram of the Fe–Ni system was determined using Monte Carlo simulations in the semi-grand canonical ensemble (Fig. 4) and compared with experimental studies and other models. In addition to the γ solid solution and the $FeNi_3$–$L1_2$ phase, the FeNi–$L1_0$ phase is found to be stable below 684 K. The model also predicts a phase separation between ferromagnetic (γf) and paramagnetic (γp) solid solutions.

The pair interaction model was then extended to include vacancy diffusion. Vacancy-pair and saddle-point interactions were fitted on electronic structure calculations of vacancy formation and migration energy and to experimental tracer diffusion coefficients in dilute alloys. AKMC simulations were performed to calculate tracer and interdiffusion coefficients in concentrated solid solutions and compared with available data. Finally, a BCC and FCC Fe–Ni phase diagram below the magnetic-transition temperatures based only on electronic structure calculation results was constructed. The free energy of the various phases was determined by including the vibrational and the ideal configurational entropies. The resulting phase diagram is in very good agreement with the experimental data and suggests possible improvements for upper-scale semi-empirical approaches (such as CALPHAD). In order to go further in the thermodynamic prediction of the Fe–Ni alloys at higher temperatures, when magnetic excitations and transitions occur, an effective interaction model for Fe–Ni, which describes chemical and magnetic interactions explicitly and the effect of vibrational entropy, was explored. This model is currently extended to describe the properties of defects (vacancies and self-interstitial atoms) in Fe–Ni for various chemical and magnetic states [19].

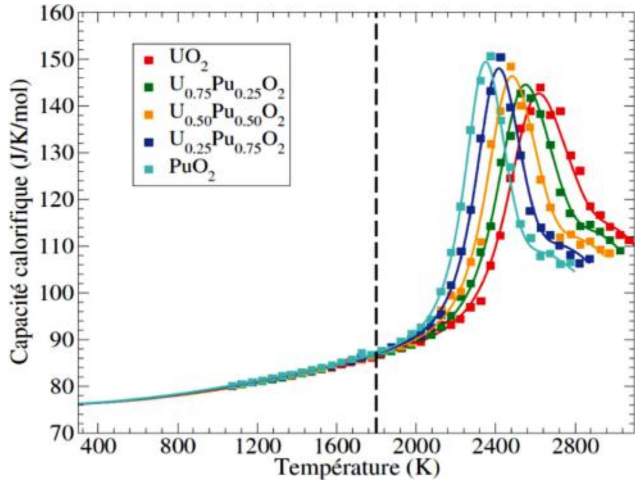

Fig. 5. Heat capacity as a function of temperature and Pu content yielded by atomic-scale calculations and analytical law (solid lines) fitted on these results that were implemented in the GERMINAL fuel performance code.

4 INSPYRE: basic research on U–Pu mixed oxide fuels to improve fuel performance codes

The INSPYRE project (Investigations Supporting MOX Fuel Licensing in ESNII Prototype Reactors), which ended in February 2022, was partially funded by the Euratom research and training work programme 2014–2018. INSPYRE aimed at:

(1) using a basic research approach that combines out-of-pile separate effect experiments with physical modelling and simulation to get further insight into the underlying phenomena that govern the behaviour of (U, Pu)O_2 mixed oxide (MOX) fuels under irradiation.
(2) Performing additional post-irradiation examinations (PIE) on selected samples to complete the results available in the literature.
(3) Extending the reliability regime of empirical laws that describe nuclear fuel under irradiation using the results obtained in the project, as well as those of previous integral neutron irradiation tests.
(4) Using these results to improve the reliability of European operational fuel performance codes in normal and off-normal situations to facilitate nuclear fuel licensing and improve safety.
(5) Training the next generation of researchers on nuclear fuels.

These objectives are presented in the project's video [20]. The results of the project are synthesised in [21] and summarised below.

4.1 Advances in the understanding and description of the behaviour of nuclear fuels

INSPYRE brought significant advances in the understanding of mechanisms that are crucial for the safety assessment and qualification of MOX fuels for future nuclear reactors, as well as in the simulation of the fuel behaviour in the reactor. The new experimental and modelling results significantly enhance the knowledge and understanding of the physical, thermal, chemical and mechanical properties of MOX fuels. In addition, several setups were developed to enable the detailed characterization of UO_2 and plutonium- and americium-bearing fuels in the hot laboratories of the partners.

Laser heating experiments and atomic scale calculations enabled the determination of high temperature and melting properties of (U,Pu)O_2, (Pu,Am)O_2, and O_2. Together with literature data and data from the FP7 ESNII+ project, these results improved the thermodynamic modelling of the (U–Pu–Am–O) system [22]. The specific heat of (U, Pu)O_2 was also evaluated using atomic scale calculations (see Fig. 5), yielding information at very high temperatures and over the full composition range, which is very difficult to measure experimentally [23].

Atomic scale calculations provided further insight into the elementary processes of formation and migration of defects in (U,Pu)O_2 and a new diffusion model for plutonium in MOX fuel and an associated mobility database were developed [24]. In addition, diffusion couples were designed to enable refined experimental measurements of diffusion coefficients.

Diffusion coefficients of inert gases Xe, Kr, and He in fresh UO_2 and MOX were determined using a combination of experimental techniques and modelling methods, from the atomic to the grain scale [25]. Finally, MOX fuel samples from past irradiation campaigns with various Pu contents and at various locations of the pellet, i.e., subjected to different burnups and irradiation temperatures, were characterised using inter alia electron microscopy, down to the nanometer scale.

Complementary techniques and methods were combined to a precise control of materials and test conditions to determine mechanical properties and get further insight into the elementary processes governing their evolution. Elastic properties, ductile-fragile transition and ultimate strength in MOX single crystals as functions of

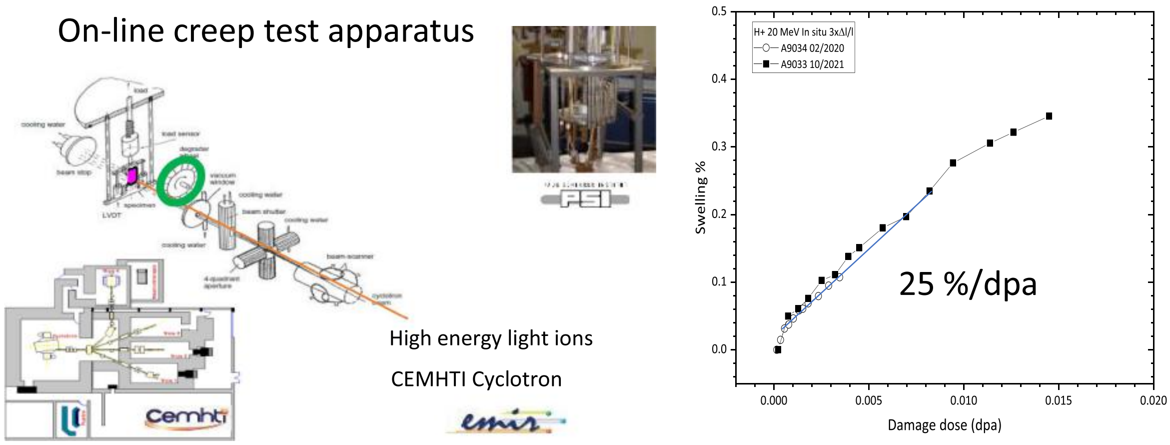

Fig. 6. Apparatus for online creep test under ion irradiation and swelling as a function of damage dose on UO_2 polycrystalline sample.

Pu content, temperature and irradiation dose were studied using atomic scale simulations [26]. Then, thermal creep in UO_2 under controlled conditions (in particular the oxygen partial pressure [27]) was measured in a dedicated setup, while new micro and nano-indenters were used to determine the room temperature elastic properties and micro-hardness at the grain scale of well-characterized fresh MOX fuel samples.

Irradiation-induced swelling in UO_2 was studied in situ using ion irradiation at the CNRS cyclotron in Orléans and MOX in the HFR reactor in Petten. As shown in Figure 6, macroscopic swelling of UO_2 was proved to increase with damage dose, in agreement with the trends shown by simulations and post-irradiation examinations [28]. In addition, deformation was recorded in situ in MOX fuels irradiated under very small temperature gradients in the HFR reactor for 6 months.

INSPYRE also improved significantly the knowledge of the "Joint Oxyde-Gaine" (JOG) layer, which is formed by the migration of volatile fission products, in particular caesium, tellurium, iodine and molybdenum, from the centre to the periphery of the fuel pellet. The incorporation and transport properties of Cs and I in MOX fuel were evaluated using electronic structure calculations. Thermodynamic data on fission product compounds in the chemical system (Cs–I–Te–Mo)–(U–Pu–O) were measured and calculated at the atomic scale [29]. The thermodynamic models on the Te–U, O–Te–U, Mo–O–Te, Cs–Mo–O, Cs–Te–O and Cs–Mo–Te–O sub-systems were then improved using these results.

Finally, properties such as melting temperatures of phases containing U, Pu, Fe and O (PuO_2–Fe_3O_4 system), which form from the interaction between MOX and cladding in the case of a severe accident, were measured for the first time using an advanced laser heating setup. In addition, a novel experimental setup enabled new data to be gathered on the liquid miscibility gap of the Fe–U–O system, in which two immiscible liquid oxide and metallic phases coexist. Thermodynamic models of the U–Fe–O and Pu–Fe–O systems were then derived using these experimental data.

4.2 Advances in the simulation of nuclear fuels

Fuel performance codes used to simulate the behaviour of Gen IV fuels under irradiation were improved using the results presented above. Physics-based correlations giving melting temperature and thermal conductivity versus fuel temperature, Pu and minor actinide content, deviation from stoichiometry, porosity and burn-up were developed for MOX and minor actinide-bearing MOX fuels under GEN IV reactor relevant conditions [30]. Several physics-based models were implemented in the SCIANTIX grain-scale module to improve the description of fission gas and helium behaviour in MOX fuels [31]: (1) a burn-up model to evaluate helium production in MOX; (2) a reduced order model of fission gas diffusion in columnar grains; (3) a model for the intra-granular helium behaviour that accounts for helium diffusivity, solubility and interaction with other fission gases; (4) an improved description of the formation of the High Burn-up Structure and the corresponding porosity evolution at the periphery of fuel pellets. Then, improved correlations were obtained for the MOX thermal expansion and Young's modulus as functions of fuel temperature, Pu content, porosity and deviation from stoichiometry. A 3D micro-mechanical model based on representative volume elements, which includes a description of the fuel rupture behaviour, was also developed for both normal operation and off-normal conditions.

The models and correlations developed in the project were used to improve three major European fuel performance codes: GERMINAL, developed by CEA, MACROS developed by SCKCEN, and TRANSURANUS, developed by JRC with the support of academic organisations. All of them were coupled with the SCIANTIX grain-scale module for inert gas behaviour [32]. The improved versions of these codes were then assessed by simulating the three past fast-neutron irradiation experiments SUPERFACT-1 (see Fig. 7), RAPSODIE-I and NESTOR-3. In addition, data obtained in the second half of the project are available to further improve models and codes.

The code validation against local and integral experimental data reveals harmonized predictions of fuel

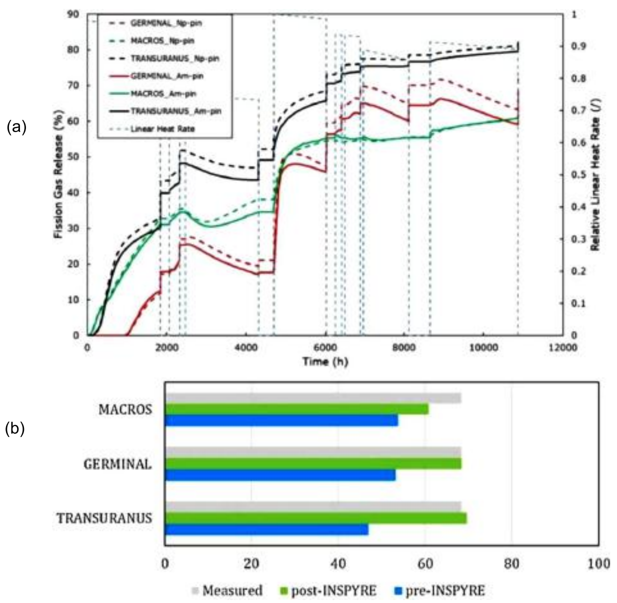

Fig. 7. (a) Relative linear rate and fission gas release at peak power node yielded by improved FPC. (b) Integral fission gas release yielded by pre and post-INSPYRE versions of FPC and comparison with experimental data.

restructuring (as fuel inner void formation). In particular, fuel central temperature predictions are now more consistent between the various codes [33].

4.3 Simulation of ESNII reactor cores

The new versions of the codes were used to simulate normal operation conditions in the ASTRID sodium fast reactor prototype [34], as well as normal and transient conditions in the LBE-cooled reactor of MYRRHA [35]. This enabled the evaluation of the safety margins of the fuel designs (e.g., margin to fuel melting, cladding plasticity) under relevant conditions.

5 M4F: bringing together fusion and fission materials communities to predict the behaviour of ferritic-martensitic steels under irradiation

The M4F project (Multiscale Modelling for Fusion and Fission Materials), which ended in December 2021, was partially funded by the Euratom research and training work programme 2014–2018. It brought together fusion and fission materials research communities to work on the prediction of irradiation-induced microstructural damage and deformation mechanisms of irradiated ferritic/martensitic (F/M) steels, applying a multidisciplinary approach that integrates modelling and experiments at different scales. The main objectives were:

- to develop physical understanding and predictive models of the origin of localised deformation under irradiation in F/M steels and its consequences on the mechanical behaviour of components. This is meant to set the basis for the future elaboration of physically-motivated, non-over-conservative design rules for this class of steels, of use for both fission and fusion applications.
- to identify good practices for the use of ion irradiation as a tool to evaluate radiation effects on materials for modelling and screening purposes, minimising artefacts with respect to neutron irradiation experiments and allowing the evaluation of not only microstructural changes but also mechanical property changes.

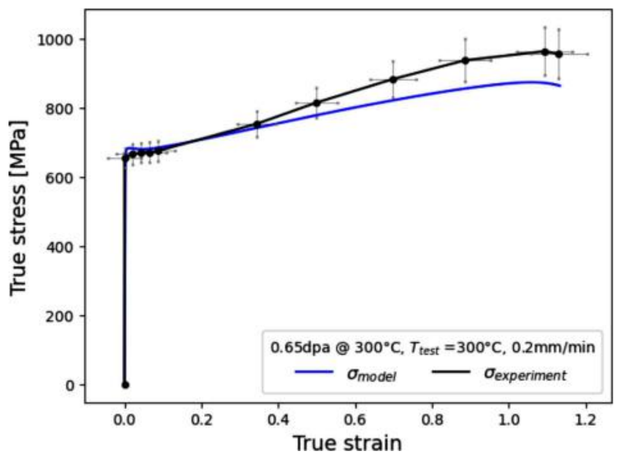

Fig. 8. Simulation of tensile test on irradiated EUROFER97 (0.65 dpa@300 °C): comparison of simulated and experimental true stress vs. true strain curves.

The rationale of these objectives, reviewing past work and summarizing research pathways and first results of the M4F project, is the subject of reference [36], while the overall results are summarized in its Final Report [37]. Here we, therefore, provide only a brief highlight of the main results of the project with respect to the above objectives, emphasizing result exploitation and impact aspects.

The project impact concerns two main items:

(1) cross-fertilization between fission and fusion;
(2) overcoming bottlenecks that are limiting developments in fission and fusion.

In connection with cross-fertilization, a continuous effort was made to identify and disseminate cross-cutting research activities of equal interest for fission and fusion applications. Thanks to this effort, the spectrum of these commonalities has progressively widened over time. The pioneering role of the project is proven by the fact that synergies between fission and fusion are currently being sought for also by the IAEA [38]. The outcome of the M4F project in terms of the identification of commonalities between the two materials communities will certainly impact the outcome of this IAEA effort.

Concerning the goal of overcoming the bottlenecks that are limiting developments in fission and fusion, it has

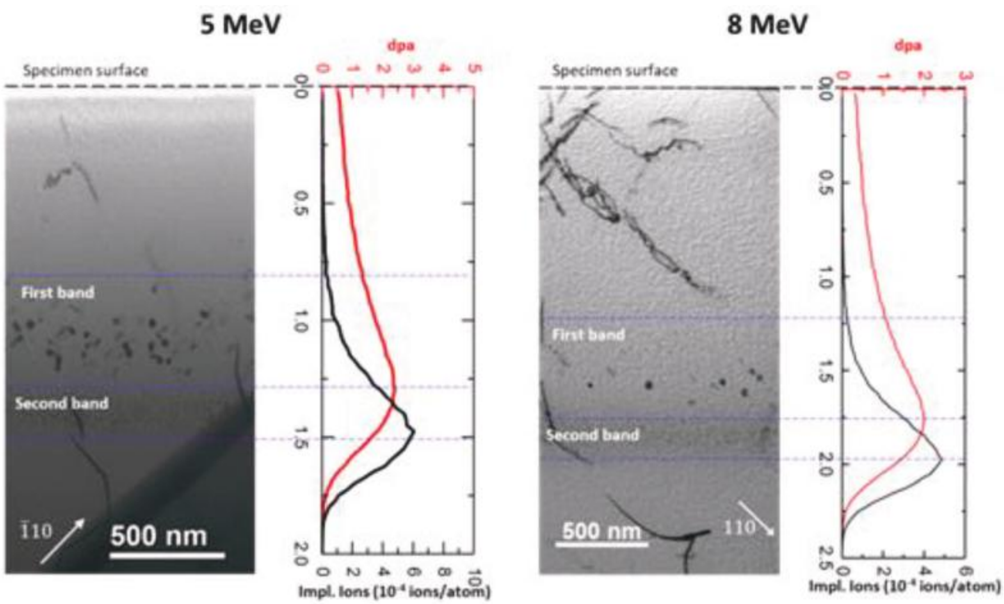

Fig. 9. Ion irradiation damage for two different beam energy values (5 and 8 MeV) as a function of depth: transmission electron microscopy micrographs; dpa and implanted ion profiles calculated.

to be evaluated in terms of advancing towards the two above-stated goals.

Regarding the first one, the problem of plastic flow localization has been addressed covering all scales, from the study of elementary processes concerning dislocation motion in the matrix, through obstacles [39] and across grain boundaries [40,41], using atomistic simulation techniques, to dislocation dynamics [42] and finite element approaches [43–47]. In particular, the visco-plastic modelling approach developed in [45–47] allows the simulation of flow localization in F/M steel structures under neutron irradiation, taking into account finite strains and ductile damage. The model is a powerful tool for the assessment and development of new criteria for immediate plastic flow localization and can also be used to assess other failure modes caused by ductile damage. In case of irradiation causing loss of ductility, it predicts immediate local fracture due to exhaustion of ductility and its dependence on triaxiality. As an example of application, Figure 8 shows how the model can reproduce to a good approximation the experimental true-stress/true-strain curve of irradiated EUROFER97.

Advances were made also in the direction of identifying good practices for ion irradiation experiments [48], with the support of advanced microstructure evolution models [49–51]. The importance of choosing a high ion beam energy value, to mimic as much as possible neutron irradiation, has been clearly evidenced. A characteristic pattern of defect bands linked to the dpa and to the implanted ion profile has been identified, as shown in Figure 9.

One of the bands, between the surface and the damage peak, "safely" resembles the microstructure that is observed under neutron irradiation, provided that the Fe-ion beam energy is $\geq$5 MeV [48]. 8 MeV also give neutron-closer results than 5 MeV in terms of solute-rich cluster formation, but differences are detected as compared to irradiations performed with 5 MeV. It is the first time that the influence of ion energy on the microstructural features has been observed [52]. For the interpretation of the experiments, three microstructure evolution models were developed which, combined, can provide a complete description of the radiation-induced microstructure under neutron and also ion irradiation, including all the specific features of the latter [49–51].

The project included also an important activity on nanoindentation as a tool to evaluate mechanical property changes due to irradiation using ion-implanted specimens [53–56], which are only affected within a depth of a few μm from the surface. In connection with this, the publication of the CEN NATEDA (NAnoindentation TEsting DAta) Workshop Agreement [57] represents an important precedent for the standardization of nanoindentation testing, as a tool for the characterization of the mechanical behaviour of ion-irradiated specimens.

6 Summary and conclusions

GEMMA, INSPYRE and M4F represent examples of multidisciplinary projects with similar goals and approaches, but applied to different materials and conditions, showing the cross-cutting character of these approaches. GEMMA was mainly dedicated to the qualification of structural materials in corrosive environments, stress relief and irradiation effects. INSPYRE and M4F had a heavier modelling component, with a view to improving engineering tools, such as fuel performance codes or component design codes. In the three projects, advanced modelling tools were combined with microstructure examination and experimental measurements in order to improve our level of understanding of the mechanisms and rationalise collected data, enriching experimental data with data obtained from models. These and other cross-cutting materials science approaches, organized into five research lines, constitute the warp, while materials classes constitute the weft, on which the SRIA of ORIENT-NM is being built. In addition, all projects had an intensive and partly common education and training programme not described here, which corresponds to another important cross-cutting activity. It is expected that, by centralising these activities within the same initiative, such as a co-funded partnership, they can maintain their continuity, while benefitting on the one hand from cross-fertilisation and on the other hand from a single management and coordination structure.

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 reasons.

Author contribution statement

The four authors wrote the manuscript and coordinated the reported projects. The content of the work is the merit of the long list of project participants.

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Review Article

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ARIEL & SANDA nuclear data activities

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Abstract. Nuclear data are fundamental quantities for developing nuclear energy concepts and research. They are essential for the simulation of nuclear systems, safety and performance calculations, and reactor instrumentation. Nuclear data improvement requires a combination of many different know-hows that are distributed over many institutions along Europe. In the EURATOM call for Nuclear Fission and Radiation Protection NFRP-2018, two nuclear data projects were started in September 2019: the Coordination and Support Action ARIEL (Accelerator and Research reactor Infrastructures for Education and Learning) and the Research and Innovation Action SANDA (Solving Challenges in Nuclear Data for the Safety of European Nuclear facilities). The ARIEL project integrates education and training of young scientists and technicians with access to neutron beam research infrastructures and supports scientific visits to conduct short-term research projects relevant to thesis works. The SANDA project is focuses on research innovation actions, including detector and nuclear target development, important nuclear data measurements, nuclear data evaluation, and validation. A description of these ongoing projects, including the first results, is the subject of this article.

1 Introduction

Nuclear data are the fundamental base for developing all nuclear technologies, whether for nuclear energy, nuclear waste management, or other applications, e.g., in the medical sector. For the safety assessment of current and future advanced nuclear systems, particle transport calculations that simulate realistically the ongoing nuclear and atomic processes play a crucial role. Building prototype reactors and performing test experiments is extremely costly and time-consuming. Detailed and accurate simulations are the most relevant methodology for the cost-effective design of new concepts. They are relevant for designing, optimizing, and interpreting critical experimental tests and validations and thereby pave the way to efficient deployment. They are used for determining system behavior in various possible configurations and running conditions and allow selecting progressively between different technological options using only a limited number of experimental validations and prototypes. High-quality nuclear data, in particular complete and accurate information about the nuclear reactions taking place in nuclear systems, are an essential component of such modeling capabilities. The quality of a simulation depends on many aspects, but a significant uncertainty component is associated with the quality of nuclear data. No simulation or interpretation of measurements can be better than the limit imposed by the nuclear data. Several parameters, particularly safety parameters of reactors and other nuclear facilities, need to be known with a precision well below 0.1% resulting in nuclear data precisions better than a few percent, sometimes below 2%. In other cases, the precision needed can range from ca. 5−20%, but the isotope or material under investigation is radioactive or scarce. The advent of multi-physics simulations is also a challenge for the basic nuclear data required [1]. Nuclear data research has still not reached these levels of precision in all cases. The quality and completeness of the nuclear databases are continuously improving thanks to EURATOM-supported research projects in many framework programs (FP5, FP6, FP7, Horizon 2020, and Horizon Europe). The nuclear databases consist of numerous nuclear reaction data like cross sections of neutron-induced nuclear reactions, particle emission probabilities, as well as nuclear structure properties of the ground and excited states, e.g., masses, decay half-lives, level energies, and branching ratios, to name a few. Producing these nuclear data is a complex and lengthy process that relies on access to modern neutron beam facilities and highly-trained nuclear physicists. The nuclear data path to an

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evaluated complete nuclear data library requires work from many experts: measurements with neutron beams, production of radioactive actinide samples, data evaluations to create a consistent and complete nuclear data library, validation of the library with benchmarks, and integral experiments, finally inclusion of the nuclear data into the simulation codes.

Present-day nuclear data measurement activities follow the demands of the nuclear industry and research laboratories for complete and evaluated data files on neutron-induced nuclear reactions. On the European level, these data files are maintained by the OECD/NEA databank, which manages the Joint Evaluated Fission and Fusion File (JEFF). The experimental needs are prioritized on an international level by the Working Party for Evaluation Co-operation (WPEC) of the OECD/NEA Nuclear Science Committee. To prioritize research needs for improving the database to match the requirements for the development of advanced nuclear energy systems, a subgroup of the WPEC performed a comprehensive sensitivity study assessing the impact of uncertainties in the nuclear database on the modeling of a series of selected innovative systems which are presently under development. The most important requests for improvements in the nuclear data files are being collected in the High-Priority Request List (HPRL) of the NEA.

The best experimental data are collected internationally in the EXFOR database maintained as an open source of reliable information by the IAEA. Once the data are analyzed and evaluated, they are stored as ENDF libraries, also maintained by IAEA, NEA, and some worldwide laboratories, ready to be used for research and commercial applications from open repositories. The corresponding database for decay and structure data is ENSDF, and it is also maintained in an open platform with support from the IAEA and national nuclear data centers. All the results from EURATOM projects are introduced into these three databases that provide an excellent storage and dissemination tool both at EC and worldwide nuclear data research and user communities.

1.1 ARIEL (Accelerator and Research reactor Infrastructures for Education and Learning)

Integration of access to neutron facilities with education and training

Transnational access to European research facilities for nuclear data measurements, nuclear technology development, and nuclear engineering has been a valuable and successful activity in applied nuclear research through many EURATOM-supported projects. In the Framework program FP6, the EFNUDAT project (2006−2010) started with a transnational access consortium of 9 partners; in the project ERINDA (2010−2013) of FP7, the consortium had grown to 13 partners, while in the TAA activity of CHANDA (2013−2018) 16 partners out of 35 participated. The JRC neutron facilities in Geel took part in these projects while maintaining their own successful access schemes of NUDAME and EUFRAT.

An active league of nuclear data facilities in Europe has been formed. It is the objective of ARIEL to support transnational access of scientists and technical staff to these facilities on the national and transnational levels for training, education, and competence building. Many young scientists found jobs in the energy industry, medical physics, or in the state or federal governing administration for nuclear power, waste management, radiation protection, and the environment.

The ARIEL project combines the most modern and state-of-the-art European neutron beam laboratories using the full range of neutron sources from high-energy proton synchrotrons to research reactors. Experiments in international teams at these facilities provide hands-on training for students at the master, graduate, and postgraduate levels leading to PhD and master theses, as well as postdoctoral competence building. Based on the experience from the earlier projects, now technical staff, e.g., accelerator operators or research engineers, are able to participate fully in the training activities planned in ARIEL facilities.

To make the transnational access to these facilities most attractive for early stage researchers, the spectrum of research activities offered has been widened and includes nuclear data measurements and evaluation, radiation detector development, integral experiments of reactor parameters, material irradiation & nuclear data for isotope production, fundamental nuclear physics, medical applications, neutron imaging, and radiochemical experiments.

Twenty-six partners from 15 European countries are working together for the education and training of a new generation of young scientists and technical staff. The ARIEL project provides:

- transnational access to state-of-the-art neutron facilities,
- training of early-stage researchers through scientific visits,
- four schools for students to increase attractivity at the university level,
- three scientific workshops and progress meetings.

The ARIEL consortium provides access to research infrastructures with neutron beams in a large parameter range from cold and thermal neutron beams with meV energy to multi-MeV fast neutron beams, see Figure 1. The neutron sources can be grouped into four categories:

- time-of-flight facilities for fast neutrons GELINA (JRC-Geel), nELBE (HZDR, Dresden), NFS (GANIL, Caen), n_TOF (CERN, Geneva),
- charged-particle accelerators producing quasi monoenergetic neutron beams at Bordeaux, Orsay, Grenoble, Bruyères-le-Châtel, Frascati, Sevilla, Uppsala, and Bucharest,
- neutron reference fields at PTB Braunschweig, NPL Teddington and IRSN Cadarache,
- research reactor facilities at Budapest, Mol, Mainz, Řež, and Grenoble.

The consortium has several new or upgraded facilities: the Neutrons for Science facility (NFS) at GANIL, Caen, is

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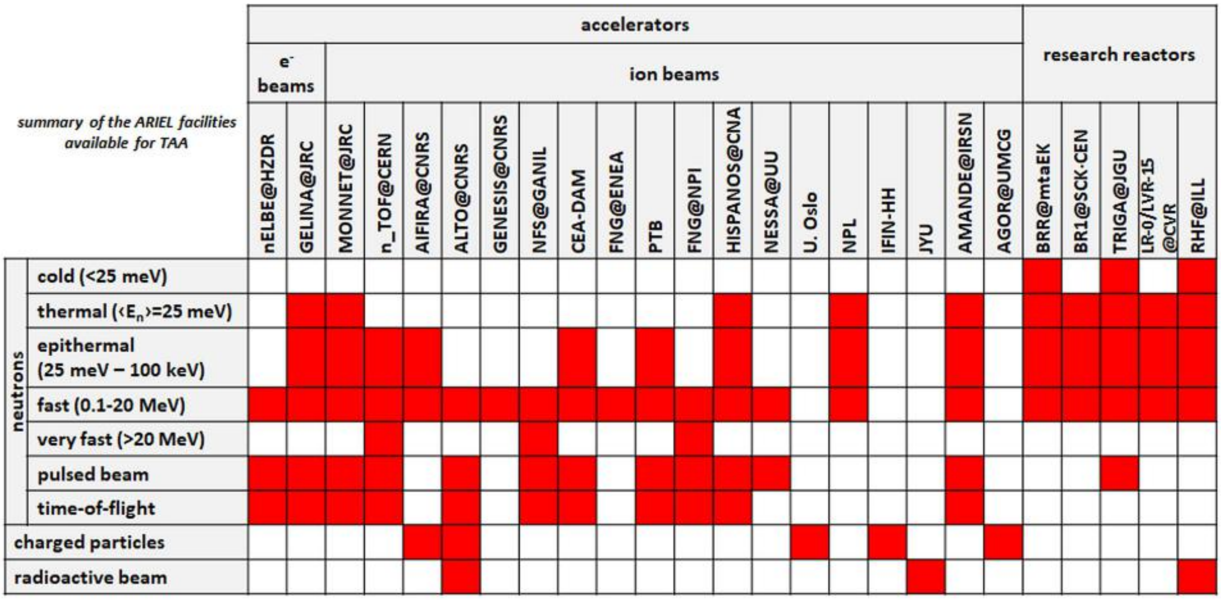

Fig. 1. Neutron and ion beams available at the ARIEL research facilities.

the first operational area at the SPIRAL-2 LINAC [2]. It provides high-intensity fast neutron beams up 40 MeV using a deuteron beam on a thick converter target with a maximum source strength of up to 1.8×10^{13} n/s using a 4−30 m flight path. Quasi mono-energetic neutron beams up to 31 MeV can be produced using protons on a thin lithium converter. In addition to time-of-flight measurements, irradiation stations for neutron beams and ion-induced reactions (protons 2−33 MeV, deuterons, helium 2−20 MeV/u) are available in the NFS converter room. The NFS facility has an excellent energy resolution due to the short pulse length of the SPIRAL-2 LINAC and compact converter target. The background due to the instantaneous gamma-flash from the neutron-producing reactions is less intense than at photoneutron or spallation sources. First experiments on neutron-induced light charged particle production, e.g., $^{16}\mathrm{O}(n,\alpha)$, fast neutron-induced fission and neutron emission (n,f), (n,xn) with radioactive samples and fission fragment spectroscopy with the FALSTAFF spectrometer are ongoing. The development of the SCONE detector for (n,xn) reactions is supported by SANDA.

After the long-shutdown LS2 of CERN, the n_TOF facility became operational again in April 2022. A new nitrogen gas-cooled spallation target with a water-moderated spectrum and optimized beam intensity and energy resolution for the two experimental areas has been built and performs as predicted. In addition, a near station (close to the spallation target) has been built for long-term irradiation up to 1 MGy/year and material research and activation measurements in mixed fields. The physics program at n_TOF for the year 2022 includes important nuclear data measurements that are supported by SANDA and ARIEL: The measurement of the $^{239}\mathrm{Pu}(n,\gamma)$ cross section and capture to fission ratio in the resolved resonance range with high resolution using dedicated thin and thick ^{239}Pu targets produced at JRC-Geel is prepared for the autumn of this year. The setup consists of a fission chamber with 10 deposits inside the 4π $\mathrm{BaF_2}$ total absorption calorimeter at the long flight path EAR1.

At the accelerator laboratory of the University of Jyväskylä, a new Multi-Reflection Time-of-Flight Mass Separator has been built to allow separating and identifying isobars from proton-induced fission at the IGISOL-4 facility for mass measurements and decay studies [3]. Fission fragment isomeric yields studies and the improvement of the IGISOL setup are supported by the SANDA project.

A total of 3000 h of additional beam time for external users will be provided by the ARIEL project. This corresponds to 30 typical experiments. Up to 4 users with a preference for early-stage researchers not more than 6 years after the PhD can be supported to work in these experiments.

The education and training of young scientists will be supported by scientific visits at the participating institutes, typically 8 weeks up to 12 weeks duration. In total, 30 visits will be organized. Early-stage researchers and short-term visitors will be able to work within the full spectrum of experimental capacities of the consortium resulting in a high potential for competence building. These activities are meant to support student graduate education, train engineers and technicians or share knowledge between facilities by visits of experienced researchers. IAEA, NEA has expressed interest in participating in this activity.

The transnational access and education and training activities are based on a semi-annual call for proposals that is peer-reviewed by a Project Advisory board consisting of 5 external experts. The selection will be based on scientific excellence and value to education and training through the participation of early-stage researchers.

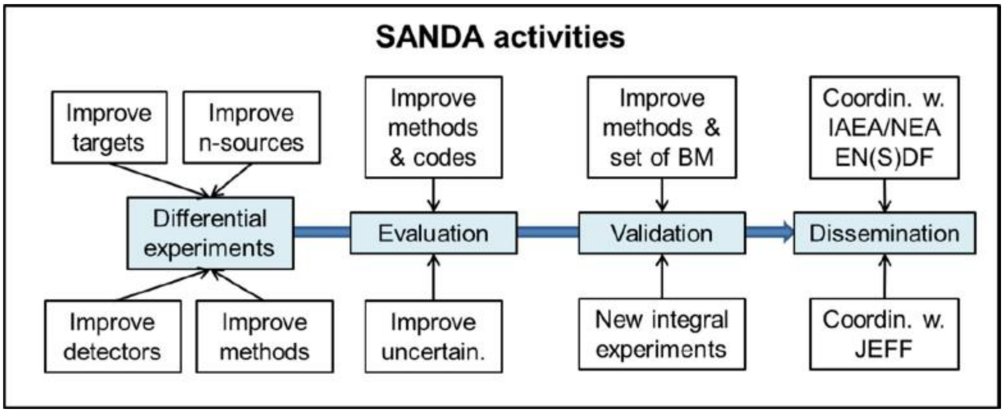

Fig. 2. SANDA activities and objectives on the full nuclear data cycle.

The strategic value shall be determined along the following list:

– focus on nuclear safety and support to modeling and evaluation (e.g., for advanced development for MYRRHA, molten salt reactors, spent fuel concepts, and decommissioning).
– Research experience for early-stage researchers with advanced techniques for radiation measurements, testing, and development of novel detector concepts. Transfer and exchange of knowledge and methodologies for senior scientists and technical staff.
– Coordination with research initiatives from ongoing EURATOM projects related to nuclear data (e.g., High precision nuclear data for the major actinides present in advanced reactor fuels).
– Coordination with OECD/NEA (High Priority Request list, JEFF, NEST), the IAEA International Nuclear Data Evaluation Network (INDEN), and European Technological Platforms.

Education and training activities will be complemented by four schools to attract students to the nuclear data field. The schools cover theoretical lectures and practical hands-on laboratory exercises on all aspects of the nuclear data path from experiment to the end-use in applications. They are held at consortium laboratories with an excellent background in providing these courses to early-stage researchers and graduate and postgraduate students. The course duration is one to two weeks. The target group here is any young European scientists or engineers. Cooperation with ENEN will allow advertising these courses to a wider research community.

Four schools are organized by the partners in Madrid, Seville, Uppsala, and Mainz:

- international online school on nuclear data: the path from the detector to the reactor calculation, CIEMAT, Madrid (24 participants) February 22 – March 4, 2022 [4].
- Hands-on school on the production, detection, and use of neutron beams, University of Seville (18–24 participants) September 2022.
- EXTEND'2023 summer school at Uppsala University (20–25 participants) June 2023.
- Lab course in Reactor Operation and Nuclear Chemistry, University of Mainz (10 participants) October 2023.

The scientific results are disseminated in four scientific meetings. The kick-off meeting was organized by HZDR, the first progress meeting and scientific workshop by JRC Geel, the second by NPL, and the final scientific workshop by IPN Orsay. The first ARIEL progress meeting [5] was part of the Joint ARIEL-SANDA meeting in March 2022 to maximize the networking between the two communities with a turnout of 89 registered participants.

1.2 SANDA

The SANDA project unites most of the European nuclear data community, infrastructures (35 partners from 19 countries), and resources. The main goals are to improve and develop experiments determining microscopic nuclear data (differential experiments), nuclear data evaluation, and validation to the very high level required to comply with the needs for safety standards mandatory for present and future European nuclear reactors and other installations using radioactive materials, see Figure 2. The selection of activities has been made considering the relevance, expected impact, and priorities of the resulting data according to the NEA/OECD and IAEA high priority lists. The impact has been evaluated from the perspective of safe, efficient, and competitive use of nuclear technologies.

Improving detectors. For nuclear data improvements, measurements and experiments need to be improved. To make progress beyond the state of the art, advanced detector and data acquisition systems need to be developed that will be used in new measurements for energy and non-energy applications. In particular, equipment is required which allows high precision measurements for the major actinides and the new nuclides present in advanced reactor fuels and fuel cycles (e.g., closed fuel cycles). In SANDA, new equipment and nuclear targets will be developed, and equipment and nuclear targets constructed during the previous CHANDA project will be used in new measurements.

The innovative detector developments address improving the experimental determination of:

- actinide fission cross sections to improve modeling of new fast reactor systems;
- fission yields and radioactive decay data to improve spent fuel heat, dose rate, and β-delayed neutron yield estimates;
- (n, xn) reaction cross sections to improve fast neutron flux distributions in new (fast) reactors. This includes the development of fast neutron spectrometers based on organic single crystals for neutron flux measurements with gamma-ray discrimination in complex environments and the development of a plastic detector array with a large solid angle for (n, xn) (e.g., ^{239}Pu(n, xn)) reaction studies at NFS;
- radiative neutron capture cross sections for actinides. This implies developing detectors that work well under high background conditions. (i-TED and Cs2LiYCl6:Ce (CLYC) inorganic scintillators);
- neutron-induced light charged particle emission cross sections and yields. A Si-detector-based $\Delta E-E$ telescope is under development at multi-MeV neutron energies where these reactions can cause secondary dose e.g., in proton therapy.

Nuclear data measurements. New nuclear data are determined by the measurement of the

- average neutron multiplicity of ^{235}U(n, f) and the fission cross sections of the ^{230}Th(n, f), ^{241}Am(n, f) and ^{239}Pu(n, f) reactions;
- neutron capture cross sections of the ^{239}Pu(n, γ) and ^{92,94,95}Mo(n, γ) reactions;
- neutron elastic and inelastic scattering and neutron multiplication cross sections for the nuclides ^{14}N,^{35,37}Cl, ^{209}Bi, ^{233}U, ^{238}U, and ^{239}Pu;
- decay data of ^{95}Rb, $^{100\text{gs}}$Nb, $^{102\text{m}}$Nb, ^{103}Tc, ^{140}Cs with Total Absorption Gamma-ray spectrometry and of ^{106}Ru, ^{153}Sm, ^{166}Ho, ^{186}Re, ^{212}Pb, ^{225}Ac, and ^{223}Ra half-lives and branching ratios for reactor and medical applications;
- fission yields and related distributions from neutron-induced fission of ^{235}U at LOHENGRIN (ILL) and PI-ICR at IGISOL and $(p, 2p)$ inverse kinematics fission reactions for ^{238}U and ^{237}Pa;
- spectrum-averaged cross sections for the ^{117}Sn(n,inl)$^{117\text{m}}$Sn and ^{60}Ni(n, p) reactions in a ^{252}Cf spectrum for dosimetry, ^{12}C double differential cross sections relevant for hadron therapy and the production cross sections of $\beta+$ emitters ^{11}C, ^{13}N, ^{15}O, ^{30}P for proton-induced reactions up to 250 MeV energy (non-energy applications);

Nuclear targets. The demand for high-quality targets, specially designed for the envisaged experiments and targets manufactured for nuclear reaction studies in a wide variety of application fields is constantly increasing, with the production of radioactive samples comprising particular challenges due to the special requirements arising from the emitted radiation. Only a handful of laboratories in Europe are capable and equipped to address these special requirements. In SANDA, the target production for the nuclear data community is structured so that resources and knowledge are shared, and requested targets can be produced and used efficiently for the project. A special feature is the development of an isotope separator allowing the production of rare, isotopically enriched targets for which stock material is not available otherwise.

Evaluation of nuclear data. Nuclear data evaluation aims to obtain a complete and consistent set of nuclear data files, such as those of the JEFF library, which can be used for modeling applications. Such files are delivered in a format readily processed into the data files used by a broad set of simulation tools. The SANDA project aims at contributing to nuclear data evaluation for international data libraries, such as JEFF, by

- developing open-source evaluation codes with improved phenomenological and microscopic models (those of the TALYS and EMPIRE codes for reaction nuclear data, dedicated codes for decay and structure data, as well as codes modeling the fission process to determine yields and spectra);
- performing evaluations of neutron-induced reaction data of actinides and fission products;
- providing processed data ready for use by simulation codes;
- providing sensitivity vectors for uncertainty quantification and sensitivity analysis;
- recommending benchmarks for the validation of the new evaluations against a wider suite of integral parameters, thereby aiming at a true general-purpose library;

Validation of nuclear data. The evaluated nuclear data are subject to a validation process, where experimental data, e.g., from benchmarks and integral experiments, are compared with realistic simulations using different evaluated nuclear data sets. Impact studies of data and uncertainties aim at relating nuclear data improvements to the needs dictated by their end-use in selected applications. SANDA includes the performance of new validation experiments in existing experimental facilities. The validation work comprises

- sensitivity analyses, impact studies, and uncertainty estimates for the following selected systems: ESFR/ASTRID, MYRRHA, JHR, LWR; MSR and waste management;
- validation studies for the above applications using the relevant experiments from the IRPhE, ICSBEP, SINBAD, and SFCOMPO databases of the OECD-NEA;
- new validation experiments at GELINA, LR-0, and TAPIRO and determining the needs for new integral data;

2 Impact and outlook for the nuclear data field

The two projects SANDA and ARIEL focus on the improvement and availability of precise nuclear data, including all required activities from the experiment to the final nuclear data library. In addition, ARIEL has an important focus on competence development, in particular of young researchers. As ARIEL and SANDA are still ongoing projects, delayed significantly by COVID, only a fraction of all planned activities have been completed. A short discussion is presented below.

Experiments at the consortium facilities will lead to a better knowledge of nuclear reaction cross-sections in the full energy interval of relevance to existing and future nuclear facilities, as well as for certain aspects of non-energy applications. The safety assessment of innovative nuclear technologies, e.g., accelerator-driven systems or reactors using a fast neutron spectrum, also depends on accurate nuclear data to be used in the respective numerical simulations. Data measured at the ARIEL facilities can be relevant for several activities in the current EURATOM work program, e.g., the GEN IV safety validation and radiation protection research and the current intensive research into small modular reactors.

Young scientists will develop multi-disciplinary and nuclear competencies through the research projects of ARIEL and SANDA, leading to PhD and master theses. Access to high-quality neutron beam facilities through experiments and education and training visits will lead to increased availability of experts and researchers for nuclear safety, radiation protection, and radioactive waste management.

The EURATOM-supported research is of special value as it forms a scientific community distributed over many countries with a strong exchange of people and knowledge to help develop science-based solutions in the different local energy sectors and the national energy policies.

2.1 Impact of ARIEL

The transnational access to neutron beam facilities in ARIEL has received 21 proposals in the first four calls, out of which 15 were endorsed by the PAC, and 6 experiments were already completed. This implies that 1265 beam time hours are committed (of 3000), and 596 h have been delivered up to now.

The completed experiments are:

- the response matrix of stilbene and p-terphenyl, including pulse shape discrimination, was investigated at PTB Braunschweig by M. Kostal et al., Rez.
- The light yield and energy resolution for fast neutrons of the scintillator CLYC-7 with 99% enriched ^{7}Li were measured at HISPANOS, CAN Seville, in a remotely controlled experiment by M. Nocente et al., ISTP-CNR Milano with dd − neutrons and ^{9}Be(d,n) neutron spectra.
- The response function and absolute calibration of a stilbene compact fast neutron spectrometer have been determined at PTB Braunschweig by A. Sardet et al., Cadarache with 2.5 MeV neutrons (ISO neutron energy, pT reaction) and with a time of flight spectra from the cyclotron d+^{9}Be continuous energy neutron source reaction. The data acquisition was remotely controlled by the users during the experiment.
- The Medley setup was used to measure double differential cross sections for light ion production on carbon at the new Neutrons for Science facility at GANIL by A. Prokofiev et al., Uppsala.
- A fiber -mounted scintillation neutron detector for measuring scalar flux and gradient was calibrated in the BR1 reactor in Mol by Imre Pazsit et al., Göteborg.
- The plasma delay effect on the timing of PIPS silicon detectors was measured at the ILL Lohengrin fission fragment spectrometer by A. Al-Adili et al., Uppsala.

For education and training activities, 16 proposals were submitted and endorsed in the first four calls amounting to 119 weeks of stay. Eight visits already took place even during pandemic conditions. The completed E & T activities are:

- the OPEN-CL framework was used to optimize data acquisition algorithms for fast Digitizer FPGA signal processing to be faster than external CPU processing by M. Astrain from Universidad Politecnica de Madrid visiting HZDR, Dresden.
- The VERDI fission fragment spectrometer was reassembled with new preamplifiers and new digital DAQ systems, and a two-arm measurement of ^{252}Cf (sf) will be prepared by A. Gomez Londoño, Zhihao Gao, and A. Al-Adili, Uppsala visiting JRC, Geel.
- The fine structure in the prompt fission neutron angular distribution with respect to the fission axis of ^{235}U(n_{th}, f) was theoretically investigated by N. Carjan, Bucharest, visiting JRC, Geel.
- The neutron capture of ^{103}Rh was measured at the GELINA 12 m measurement station, and ^{241}Am(n,γ) time-of-flight data in the resolved resonance region were analyzed, and resonance parameters were determined by A. Oprea, Bucharest, visiting JRC Geel.
- The simulation of the proton recoil telescope for the ^{235}U(n,f) cross section measurement relative to ^{1}H(n,n)p at n_TOF was completed by Q. Ducasse, Cadarache visiting PTB Braunschweig. The results are relevant for SANDA subtask 2.6.2.
- The ^{155,157}Gd resonance parameters were determined from transmission and capture measurements at GELINA, and a transmission measurement of Mo was prepared by R. Mucciola, Perugia, visiting JRC Geel.
- The feasibility of fast neutron-induced reaction measurements with a laser-driven neutron source of the DRACO Laser at HZDR, Dresden, was determined by M. Millán Callado, Seville.

The transnational access to neutron beam facilities and education and training activities were partially delayed due to the pandemic conditions. For the final three calls of the project until February 2024, about 15 new experiments with 1735 h of beam time can be supported. This year CERN n_TOF and NFS at GANIL are operational and should be able to receive support from ARIEL for nuclear data research.

Results from completed activities

A long-standing problem at pulsed radiation sources, like neutron time-of-flight facilities, is the occurrence of a high-intensity burst of gamma-rays and particles close to the

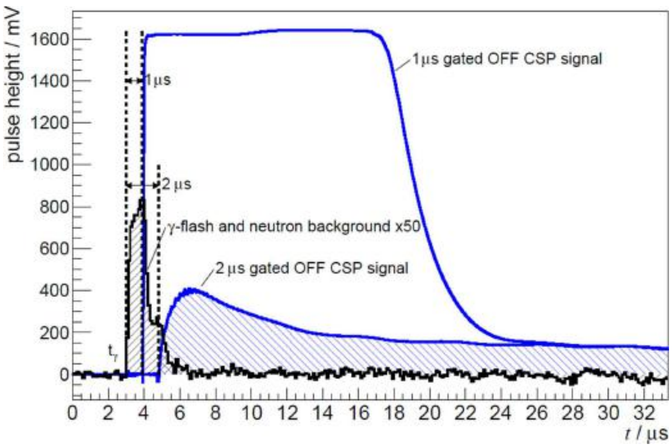

Fig. 3. Averaged Frisch Grid Ionization Chamber (DFGIC) anode signal traces from a detector test at CERN N_TOF EAR2. The directly measured detector current (without using a preamplifier) is depicted as black hatched line. It contains the gamma-flash superimposed with neutron-induced background. The γ-flash starts at $t = 3\,\mu s$. The charge-sensitive preamplifier has a short decay shaping time of $3\,\mu s$. The preamplifier signals are shown in blue with two different gate lengths ($1\,\mu s$ and $2\,\mu s$) for gamma-flash, for gating off the signals by the switch. The $1\,\mu s$ gated off preamplifier signal is saturated for about $15\,\mu s$. The $2\,\mu s$ gated off preamplifier signal (hatched area) has no more saturation. (Figure courtesy S. Urlass, PhD thesis TU Dresden, 2022).

speed of light, which saturates the detection setups meant for the detection of neutrons that arrive only a few tens to 100 ns after. A novel switch circuit was developed to connect the detector output to the ground and, therefore, effectively drain the charge while the detector is saturated with the high-intensity gamma-flash. After the burst and before the first neutrons arrive, the switch connects within a few ns time the detector input to the charge-sensitive preamplifier, and later arriving particles can be detected. A combination of this switch with a charge-sensitive preamplifier can be used to extend the usable neutron energy range at facilities that have a high instantaneous intensity, e.g., spallation sources [6].

Figure 3 shows a Frisch Grid Ionization chamber signal at n_TOF@CERN that is saturated from the gamma-flash for up to 20 ms if the detector is not gated off during the charge collection time related to the gamma-flash.

The production and detection of neutrons at the Peta-Watt LASER facility DRACO at HZDR, Dresden, was investigated using neutrons produced on different pitcher-catcher target assemblies consisting of Cu or LiF. Short, intense pulses of protons or deuterons accelerated up to 60 MeV were created by laser shots of the DRACO laser (30 J, 30 fs) on pitcher targets using the TSNA acceleration mechanism [7]. These ions created neutrons in nuclear reactions in the catcher targets of copper and LiF. A neutron intensity of the order of 10^8 n/shot was reached. In total, about 1200 laser shots were used to systematically study neutron production with different types of detectors. For example, with a thick single crystal diamond detector, a single event time-of-flight spectrum was recorded, see Figure 4.

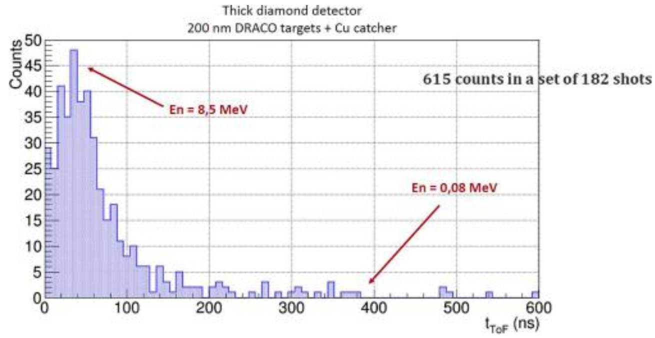

Fig. 4. Single particle neutron time-of-flight spectrum measured with the DRACO PW Laser using 182 laser shots. The flight path from the catcher target to the diamond detector was 145 cm. (Courtesy M. Millan Callado PhD thesis in preparation, Univ. of Seville, 2022).

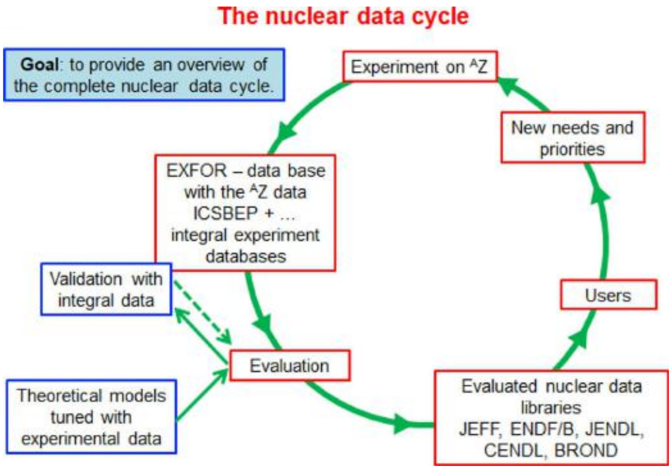

Fig. 5. The nuclear data cycle. All aspects were discussed in supervised online courses in small groups in the Nudatapath school organized by CIEMAT. (Courtesy: Daniel Cano-Ott, CIEMAT).

The International online school on nuclear data: the path from the detector to the reactor calculation was a virtual course on all topics of the nuclear data cycle, see Figure 5. Groups of 4−5 participants worked in supervised groups online with specially developed tools. Hands-on lectures with computer tools developed for this school included: sensitivity analysis of nuclear data for thermal and fast reactors, neutron reaction calculator of transmission, capture and fission experiments simulating experimental effects and backgrounds, visualization and processing of nuclear data, validation with integral experiments and simulations. The hands-on lectures were accompanied by introductory and overview online lectures.

2.2 Impact of SANDA

SANDA, as proposed, has made the most efforts and got achievements mainly on the developments of new innovative detector devices, differential measurements, and target preparation, initiating the work on data evaluation and validation with integral experiments.

Large achievements on new detectors for fission include the experimental validation of a new Gaseous Proton Recoil Telescope, the simulation, and calibration of FALSTAFF-FIPPS (Milestone MS1), the design and test with sources of the new 4pi-neutron detector BRIKEN, the design and test of other neutron detectors (Stilbene, SCONE) and the test of the new facility for measurements of half-lives at CEA/DRT/LNE-LNHB. In addition, large progress has been made for gamma detectors, including new electronics and tests for HPGe at n_TOF and the construction and tests of the sTED and validation of i-TED for n_TOF (EAR2). Attention is also being devoted to detectors for non-energy applications (DDX data for the n-induced emission of light-charged particles).

As for target preparation, the first set of samples has been identified, and the preparation of these targets started. Additionally, the design and simulations of beam optics for developing an isotope separator (IS) have been achieved, and the preparation of the site for the IS at PSI has also started. This device will become a key element to allow important measurements once operative.

SANDA is also preparing and performing new nuclear data measurements, including:

- data have already been taken and partly analyzed at n_TOF for neutron-induced fission cross sections of ^{235}U, ^{230}Th, ^{241}Am, and ^{239}Pu, and nubar data taken at MONNET@JRC-Geel.
- Key detectors (MEDLEY, SCALP) have been moved to NFS for in beam tests and measuring ^{16}O(n,α) and $^{\rm nat}$C(n,chp) and other (n,chp) reactions (chp – charged particle).
- Construction of the fission tagging chamber for the ^{239}Pu(n,γ) and preparation of Mo(n,γ) reactions to being measured at GELINA and n_TOF.
- New data taking and analysis of the ^{238}U(n,inel) reaction is completed; see reference [8], and new data taken for ^{233}U(n,inel), ^{209}Bi(n,γ) and ^{209}Bi(n,tot).
- Improved analysis methods have been developed with better results for decay data taken with DTAS – the segmented total absorption gamma-ray spectrometer [9].
- Preparation of fission yield measurements for ^{235}U at ILL with LOHENGRIN and a new methodology for the evaluation of the database of thermal neutron-induced fission yields.
- For non-energy applications: data for dosimetry have been measured and analyzed (^{117}Sn(n,inl)$^{117\rm m}$Sn), and the measurement of production and analysis of long-lived beta+ emitters (^{11}C and ^{13}N) is also done.

For most of the other experiments proposed, the simulation and some tests with radioactive sources have already been done.

In parallel, great efforts are being applied to improve processing and sensitivity calculations that have already helped to improve JEFF3.3. Work for new evaluations is ongoing, already resulting in a new version of the GEF model [10]. Furthermore, the identification of the most relevant experimental benchmarks for validation with existing databases has already been achieved, and validations are ongoing. Additionally, new integral experiments are being prepared at GELINA, MINERVE, LR-0, and TAPIRO, and although the actual experiments had to be postponed some months (COVID-19), progress has been made on their simulations.

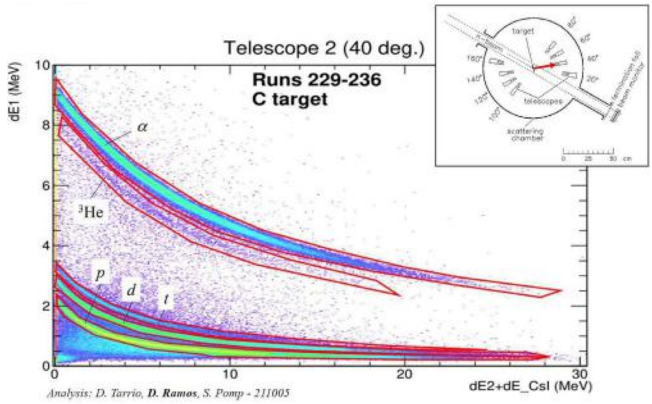

Fig. 6. Preliminary particle identification of light charged particles ($p, d, t,\ \alpha,\ ^3$He) from the LIONS experiment at NFS. (Courtesy: S. Pomp, Uppsala).

2.3 Synergy of ARIEL and SANDA

The transnational access to neutron beam facilities and education and training activities available through ARIEL and the joint research activities for new nuclear data measurements and innovative detector developments from SANDA offer a synergetic research program to improve relevant nuclear data through measurements evaluation and validation. The synergies are related to several aspects. The mobility support of ARIEL has been made available for young scientists to participate in several research projects that relate to SANDA experiments or related scientific questions. Below is only a small fraction of the projects listed that have already been completed.

The measurements of neutron-induced light-charged particle emission on carbon at the Neutrons for science facility at GANIL by a group from the Uppsala University are task 2.1.2 of SANDA and have also received support for transnational access to neutron beam facilities from ARIEL. A first particle identification $\Delta E-E$ plot is shown in Figure 6. The SCALP measurement at nELBE with ARIEL support contributes to the same SANDA task.

The validation of a stilbene detector response matrix by the Rez group is relevant for the validation subtask 5.3.2. A stilbene single crystal detector was characterized at PTB for use as a compact fast neutron spectrometer development in SANDA task 1.2.1.

ARIEL also supported theoretical and simulation studies that are relevant for the detector development in SANDA task 2.6.2 and for the fission yield evaluation of task 5.1.2.

In addition, close collaboration is supported with JRC Geel with several projects involving young researchers from Uppsala and Perugia, as well as the exchange of knowledge in fission theory with senior experts from Bucharest. The VERDI fission spectrometer setup has been supported by ARIEL and has a crucial effect on the time resolution, the plasma delay time in silicon detectors has been studied at the ILL Lohengrin spectrometer.

The radioactive target and sample production strongly collaborate with JRC Geel and target-making groups at PSI Villigen and the University of Mainz. A future concept of an isotope separator for enriched isotopic materials is being investigated.

3 Future strategy organization of nuclear data activities within European joint programs

The SANDA and ARIEL projects intend to contribute to the development of instruments like new detectors, new laboratories for target preparation, commissioning of new neutron sources, and new devices for integral experiments and new IT codes. These developments are important to make possible in the near term, but not necessarily within the project duration, the measurement and preparation of well-identified nuclear data that cannot be made with the presently available tools. So, within SANDA, there are coordination efforts to make sure that there is a coherent organization and support of the partners and other European nuclear data research groups, projects, and financing programs to guarantee that the data, tools, and methods produced will effectively serve the end-users, and will become part of a sustainable vehicle for nuclear data research within the EU.

Indeed, within the nuclear data EU research community, it is clear that there are already known data needs that cannot be solved within the scope of SANDA (because resources are limited and because they are beyond our present technical capabilities). We also know that there are new nuclear data needs being identified from the developments of new proposals like for small modular reactors (SMR) of different technologies, including a range of molten salt reactors (MSR) and new fuels and fuel cycles as well as new applications of nuclear technologies. We also know that the new detectors, methods, and laboratories being developed will progressively clear present technical barriers.

This is a well-known situation that has repeated over the years for several decades and that, indeed, shows the need for a continuous effort of the nuclear data R&D community to improve the technical limits and continuously provide the nuclear data needed for the new technological developments within the required uncertainties. In this sense, it is important to acknowledge those needs and to organize the corresponding support resources, preferably in the form of a coordinated European partnership, and SANDA includes actions to inform of these needs and to try mobilizing the different Member States to promote sustainable solutions. The new partnership could include activities for other basic data needed for safety and sustainability and simulation tools.

4 Conclusions

ARIEL and SANDA are two projects of EURATOM H2020 that support the measurement, evaluation, and validation of nuclear data that will improve the safety of present reactors and improve the precision and efficiency of the new advanced reactor and fuel cycles designs and of the applications of nuclear technologies. They respond to the high priority request list of nuclear data (HPRL) collected by the international organizations IAEA and NEA/OECD from the inputs and discussions with nuclear data users and producers. In addition, they provide significant progress on the detectors, neutron sources, methodologies, and laboratories that will allow future experiments to measure and evaluate data that today are beyond our technical capacities.

Despite the large delays introduced by the COVID pandemic (between 6 and 12 months on different activities of SANDA and ARIEL), both projects have already achieved significant results in developing and improving detectors, commissioning new neutron sources, performing some new measurements, and improving the tools and environment for evaluation and validation.

Despite the improvements in nuclear data already made and expected from both projects, it is clear that there will be remaining needs from the HPRL and the new needs identified in the research and demonstration of innovative nuclear system designs and technologies. It is important to focus and coordinate within a EURATOM framework all the available resources at the European level to prepare an efficient and sustainable R&D responding to those needs.

Special attention is given to the use of the research in SANDA and supported by ARIEL for training young scientists and engineers who will learn by doing during their PhD. Also, special care will be applied to the early and efficient dissemination of the project results to the EU community of nuclear data users.

Acknowledgement

Scientific results provided from ARIEL and SANDA project partners before publication are gratefully acknowledged.

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 yet due to legal reasons.

Author contribution statement

All authors contributed equally to the conception and writing of the paper. A.J., C.F. and A.P were responsible for the parts concerning the project ARIEL; E.G. was responsible for the parts concerning SANDA.

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FISA 2022
EURADWASTE'22

SESSION 3: EDUCATION AND TRAINING, RESEARCH INFRASTRUCTURES, LOW DOSE RADIATION PROTECTION, DECOMMISSIONING AND INTERNATIONAL COOPERATION

Co-chair: Tatiana IVANOVA (FR, OECD/NEA)

Co-chair: Roger GARBIL (EC, DG RTD)

Rapporteur: Said ABOUSAHL (FR, Expert)

SESSION 3 - SUMMARY

Said ABOUSAHL

1- Agenda of the session:

- Keynote: Growing Synergies between Fission and Fusion Research towards demonstration plants. Towards more integrated Fusion and Fission programmes: Marco UTILI (ENEA, IT)

- Education, Training and mobility, knowledge management: towards a common effort to assure a future workforce in Europe and abroad: projects ENENplus – GREaT-PIONEeR – ENEEP – PIKNUS – A-CINCH: Joerg STARFLINGER (ENEN, DE)

- Radiation protection and medical applications, European challenges and opportunities: projects MEDIRAD – HARMONIC – SINFONIA – EURAMED rocc-n-roll: Isabelle THIERRY-CHEF (ISGLOBAL, ES), Christoph HOESCHEN (OVGU, DE)

- RADONORM project: Ulrike KULKA (BFS, DE)

- MEENAS project: Hildegarde VANDENHOVE (SCK-CEN, BE)

- Improved expertise and innovations in decommissioning

  SHARE: Robert WINKLER (CEA, FR)

  INNO4GRAPH – PLEIADES – LD-SAFE – CLEANDEM- INSIDER: Nicolas MALLERON (EDF, FR)

- Supporting Access to key pan-European research infrastructures and international cooperation.

  JHOP2040 – TOURR – JHR ACCESS RIGHTS – OASIS JRC Open Access: Petri KINNUNEN (VTT, FI)

- Keynote: NEA Seeking Excellence in Nuclear Education, Training, Knowledge Management and Supporting Research Infrastructure. Insights of the NEA Education initiatives and the Framework for Irradiation Experiments (FIDES): Tatiana IVANOVA (OECD/NEA)

2- Introduction:

Session 3 is a large and a rich session covering several horizontal and synergetic areas complementing the two first FISA sessions dedicated to nuclear safety of current and advanced systems as well as the waste management sessions of the EURADWASTE conference agenda. Horizontal nuclear areas include the presentations of Euratom activities on training, education, knowledge management and open access to nuclear research facilities. Presentations of activities having synergies with other Commission research programmes were in the areas of nuclear medical applications, radiation protection as well as decommissioning. They also included the synergies between Euratom research activities in the field of nuclear fission and fusion. In addition to the Euratom projects presented at the session, several relevant posters have been exhibited during the conference days. Most of them provided additional information to the audience on results from other R&D projects funded by other programmes than Euratom Research and training.

3- Presentations:

SYNERGIES BETWEEN NUCLEAR FISSION AND FUSION

The session started by a keynote presentation on Synergies between Fission and Fusion.

The presentation highlighted the relevant areas of synergies such as Materials (coating materials), Tritium (purification), metal chemistry control, liquid metal pumping system, facilities and instrumentations for measurement and characterization.

The project ORIENT-NM was presented as a good example of how the synergies are evaluated by looking to the research roadmaps of Eurofusion and EJP on materials programmes.

The presentation triggered a good discussion between the participants. It was agreed that working on synergies helps bringing the fission and fusion scientist communities to work together. One participant highlighted the issue of the activation of materials used in some SMR concepts and asked if the solution can be on the use of materials from fusion which are less neutron activated. A representative from IAEA underlined the role of the agency on promoting such synergies through dedicated project.

TRAINING, EDUCATION AND KNOWLEDGE MANAGEMENT (TE and KM)

Attracting, developing and retaining young talents is a key task for this decade to support the contribution of nuclear energy towards the 2050 carbon neutrality strategy.

This challenge was at the centre of a presentation covering 4 dedicated euratom projects. General Nuclear TE is done through projects such as ENEN+ while more thematic TE are provided under projects such as A-CINCH, GRE@T-PIONEeR and ENEEP.

The ENEN+ project provided fund to more than 535 mobilities to BSc, MSc, PhDs and other young professionals to perform an E&T activities outside of their home country. A-CINCH project contributed to fill in the identified gaps in education in the field of nuclear radiochemistry (NRC). The project relies on a combination of classical and alternative/virtual teaching methods 3D NRC lab, RoboLabs (Remotely operated robotic laboratory) maintenance, NucWik (Nuclear wiki database of NRC teaching materials) updates, Open Educational Resources, or Citizen NRC MOOC preparation. The project GRE@T-PIONEeR aims to close an E&T gap in reactor physics by means of developing and providing specialised and advanced courses in computational and experimental reactor physics at the graduate level (MSc and PhD levels) and post-graduate level. Four training courses offered so far at different research reactor locations (3 training reactors). ENEEP (European nuclear experimental education platform) Focuses on operation of nuclear reactors and access to nuclear infrastructures.

The most important comment made by the audience after the presentation was on Marie Skłodowska-Curie Actions. It was welcomed the decision made by Euratom Programme to offer support through financial contributions so that researchers in the nuclear field become eligible to benefit from (MSCA) on an equal footing with researchers in other fields.

Knowledge Management has been illustrated by the JRC pilot project (PIKNUS) platform which is under development and aims to improve the accessibility to the results of various EURATOM funded projects. The pilot project focuses on recent "materials projects". An end-user group has provided valuable recommendations concerning the main features of the system. A first version of the system should be available for testing in autumn 2022. The start of operation is foreseen in 2023.

At international level, EU is also active in the field of E&T. A poster on training and education supported by the European Instrument for Nuclear Safety Cooperation (EINS) has been presented. It highlights the support to countries outside EU borders to maintain and improve the safe use of nuclear energy which requires competent and independent National Nuclear Regulatory Authorities (NRAs) and Technical Support Organizations (TSOs).

It is important also to mention here the presentation provided by NEA at this session on their activities in the fields of TE and KM through initiatives such as the Mentoring Workshops and NEA Global Forum on E&T.

SUPPORTING ACCESS TO KEY PAN-EUROPEAN RESEARCH INFRASTRUCTURES AND INTERNATIONAL COOPERATION.

One of the objectives of Euratom research programme is the support for the provision, availability and appropriate access of European and international research infrastructures, including JRC's infrastructures. Euratom programme is currently supporting several initiatives including the current one managed by the JRC. The current scheme of open ACCESS to JRC's infrastructure funded by Euratom programme under the OASIS project helps to bridge the gap between high and less wealthy institutions in the EU. The selection procedure is based on scientific merit of the proposals. An other important project is the "TOURR" project which is currently focusing on the strategic planning for optimising the use of the research reactors. One of the most important future research facility, namely the Jules Horovitz Reactor (JHR), is under construction. The JHR will aim at new generation of research capacity with the wide experimental device fleet. Euratom 6% access right of the future JHR capacity will be benefitting to the whole Euratom community. Road map has been developed for the first 4 years operation of JHR. There are several options for the Euratom share depending of the type of the irradiation scenarios.

Another project called "ARIEL" has been presented in session 2 and could be also part of this session since the project is focused on ET and access to Accelerators and Research Reactors for nuclear data measurements.

The implementation of open access schemes is a very complex process where several challenges are faced at technical and administrative levels. The experiences gathered in previous and current Euratom research & training programmes are a very good basis to be used for the design of future schemes, for all kinds of nuclear facilities.

MEDICAL APPLICATIONS OF IONIZING RADIATION AND RADIATION PROTECTION FOR EUROPEAN PATIENTS, POPULATION AND ENVIRONMENT

The focus of the presentation was on improving exposure estimation and studying the effects of diagnostic and therapeutic medical exposures in patients and staff using different endpoints. The presentation includes 4 euratom projects (MEDIRAD, SINFONIA and HARMONIC EURAMED rocc-n-roll). Beyond the classical exploitation of scientific publications, the projects aim at translating the scientific evidence into procedure and practice guidelines as well as into policy recommendations. In this context, the presentation showed the importance of collaboration with collaboration the existing EU Radiation Protection research platforms including MELODI, EURAMED and EURADOS which have developed and regularly update their SRAs. This collaboration aims at development of a common strategic research agenda and a roadmap for research priorities to improve estimates of the detrimental effects of medical applications, and to provide evidence based input and new approaches to reduce associated risks to patients and medical professionals and ultimately to provide evidence for further updating of the current BSS directive.

Together the four projects presented target all applications of radiation in medicine:

- Cancer treatment: HARMONIC (pediatric cancer patients), MEDIRAD (thyroid cancer patients and cardiovascular changes after radiotherapy for breast cancer) and SINFONIA (patients and workers);
- Cardiology: HARMONIC (pediatric cardiology) and MEDIRAD (patient and workers in fluoroscopy guided procedures)
- Diagnostic exposures: MEDIRAD (CT scanning) and SINFONIA (diagnostic of brain tumor and lymphoma)

EURAMED Rocc-n-Roll: strategic Research agenda in medical application of ionizing radiation in support to the Commission initiatives such as the SAMIRA action plan and the Beating Cancer Plan.

A further shared component of these projects and of all research in medical RP, is the importance of ethics considerations_throughout the implementation of the projects, as well as in the medical uses of IR.

After the presentation, some questions raised by the audience mainly on the data privacy challenge when handling personnel medical information. Here, the full implementation of the GDPR regulation is required. Other questions were on the cooperation with Radiation Protection platforms. It was confirmed that the structure of such cooperation exists and there are already some exchanges with other projects and initiatives like MEENAS.

Radiation protection research and innovation was at the centre of a presentation provided by a MEENAS association representative. MEENAS association has been established under a MoU of six European radiation protection research platforms MELODI, EURADOS, EURAMED, NERIS, ALLIANCE, SHARE for an integrative approach for RP.

MEENA is behind the PIANOFORTE partnership (HORIZON-EURATOM-2021-NRT-01-09 call) aims to provide a European scientific and technological basis for a robust system of protection and consolidated science-based policy recommendations to decision makers. In the long term, these efforts will translate into new and improved practical measures and better outcomes for the effective protection of people (public, workers, patients) and environment. This will be done through the interaction with many other Euratom projects (fuel design, socio-economic,…) on RP aspects as well as interaction with Horizon Europe Research and innovation programme such as the BCP (beating Cancer Programme), SAMIRA action plan, digital industry, space,…

Another presentation on radiation protection focused on managing risks from radon and NORM exposure situations to assure effective radiation protection based on improved scientific evidence and social considerations. This is done under the Euratom project called RadoNorm. The project supports EU Member States and the EU Commission in implementing the Basic Safety Standards for protection against ionising radiation hazards at the legislative, executive, and operational levels (Directive 2013/59 / EURATOM) with the aim to significantly reduce uncertainties in all steps of radiation risk management for radon and NORM (naturally occurring radioactive materials). Protocol and methods for data collection are completed as well as the compilation of the data. The STORE db has been adapted to the requirement of partners.

NUCLEAR DECOMMISSIONING

The session focused on how to make the dismantling operations more efficient, safer and more cost-effective. Two presentations provided some answers to the question. The first presentation was on the "SHARE" project aiming at the development of A roadmap for Research in Decommissioning. The approach used for that primarily based on consultation processes (including a survey and a number of workshops) aiming at identifying the needs and opinions of stakeholders throughout the value chain. The project also considered existing and emerging innovative solutions, as well as international best practices in nuclear decommissioning. The survey covered a total of 71 sub-thematic areas categorized under 8 thematic groups. In-depth analysis of the responses resulted in a detailed assessment of stakeholders' needs to improve the status quo. Simultaneously, an extensive literature review was carried out along the same thematic areas focusing on surveying existing methodologies and current international initiatives. About 250 proposed activities to close the gaps have been listed among them the International cooperation on waste criteria, characterization, knowledge sharing, TE,…

One issue that the SRA pointed out is the need to rapidly bring to maturity technologies (digital technologies, automatised or semi-automatised robotics, LASER cutting). It is the common objective of the five European projects (INNO4GRAPH, LD-SAFE, PLEIADES, CLEANDEM and INSIDER) presented after the presentation of SHARE.

The PLEIADES project (PLatform based an Emerging and Interoperable Applications for enhanced Decommissioning processES) is demonstrating an innovative digital decommissioning approach inspired by the BIM (Building Information Modelling) concept. INSIDER is proposing a methodology that allows to define and select the best nuclear decommissioning and dismantling operations (D&D) and remediation scenarios, which produce well-characterized waste for which storage and disposal routes are clearly identified. STRATEGIST (Sampling tool). CLEANDEM aims at reducing human exposure to radiation, as well as the duration and costs of D&D operations. It is a first example of BIM use in a digital twin approach. In this approach, the building model is coupled to its physical twin and updated in real-time as soon as the autonomous characterisation system is acquiring new data. The LD-SAFE project focuses on the promising LASER cutting, and more particularly on how to ensure total operational safety of this technology during cutting operations in future dismantling sites. Tests are ongoing. The INNO4GRAPH project is about the development of physical and digital tools and methods to support the decommissioning of European graphite reactors. Full scale mock-up of the Chinon A2.

In addition to the two above mentioned presentations, there were several posters presenting dedicated technologies and approaches for efficient decommissioning.

The poster made by Assystem was on its digital suit « DEMologist » which, coupled with a number of dedicated digital tools, act as a co-designed platform between the project owner and the prime contractor.

From Hassel University, the poster described A developed Compton camera combined with a 3D camera as an alternative to the more common scanning based spectrometric approach for radiological mapping.

From Spain, the poster was on an active mode use of the developed 3D tool which brings a real added value for the implementation of complex projects in the nuclear fuel cycle (building, decommissioning, waste management,...).

Being used in CERN, a modular interface for the control of heterogeneous robotic systems for remote unplanned interventions in hazardous environments has been one of the best posters.

One important question raised by the audience was on the possibility of having a place where some of the well characterized materials (piece of concrete, metals,…) can be stored and accessible to partners. This can help benchmarking and round robins exercise for characterization of materials from decommissioning and dismantling activities.

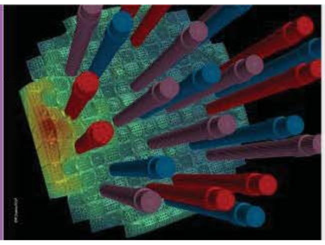
4- Conclusions:

Maintaining and further improving the safe and secure use of nuclear and radiation technologies necessitate an important effort for maintaining and developing the necessary skills and expertise in Europe. Euratom support to TE and KM as well as to open access to nuclear facilities remain crucial. Almost all the projects in session 1 and 2 had specific ET and KM components but the dedicated projects presented at session 3 could clearly demonstrate the European dimension of their E&T activities and a high attractiveness of the courses they offer. The experiences gathered in the implementation of open access projects in previous and current Euratom research & training programmes, are a very good basis to be used for the design of future schemes, for all kinds of nuclear facilities.

The integrative approach for Radiation Protection at the origin of the newly established MEENAS association is a real challenge not only for its six members but also for its cooperation with other partners outside the Euratom programmes.

Nuclear medical applications is a growing area under Euratom programme where the synergies between Euratom and health programmes are evident but need to be well coordinated and supported by the two programmes in order to maximise the results of the projects. This is especially needed when the activities are beyond the radiation protection areas.

Decommissioning is also a growing industrial area and thanks to Euratom programme a dedicated Strategic Research agenda has been established. The challenge here will be on the monitoring of the SRA implementation to ensure that the various current and future projects are fully in line with it.



FISA 2022

30 May - 3 June 2022
Lyon, France

GROWING SYNERGIES BETWEEN FISSION AND FUSION RESEARCH TOWARDS DEMONSTRATION PLANTS

M. Utili, C. Alberghi, D. Diamanti, D. Martelli, F. Papa,
A. Venturini, M. Tarantino

Introduction

The **scope** of this lecture is to identify common technologies developed in both Fusion and Fission Reactors to promote synergetic R&D programs. **In the last years**, several **platforms** have identified cross-cutting activities between fission and fusion projects in particular in the frame **of structural materials** and several research programs were developed by NUGENIA, EERA-JPNM, OECD-NEA and IAEA.

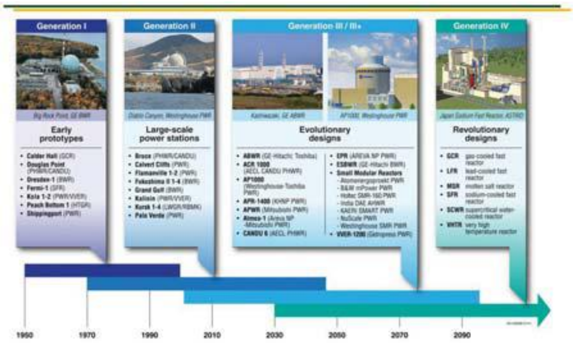
In the frame of **ORIENT-NM** project, possible collaborations were explored with international organisations, standardization, safety and data/knowledge management bodies involving different stakeholders. In particular, the task 4.3 of the project intends to secure complementarity, consistency and commonalities on research between the **EUROfusion roadmap** and the **Europea Joint Program (EJP)** SRA, thereby identifying possible **cross-cutting projects**.

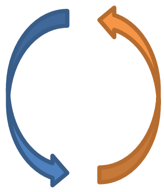
Introduction

Fission Power Plant Reactor

Fission Roadmap will be able to demonstrate:

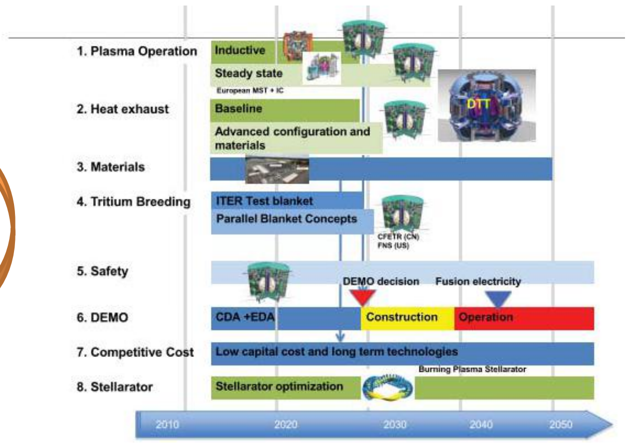
- ❑ Short term: SMR-oriented features aimed at being a competitive option for the future Nuclear Power Plants
- ❑ Middle-term: potentialities to demonstrate that the LMFR/GFR large scale reactors can meet the goals set out by GIF for Generation-IV reactors.





Fusion Reactor

In a longer term, fusion has the potential to provide the baseload energy production needed to provide electricity to final users.



Synergies between Fission and Fusion R&D

A common program considers developing core technologies of coolants and auxiliary systems, evaluate structural issues, set-up a collective database for Engineering Design and share knowledge about manufacturing, technologies and codes used. The added value of interacting with **EUROfusion** is also that it is an EJP with **established QA, Engineering & Technology schemes**, the knowledge of which will be beneficial for the design of the future EJP.

Among the possible R&D program identified to grow up synergies, particular attention has to be dedicated to some open technical issues:

- ❑ **Mitigation strategies to protect materials from the aggressive environment**
- ❑ The experience and knowledge developed for **the tritium extraction system** of fission reactors can find application to fusion reactor for Water-Cooled-Lithium-Lead (WCLL) and Helium-Cooled-Pebble-Beds (HCPB) BB concepts
- ❑ Liquid **metal chemistry control** of LMFR and WCLL BB concepts of EUROPEAN DEMO Reactor
- ❑ **Liquid metal pumping system**
- ❑ **Facilities and Instrumentation**: the experience and knowledge gained in the design and operation of experimental facilities supporting liquid metal fast reactor development can be transferred to fusion reactors and vice versa.

Protective coating

Mitigation strategies to protect materials from the aggressive environment in the coolant for fast Fission reactors and Fusion Reactor: WCLL and HCPB Breeding Blanket concepts.

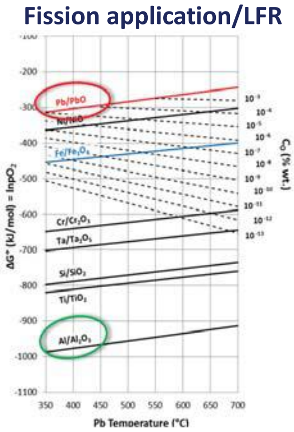
	Fission Coating	**Fusion Coating**
Function	▪ Protect materials from the aggressive environment: corrosion, erosion, LME	▪ Protect materials from the aggressive environment: corrosion, erosion ▪ Avoid tritium permeation ▪ Electrical isolation of structural materials
Loads	▪ Neutron Flux up to 100dpa ▪ Temperature up to 800°C ▪ Environments: Pb/PbBi/He/Na/H_2O	▪ Neutron Flux up to 80dpa, up to 2.010+14 (n/cm2/s) ▪ Temperature up to 550°C ▪ Environments: PbLi/He/H_2O
Materials	▪ Substrate: **AISI 316L/15-15Ti /AISI 300 series** ▪ Al2O3/ FeCrAl diff. coating, AlTiN / AFA steel	▪ Substrate: **EUROFER** ▪ Al2O3/ Multilayer
Manufacturing process	▪ PLD, ALD, Diffusion/Detonation gun/ pack cementation	▪ PLD, ALD, ECX, Packed cementation

Protective coating

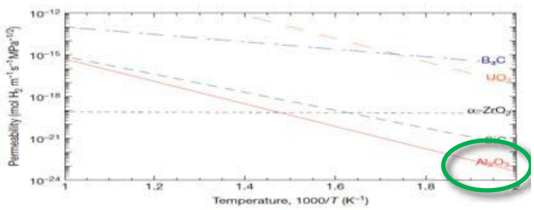
Experience and knowledge gained in the coating processes development can be transferred to fusion reactors and vice versa by the identification of:

- ❑ common **coating materials** with relevant TRL: Al2O3;
- ❑ common manufacturing process: Pulsed Laser Deposition and packed cementation processes;
- ❑ common characterisation program:
  - ➢ Mechanical characterisation in Liquid Metal
  - ➢ **Irradiation program**
  - ➢ coating manufacturing

Fission application/LFR



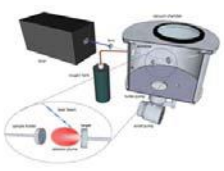
Fusion application



The final scope is to Demonstrate the possibility to manufacture suitable coating at relevant scale characterized at relevant operative conditions

Protective coating

Al2O3 coating developed by Pulsed Laser Deposition (PLD)



In the *PLD* a high-power pulsed laser beam is focused inside a vacuum chamber to strike a target of the material (EUROFER/AISI). Al is vaporized from the target and as result, a high homogeneous layer of alumina is deposited.

Property @RT	Sapphire	PLD Al_2O_3	AISI 316L
v	0,24	0,295 ± 0,025	0,3
E [GPa]	345	193,8 ± 9,9	200
G [GPa]	175	75,5 ± 3,8	80
B [GPa]	240	159,2 ± 11,8	140
H [GPa]	27,8	10,3 ± 1	4
H/E	0,059	0,049 ± 0,007	0,025

Breeding Blanket Project in EUROfusion

Upgraded PLD facility

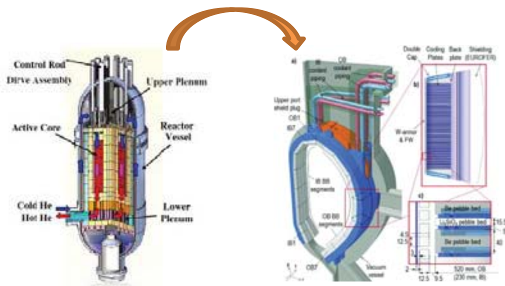
TRANSAT TRANSversal Actions for Tritium

1" tube - 300 mm long AISI 316L coated with α - AL2O3 - 3 µm

- PLD coating investigated in the frame of Fission (**TRANSAT project**) and Fusion program (**FP8-BB EUROFUSION**): compatibility with the coolant, tritium permeations, scale up of the facility
- Coating behavior and Tritium transport proprieties has to be further investigated with the support of experimental device and **numerical tools (dynamic molecular code)** that can play an important role to support the design of system.

Tritium purification in fission and fusion reactors

- The process most widely used for the tritium removal in the Coolant Purification Systems (CPSs) of **High Temperature Gas Reactors (HTGRs)** considers the oxidation of Q_2 (Q = H, D, T) into Q_2O, in high temperature copper oxide beds, and the following adsorption of the generated tritiated water in molecular sieve beds, at room temperature.
- This process has been also proposed for the CPS of **ITER and DEMO** Test Blanket Module (TBM), in the configuration **Helium Cooled Pebble Bed (HCPB)**. Also in this case, the purification of helium from tritium foresees two steps:
  - oxidation of Q_2 into Q_2O, using copper oxide beds (Q = H, D, T);
  - removal of Q_2O from He, using molecular sieves.



G-IV HTGRs

DEMO-HCPB BB

DOI: 10.1016/j.fusengdes.2019.01.141

- In fusion reactors, the CPS has also the scope to transform the removed tritium in a suitable form for the final extraction systems. In ITER, Reducing Beds (RBs), based on use of metallic alloys, are the reference technology to transform the Q_2O trapped inside the molecular sieve beds in Q_2, which will be directed to the downstream tritium processing systems.

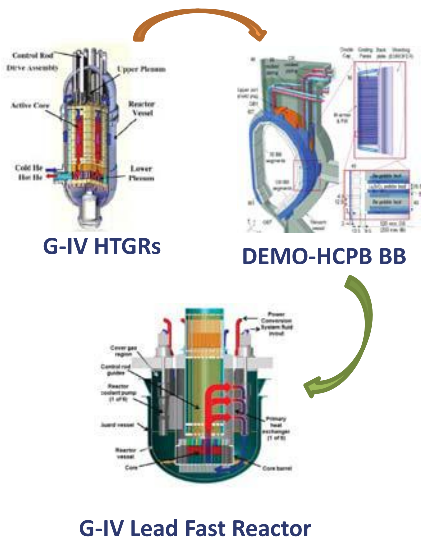
HYDREX Experimental Facility

- HYDREX (HYDRogen EXtraction) is an experimental facility, located in ENEA Brasimone Research Centre, having the scope to test processes, components and materials considered of interest for tritium extraction/purification from helium and for the purification systems of the cover gas of liquid metal cooled fast reactors.
- The performances of different types of molecular sieves, included in a PTSA column, can be studied in conditions characterized by different temperatures and pressures.
- The trapped water, released during the regeneration of the molecular sieves, can be directed to a RB, in which the performances for the reduction of H_2O into H_2 of the selected metallic getter can be studied.

HYDREX Experimental Facility

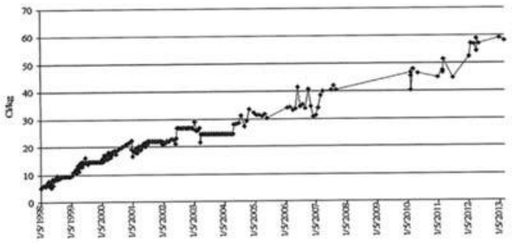
Tritium purification in GEN IV reactors

- Among the technologies selected by Generation IV International Forum (GIF) as the most interesting for the development of the future fission reactors, two are liquid metal fast reactors: Sodium Fast Reactors (SFRs) and Lead-cooled Fast Reactors (LFRs).
- In the past, the tritium concentration in the primary cover gas of SFRs using steam generators was considered very low, due to the efficiency of the cold traps for tritium removal; for this reason no dedicated device for tritium removal was considered necessary.
- However, to reduce the release of tritium in the environment at a level as low as reasonably achievable, it is necessary to consider also for SFRs the treatment of the cover gas.
- Because no significant interaction is expected between hydrogen isotopes and lead, the cold traps used for tritium purification in SFRs seem not effective for LFRs and, consequently, the treatment of the cover gas is required.
- The reference process for tritium purification considered in HTGRs and in HCPB TBM of fusion reactors can be taken into account also for the treatment of the cover gas in liquid metal fast reactors.

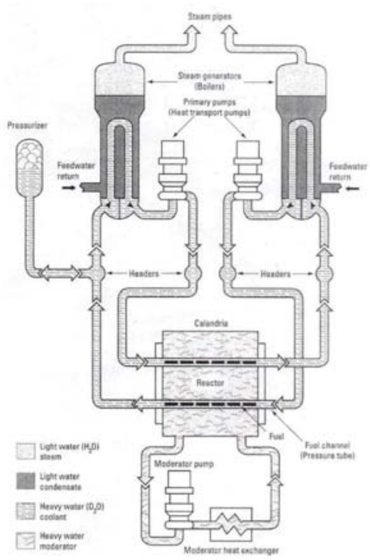


Water Detritiation Systems

- ❑ Heavy Water Reactors (HWR) use D_2O as neutron moderator and reactor coolant due to the very small absorption cross section for thermal neutrons compared to light water
- ❑ In HWR, tritium is directly generated from neutron absorption (even if it is small) by the deuterium atoms in heavy water; therefore the coolant and moderator will be contaminated with tritium
- ❑ In a CANDU 600 NPP, the HW inventory is >450,000 kg divided between moderator and coolant. The growth of tritium activity in the moderator of NPP Cernavoda Unit 1 is shown in figure.



➡ Adoption of **Water Detritiation System (WDS)**



Babcock & Wilcox Canada – Cernavoda Steam Generators Design - Project No. 7505/7506.

The experience and knowledge developed for the tritium extraction system of CANDU reactors can find application to fusion reactors Breeding Blanket (BB) concepts

Fusion reactors WDS

The general procedure to recover tritium from water foresees two processes:

- ❑ **front-end process** in which the tritium is transferred from the aqueous into a hydrogen gas stream (several processes available: direct electrolysis, CECE, LPCE, VPCE)
- ❑ **back-end process** for the separation of the hydrogen isotopologues (cryogenic distillation)

Current WDS for CANDU reactors manage water flow rates up to 360 kg h^{-1} (Darlington Tritium Removal Facility DTRF). Tritiated water is processed off-line.

Darlington Tritium Removal Facility

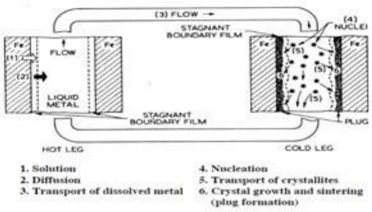
ITER, CFETR and DEMO WDS:

- ❑ **ITER WDS** is based on **CANDU WDS** design. It will process a flow rate of 20 kg h^{-1} adopting as front-end process the Combined Electrolysis and Catalytic Exchange (CECE)
- ❑ **Chinese Fusion Engineering Test Reactor (CFETR)** WDS will be based on CECE process. It will process around 500 kg h^{-1} for water-cooled BB.
- ❑ **DEMO WDS** in the case of WCLL BB must process few thousands kg h^{-1} to ensure, without anti-permeation barriers, a tritium concentration in the coolant below 1.85×10^{11} Bq kg^{-1}

In the case of DEMO, from a technological point of view, a process able to decontaminate such large amount of tritiated water is very energy consuming. ➡ Tritium permeation should be reduced with permeation barriers

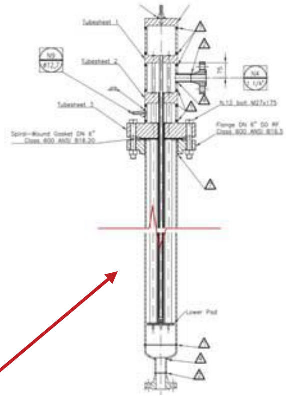
Liquid Metal chemistry

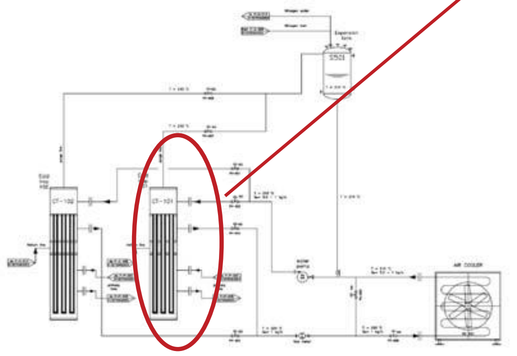
- ❑ Due to the extreme operating condition of Lead cooled fast reactor (GEN IV- Fission) and LiPb loop for the WCLL blanket (Fusion), corrosion and corrosion product transport phenomena constitute strong limitations for the loop safety (**material corrosion**, **plugging phenomena** and **region with high concentration of activated materials**).
- ❑ A system devoted to remove the corrosion product was developed in the frame of WCLL BB. The ***Cold Trap*** system consists of a heat and mass transfer device, where a **supersaturated solution of impurities is generated** as the result of the primary fluid cooling, causing the **crystallization of the impurities both on the immovable surfaces and in suspension**.

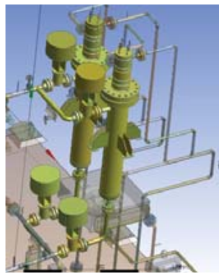


$$C_{Fe}^{S} = e^{\left(a - \frac{b}{T}\right)}$$

C_{Fe}^{S} Fe saturation concentration in LM (kg/m3)







Pumping systems for Liquid metals

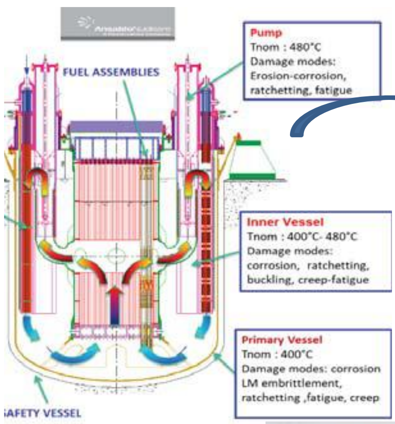
To manage liquid metal flow in the range 50-400kg/s dedicated pumping system was designed and qualified in the frame of Gen-IV LMFR. The design proposed was adapted to PbLi loop of WCLL BB Fusion reactor, based on **mechanical pump with magnetic coupling** technologies:

- ❑ **Mechanical centrifugal pump**, was considered the most promising solution due to the high efficiency (η=60%) in comparison with the electromagnetic pumps (η in the range 15-20%)
- ❑ **Magnetic coupling electrical motor with pump shaft.**

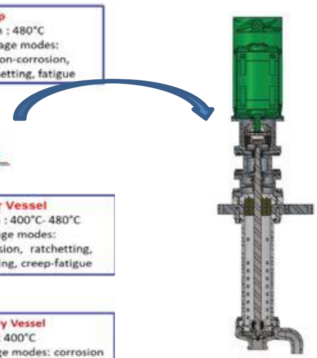
The main design parameters are:

- Rotational speed: **1000 rpm** (for outboard); 750 rpm (for inboard)
- Efficiency Electric motor estimated: 90 kW 6Poles.

Fission Gen-IV LMFR



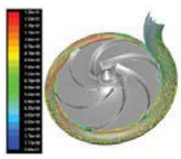
WCLL – BB DEMO



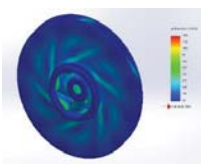
operating parameters of the pump

	Q	H
	[m³/h]	[m]
PLP	30.4	30.0
BEP	72.9	15.0

Impeller Velocity profile



Von Mises stress on impeller



Pumping systems for experimental facilities

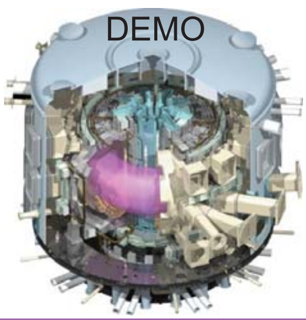
Facility name	Fluid/ Application	Type of pump	Max. Flow Rate [kg/s]	Head [bar]	Working T [°C]	Operating Time [h]
LECOR	LBE/Fission	Vertical centrifugal	10.9	5	300	12,000
CHEOPE III	Pb/Fission	Vertical centrifugal	2.7	3	420	10,000
LIFUS II	PbLi/Fusion	Vertical centrifugal	5.4	4	300	25,000
RELA III	PbLi/Fusion	Vertical centrifugal	1.0	3	300	1,000
LECOR upgrade	Pb/Fission	Vertical centrifugal	27.2	5	500	3,000
TRIEX	PbLi/Fusion	Vertical centrifugal	1.5	2.5	530	3,000
HELENA	Pb/Fission	Horizontal centrifugal	100	3.5	480	1,000
CIRCE	LBE/Fission	Axial mechanical	81.7	1.5	500	new
TRIEX-II	PbLi/Fusion	Permanent magnet	4.9	4	530	2,500
IELLLO	PbLi/Fusion	Permanent magnet	2.5	3	400	5,000

Gen-IV LFR and Fusion Experimental facilities

Experimental Facilities for Fast Reactors: IAEA database

Research Platform

- CIRCE
- NACIE
- LIFUS-5
- HELENA
- RACHEL
- PLACE
- ATHENA
- CHEMLAB
- ……….



Experimental Facilities for Fusion Reactors: database is missing

- HE-FUS3
- HYDREX
- BREST
- IELLLO
- PERI-II
- PLD device
- APRIL
- ……….

Research Platform

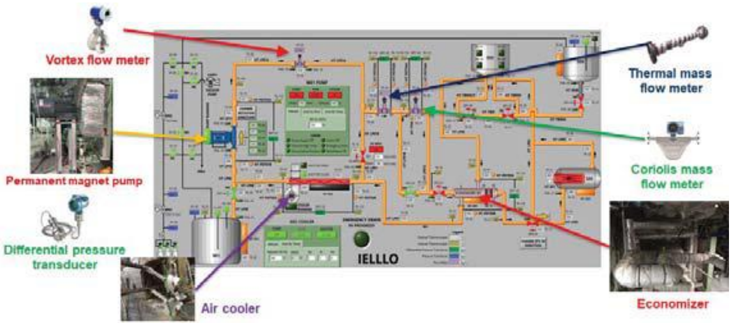
https://www.iaea.org/newscenter/news/new-iaea-database-to-support-advanced-fast-reactors-development-and-deployment

Instrumentation

Instrumentation plays a key role in the operation, control and management of Fusion and Fission reactors, thus the experience and knowledge gained in the design and operation of experimental facilities supporting liquid metal fast reactor development can be transferred to fusion reactors and vice versa.

Instrumentation developed for Gen-IV LFR Research facilities can be adopted to Fusion power plant, as:

- ❑ LM Mass flow meter
- ❑ LM Pressure meter
- ❑ Temperature sensors
- ❑ LM Level meter
- ❑ Neutron flux



Criteria
Measurement range (max)
Measurement range (typical)
Long term stability
Accuracy
Repeatability
Interchangeability
Tip sensitivity
Signal strength
Excitation
Cost
Noise problems
Extension cable
Best for
Worst for
Hysteresis
Self-heating

CONCLUSION

In order to growing synergies between fission and fusion research towards demonstration plants it is necessary to:

- ❑ Consider core technologies of coolants and auxiliary systems, evaluate structural issues, set-up a collective database for: Engineering Design, infrastructure, experimental facilities, instrumentations with focus on possible synergies between Gen-IV and Fusion power plant application.
- ❑ share knowledge about development and manufacturing of technologies and codes used.
- ❑ Create synergies among research Teams in order to promote exchange of knowledge and experience.

THANK YOU

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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)

REVIEW ARTICLE

OPEN ACCESS

Education, training and mobility, knowledge management: towards a common effort to ensure a future workforce in Europe and abroad

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Abstract. Continuous and future-oriented education and training as well as knowledge management for young talents are required for the safe and reliable operation of nuclear reactors and nuclear facilities in Europe. A dedicated line of collaborative projects addresses the specific needs, such as lack of personnel (project ENEN+: "attract, retain and develop new nuclear talents beyond academic curricula"). State-of-the-art approaches and in-depth knowledge are provided when it comes to reactor physics (project GRE@T-PIONEeR: "graduate education alliance for teaching the physics and safety of nuclear reactors") or nuclear radiochemistry (project A-CINCH: "augmented cooperation in education and training in nuclear and radiochemistry"). A highly skilled nuclear engineer must undergo experimental work to better observe theoretical principles at work. Following the ENEEP (European nuclear experimental educational platform) initiative, a network of research reactors and special laboratories is made available for performing such activities. Another issue found is that the results of Euratom-funded research activities are spread across multiple platforms and websites making it difficult to find relevant information within a reasonable timeframe. Such a situation requires the application of knowledge management actions. The PIKNUS project aims to define a concept of a knowledge management method and tool to improve the sharing and availability of Euratom research results. All projects successfully demonstrate that European collaboration could address certain needs to attract, develop and retain young talents in future-oriented nuclear fields.

1 Introduction

The use of nuclear energy is a long-term commitment. Nuclear Power Plants (NPP) could be with us for about 100 years or more[1] since lifetime extensions of several plants are already decided in many European countries. The safe and reliable operation of NPPs requires the best available knowledge and the best available skills of their employees. Therefore, a continuous supply of nuclear talent must be guaranteed, which must be attracted, developed, and retained in the nuclear field.

Expressed in more detail, highly educated personnel with very specific knowledge, skills and competencies will be still required in the future regardless of the development of the nuclear power sector in the EU, as either new builds, development of innovative and advanced reactors, long-term operations, shut-down, decommissioning, waste management and radiation protection all necessitate qualified staff. This is also the case for other industrial and medical applications making use of radionuclides and/or ionising radiation. This situation persists already since the turn of millennia when the OECD/Nuclear Energy Agency's report, "nuclear education and training: cause for concern?" (2000), demonstrated that many nations are training too few scientists to meet the needs of their current and future nuclear industries and authorities and that the European educational skill base has become fragmented to a point where universities in many countries lack sufficient staff and equipment to provide education in all nuclear areas.

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[1] Including licensing, long-term operation and decommissioning.

Many of these challenges have a transnational dimension and can be more efficiently addressed through a joint approach. A closer collaboration of higher education European institutions guarantees very high quality of education and training activities. The access to cross Member States research infrastructures allows students to learn and develop skills, e.g. using training reactors or specialized R&D facilities, not available in each country, as well as building collaboration networks and sharing safety culture fundamentals.

On the long-term perspective, it is important to both give young talents the chance to develop new skills and knowledge, and to manage the existing knowledge, i.e. preservation and dissemination of information and data It means that continuous actions and initiatives are required in education and training (E&T) combined with knowledge management (KM) for the benefit of Europe in all nuclear fields.

Through its Euratom Program, the European Commission continuously supports several E&T and KM initiatives in the nuclear field through both collaborative projects (Indirect Actions) or via direct research activities implemented by the European Commission Joint Research Centre, JRC (so-called Direct Actions). Both types of actions support research contributing to increased knowledge and competencies for nuclear safety, security and safeguards.

A dedicated line of recent collaborative projects addresses the specific needs in the sector to prevent undersupply of personnel (ENEN+) and provide state-of-the-art approaches and in-depth knowledge when it comes to reactor physics (GRE@T-PIONEeR) or nuclear radiochemistry (A-CINCH). A highly skilled nuclear engineer must undergo experimental work to better observe theoretical principles at work. Following the ENEEP initiative, a network of research reactors is made available for performing such activities. Another constraint is that the results of Euratom-funded research activities are spread across multiple platforms and websites making it difficult to find relevant information within a reasonable timeframe. Such a situation requires the application of KM actions. The PIKNUS project aims to develop a concept of a knowledge management method and related tools to improve the sharing and availability of Euratom research results. The projects are described in detail as follows.

Regarding the needs and future challenges within nuclear sciences and engineering, expertise in nuclear and radiochemistry (NRC) is of strategic relevance to the whole nuclear energy sector, being inherently present in safe nuclear installation operations, decontamination and decommissioning processes, and waste management, as described above. The non-energy fields of NRC applications are even broader and range from life sciences – radiopharmaceuticals, radiological diagnostics, and therapy – through to dating in geology and archaeology, (nuclear) forensics and safeguards, radiation protection and radioecology.

One of the challenges in Nuclear and RadioChemistry (NRC) education is the extremely time-consuming, resource and costs demanding "hands-on" laboratory training on how to work safely with possibly very dangerous radioactive material. "Hands-on" means physically working in a real radiochemical laboratory with open radioactive sources. In addition to the specialised skills required by the science, such work of course requires extensive safety training (meeting all EHS – Environment, Health, and Safety – laws and regulations). It should be clearly understood that there is no substitute for such hands-on training. However, modern computer technology offers opportunities for preparing and training for work in a real lab in advance, by using sophisticated simulations and virtual reality environments to an extent (and price), that would be unthinkable only a few years ago. The proper and balanced combination of both real and virtual training and education is one of the arising challenges in this and other nuclear fields, and the A-CINCH project focuses on it.

2 Attract, retain and develop new nuclear talents beyond academic curricula (ENEN+)

2.1 Project objectives

The main goal of the project "Attract, Retain and Develop New Nuclear Talents Beyond Academic Curricula" (ENEN+) [1] is to contribute to the revival of the interest of young generations in careers in the nuclear sector. This can be achieved by pursuing the following main objectives:

- ***Attract*** new talents to careers in nuclear,
- ***Develop*** the attracted talents beyond academic curricula,
- Increase the ***retention*** of attracted talents in nuclear careers
- ***Involve*** the nuclear stakeholders within the EU and beyond,
- ***Sustain*** the revived interest for nuclear careers.

The project itself focuses on the learners and careers in the following nuclear disciplines:

- Nuclear reactor engineering and safety,
- Waste management and geological disposal,
- Radiation protection and
- Medical applications.

Integration of project objectives together with targeted nuclear fields is outlined in Figure 1. Integration of further nuclear disciplines (e.g., nuclear chemistry, decommissioning, fusion engineering, etc.) and sustainability of the ENEN+ accomplishments beyond the project life is foreseen within the existing ENEN (European Nuclear Education Network) Association and its partners. The attraction, retention and development of the new nuclear talent can only be sustained beyond the project life through strong nuclear stakeholders partnership. Various nuclear stakeholders are involved including academia, research, industry, Technical Support Organisations as well as International Organizations.

This approach is of primary importance for the success and sustainability of the proposed activities also beyond the life of ENEN+.

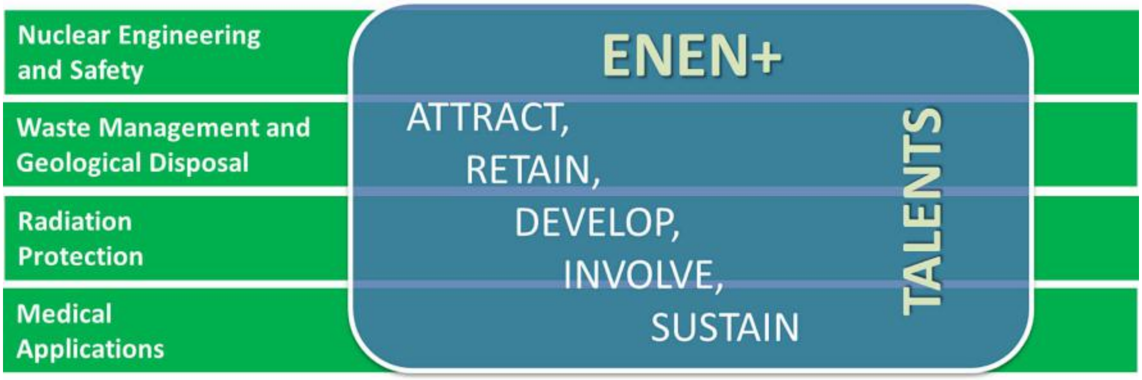

Fig. 1. Outline of the project objectives with the 4 major nuclear fields [1].

2.2 Methodology

In order to achieve the previously mentioned objectives, specific methodologies were designed.

I. Attracting new talents to careers in nuclear
The lack of new talents entering the nuclear fields is closely linked to a general loss of interest in nuclear sciences and insufficient information about the careers. In order to counter these effects, several actions were proposed based on the target groups:

- **Secondary school pupils**. Attractive basic information on careers in nuclear were developed, made available in national languages and complemented with an EU-wide competition of pupils[2]. A summer camp was organized for the winners of the competition. Electronic tools including social media were used thoroughly, especially in the context of the COVID-19 pandemic which influenced a lot the methodology the project was implemented.
- **Bachelor students**. Most of the nuclear academic curricula within the ENEN association members focuses on the master students. The existing efforts to attract the bachelor students to pursue master education in nuclear was strengthened by increasing the level of academic preparation for them.
- **Young professionals after graduation**. The nuclearisation of graduates of non-nuclear sciences and technologies has been a considerable source of nuclear talent throughout the nuclear era. Attracting more graduates to nuclearisation may require strong support from the end-user and will be put in place through attractive e-information and opportunities for individual guidance towards nuclear careers coupled with opportunities to interact with practitioners of nuclear. At the same time, "nuclearists" should get the chance to improve their knowledge and skills and having this way opportunities for better jobs.

[2] For example by creation of a public forum in which anyone can avail themselves of practical information on E&T, careers and scholarship. This may include student fair, flyers, "open door" events, etc.

II. Develop the attracted talents within and beyond academic curricula
The academic education is expected to remain the foundation of future nuclear experts and scientists. A good balance between the knowledge, skills and competencies may nevertheless need a further shift from thinking about pedagogy in terms of "teaching" to one that considers "learning" as the primary goal. This may allow us to more strongly link pedagogy with learning outcomes and student experience, for example, engagement in professional development activities with the support of industry, including course release for such activities. The use of teaching methodologies that include active learning, collaboration, problems/issues-based connections, and critical thinking must be developed in this regard and supported by individual career guidance and mobility funding.

The mobility support focuses on the following target groups and activities:

- Students:
  - Short-term internships,
  - Presentations at conferences.
- "Nuclearisation", life-long learning:
  - Internships,
  - "Nuclearisation" courses.

The mobility funding is provided through competitive calls published on the ENEN website.

III. Increase the retention of attracted talents
The retention is planned to be increased through student support and mentoring, enhanced by the mobility program.

The mobility support focuses on the following target groups and activities:

- M.Sc. students:
  - Mid-term internships (3 months),
  - Presentations at conferences,
  - Exchange compatible with the rules of the European Masters of Nuclear Engineering (EMSNE, >=20 ECTS abroad).
- Ph.D. students and post-docs:
  - Internships,
  - Access to research infrastructures,
  - Access to EURATOM research projects.

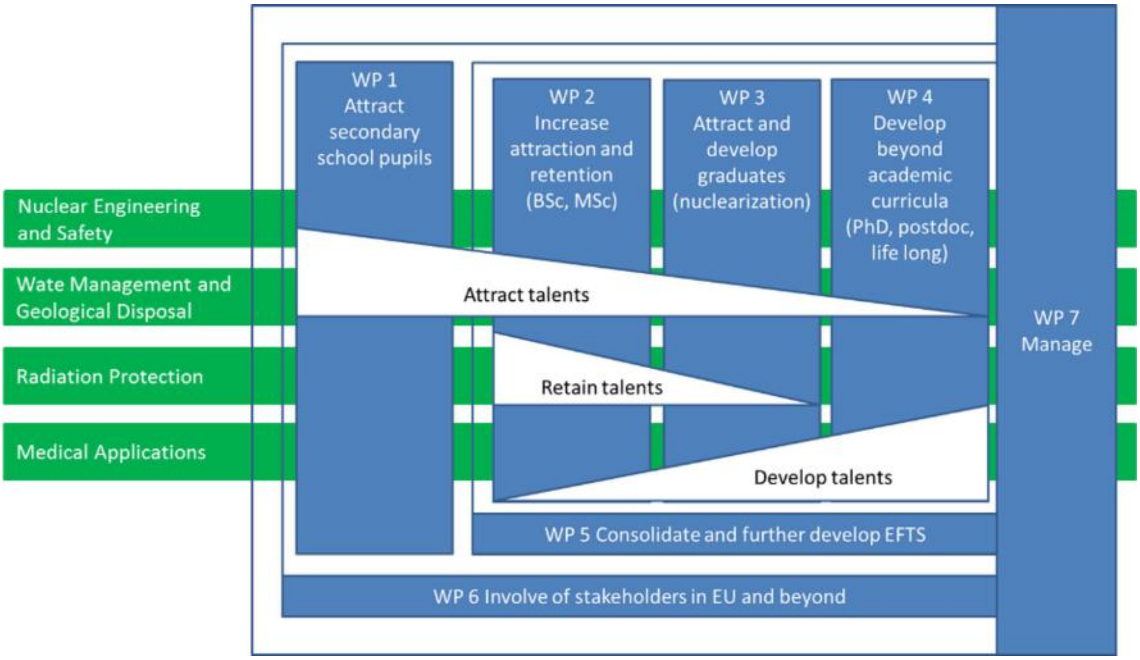

Fig. 2. ENEN+ working plan.

IV. Sustain the revived interest in nuclear careers In order to proceed in this direction, a proper communication strategy was planned to ensure consistent communication to the industry that aligns decision-makers around the strategy to provide time and investments for training new young talents. The objective is also to communicate to other stakeholders (including regulators and legislators) the value that can be derived from this initiative to maintain industry excellence and improve safety in a broad sense while ensuring the availability of nuclear expertise in the future.

In order to be able to plan the nuclear Education Training Knowledge Management (ETKM) activities beyond the life of the ENEN+ project, the projection of the nuclear workforce needs to be developed together with JRC EHRO-N (European Human Resources). This will be the basis of a proposal for a joint strategy for European ETKM considering also the developments of other initiatives at the international level.

2.3 Structure

The ENEN+ consortium is composed of twenty-two (22) participants located in different EU countries and abroad. The outline of the project working plan is presented in Figure 2.

The project is structured into six main work packages to which another Management work package is added. The focus of the Work Packages is presented below.

WP 1 – Attract new nuclear talents in secondary schools.
WP 2 – Increase attraction and retention of new talents among undergraduate students.
WP 3 – Attract and develop new talents through nuclearisation.
WP 4 – Develop new nuclear researchers beyond academic curricula.
WP 5 – Consolidate and further develop European Fission Training Scheme and Mobility.
WP 6 – Involvement of stakeholders in the EU and beyond.

2.4 Current status and outlook

The project is currently finished with an important impact on the nuclear community and beyond. Figure 3 contains one of the most successful actions in recent years related to education and training in the nuclear industry. More than 600 “mobilities” have been granted, demonstrating the European dimension for nuclear E&T.

Although the ENEN+ project ended, the consortium decided to continue the initiative and submitted a new proposal to the European Commission in the same line but with an upgraded mobility scheme.

3 Augmented Cooperation in Education and Training in Nuclear and Radiochemistry (A-CINCH)

The EURATOM Work Programme 2019–2020 – Nuclear Fission and Radiation Protection Research of its NFRP-2019–2020-11 topic identifies a loss of the younger generation’s interest in specialized nuclear knowledge and related risk that the current workforce, progressively retiring, could not be replaced as one of the current main concerns in the nuclear sector.

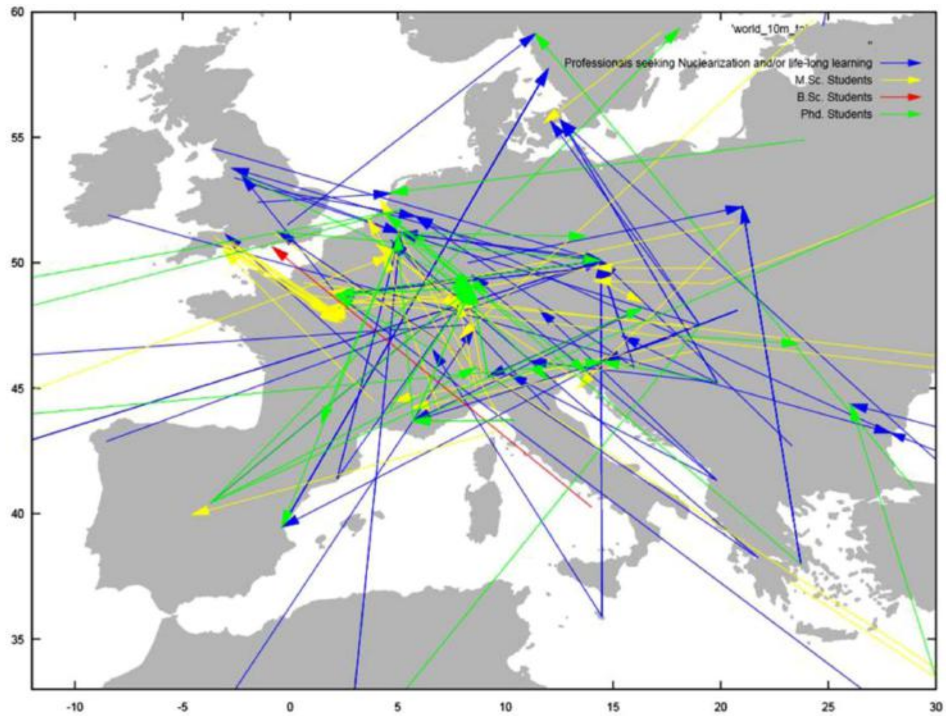

Fig. 3. Mobilities incurred following ENEN+ support.

3.1 Project definition, concept, and objectives

The A-CINCH ("Augmented Cooperation in education and training in nuclear and radio CHemistry") project is corroborating and extending achievements of previous projects. A-CINCH primarily addresses the young generation's and even the public loss of interest in nuclear knowledge by focusing on secondary education, using a "Learn through Play" concept to engage with students and teachers. For such purpose, A-CINCH augments CINCH teaching tools developed in the three previous CINCH projects – CINCH, CINCH II, and MEET-CINCH – the CINCH project series (www.cinch-project.eu), which were supported from FP7 and H2020. A-CINCH is a Horizon 2020 project No. 954301, that started in October 2020 with 17 partners from 13 countries with a duration of 36 months.

The overall objective of the project is to set up the CINCH Hub platform incorporating all previous CINCH results, completing it with newly developed courses and tools, and wrapping it all up into a user-friendly and easy-to-navigate single-page interface. Based on experience from university teaching and being well aware of the lack of valid information about the nuclear field among the public, new target groups were defined – the young generation from secondary school up to university, including the general public and interested professionals engaged through Vocational Education and Training. To address the new target groups and efficiently attract the attention of secondary school students, new didactical tools, suitable for today's youth, are being developed and improved. Implementation of a Virtual Lab, based on the involvement of augmented reality and gamification applied on nuclear and radiochemistry education is an example of the highly innovative ones.

The A-CINCH activities are grouped around three main pillars and divided into 7 work packages (WP):

1. Virtual reality laboratory for NRC education (VR-Lab), which includes VR-Lab platform development and VR Hands-on Training design and implementation (WP1+2).
2. Wrap-ups & Developments (WP3+4), which focuses on updates, improvements, and extensions of the tools, teaching materials, and various courses that are already available from previous CINCH project series or are currently under development in A-CINCH.
3. Nuclear Awareness (WP5), which focuses on making the field attractive to a younger generation and motivating school students to pursue a career in nuclear chemistry in industry or academia via the development of a distributable and sustainable toolkit of standalone resources to promote and increase awareness of the field of nuclear and radiochemistry.

The pillars are supported by two crosscutting activities (a) dissemination and networking (WP6) and (b) mobility and management (WP7).

3.2 Selected developments and progress

Virtual reality laboratory for NRC education

During the first half of the project implementation, the initial concept of the VR environment was redesigned and improved to allow better implementation of VR hands-on scenarios. Visual changes include a completely new layout of the laboratories, design, and dimensions of the respective rooms. Now the virtual space consists of several rooms such as the main lab, measurement room, neutron activation analysis lab, radiopharmaceutical lab, radioactive waste storage room, changing and locker rooms, and a decontamination room. For the purposes of the virtual environment, a module for the virtual detection of ionizing radiation was developed and implemented. It is now possible to measure radioactive samples and evaluate measured values and spectra. The environment also allows for interaction with objects, transferring, pipetting, and mixing fluids, weighting and dissolving substances, and solution preparations. The whole main lab environment, colours, scene lights, and textures have been improved.

Up to 10 storyboards for virtual hands-on tasks were suggested and described. Now the selected ones are being described in more detail and higher level of interaction. To guide users/players through the lab and particular exercises, the quest system was designed and is in the implementation phase.

Augmented reality application
A simple and smart implementation of augmented reality for NRC-education was developed as a virtual experiment for pupils. The application for Android smartphones was developed, where AR replaces radioactive sources and visualizes radiation. Pupils are able to play with several virtually augmented radiation sources of various types (alpha, beta, gamma), various augmented shielding, and a detector. Radiation from the source is visualised to help understand how the physics and propagation of the radiation works.

Massive open online courses (MOOCs)
MOOCs are powerful awareness and education tools that can deliver information in an attractive way for the target groups. “Nuclear-radiochemistry for society” MOOC was issued on 24 August 2020 and closed on 29 August 2021. During the course, 197 users from 29 countries were enrolled, resulting in 36 certificates with an average grade of 91.4. Most of the participants (65%) joined the course for personal interest and even more (71%) were motivated to complete the course. The second edition was issued immediately on 30 August 2021 and it will be finished again on 29 August 2022. In parallel, the promotion of MOOC was enhanced by addressing partner universities, websites, and YouTube. To enhance MOOC impact and get/deliver additional information, a series of CINCH Talks webinars were launched.

Hands-on training courses (HoT)
A large set of practical courses was developed and issued during the CINCH projects, which are provided on request or regularly depending on the respective target group. The course materials are available on the CINCH Moodle platform. Re-runs of HoT on radiochemical spectroscopic analysis and HoT on working with plutonium and actinides are/were complicated by the Covid-19 pandemic. HoT on Chemical Dosimetry was successfully delivered. During its delivery in September 2021, the Travel Fund procedure and the newly developed CINCH VET e-shop (eshop.cinch-project.eu) were successfully tested, 11 students were finally registered, and 7 were supported by travel fund. All the issued courses are/will be upgraded based on the feedback collected from the previous and current editions. Three new courses are now in development – HoT in decontamination and decommissioning, HoT in nuclear forensics, and HoT in radiopharmaceutical chemistry; these topics were found to be attractive according to current trends and developments in the nuclear- and radiochemistry field. These above-mentioned courses are supposed to be fully ready and available for the public in September 2023, full list of all courses is available at the CINCH VET e-shop.

Nuclear awareness
Current work on Secondary School Packages focuses on the selection of proper strategy and optimum way of delivery and promotion of the package and its content. A dedicated website for hosting educational resources including highly valuable career case videos was created. The teaching materials comprise “teacher” and “student” handbooks for nuclear medicine and Ionlab classrooms. Interactive screen experiments (ISE) and the instructions are ready. Teaching materials for pyro processing of spent nuclear fuel are being drafted. NRC summer schools are aimed at high school and bachelor students to inspire them to pursue a career in nuclear and radiochemistry, they are using a set of lectures, excursions, practical exercises, and topical games showing and explaining nuclear chemistry and related phenomena. The first Summer School under the A-CINCH project took place in Leeds (UK) from the 10th to the 14th of July 2022, and the second is planned for June 2023.

4 Graduate education alliance for teaching the physics and safety of nuclear reactors (GRE@T-PIONEeR)

4.1 Project description and objectives

The GRE@T-PIONEeR project is a project funded by the European Union’s Euratom 2019–2020 research and training program. The project started on November 1st, 2020 for a duration of three years. The various partners are Chalmers University of Technology (Sweden – coordinator), Ecole Polytechnique Fédérale de Lausanne (Switzerland), Technical University of Munich (Germany), TU Dresden (Germany), Budapest University of Technology and Economics (Hungary), Politecnico di Torino (Italy), Universidad Politécnica de Madrid (Spain), Universitat Politècnica de València (Spain), the European Nuclear Education Network (Belgium) and LGI Consulting (France).

The project aims at developing and providing specialised and advanced courses in computational and experimental reactor physics at the graduate level (M.Sc. and Ph.D. levels) and post-graduate level, as well as to the staff members working in the nuclear industry. Six-course modules are being developed. Each course module is worth 3 European credit transfer and accumulation system (ECTS). The theoretical, computational, and experimental aspects are tackled in each course. A course module typically requires one full week of self-studying, followed by one full week of hands-on training exercises under the supervision of the teachers involved in the course module. The self-studying part is referred to hereafter as asynchronous learning phase since interactions between the students and teachers do not occur simultaneously but via e-mails and discussion fora. The latter part is referred to as the synchronous learning phase, during which the students and teachers interact in real-time. Because of the self-paced nature of the self-studying phase offered entirely online and of the condensed format of the hands-on training, the course modules are also particularly well suited to industry staff members for life-long learning. This is further enhanced by the offering of the hands-on training session in a hybrid format, i.e., the course participants can decide to come onsite to the organization offering the training or to follow the sessions online. Additionally, a course module devoted to hands-on exercises on a nuclear training reactor is arranged using any of the three training reactors available within the consortium: the CROCUS reactor at Ecole Polytechnique Fédérale de Lausanne, the AKR-2 reactor at TU Dresden, and the BME training reactor at the Budapest University of Technology and Economics.

The different themes covered by the courses follow the various steps a nuclear engineer typically needs to consider when modelling a commercial power reactor, from the preparation of the nuclear cross-sections to full core calculations. More precisely, the following topics are covered:

- Nuclear cross-sections for neutron transport, focusing on:
  - The generation and evaluation of nuclear data libraries,
  - The processing of nuclear data libraries for use in nuclear applications,
  - The assessment of nuclear data uncertainties.
- Neutron transport at the fuel cell and assembly levels, focusing on:
  - The principles of probabilistic methods in steady-state conditions for fuel cell and assembly calculations,
  - The principles of deterministic methods in steady-state conditions, their approximations, and their range of validity for fuel cell and assembly calculations,
  - The use of those methods for macroscopic cross-section generation.
- Core modelling for core design, focusing on:
  - The principles of probabilistic methods in steady-state conditions for core calculations,
  - The principles of deterministic methods in steady-state conditions, their approximations, and their range of validity for core calculations,
  - The use of those methods for reference calculations or core design, operation, and safety analysis.
- Core modelling for transients, focusing on:
  - The principles of deterministic methods in non-steady-state conditions, their approximations, and their range of validity for core calculations,
  - The principles of macroscopic modelling of nuclear thermal-hydraulics and fuel thermo-mechanics,
  - The numerical techniques used for multi-physics coupling.
- Reactor transients, nuclear safety and uncertainty, and sensitivity analysis focusing on:
  - The principles of nuclear reactor safety and system behaviour,
  - The principles of uncertainty and sensitivity analysis applied to reactor transients.
- Radiation protection in a nuclear environment, focusing on:
  - The principles of health physics and radiation protection regulation,
  - Instrumentation for radiation protection in nuclear installations,
  - Shielding calculation methods (both deterministic and probabilistic methods), neutron and gamma transport, and deep penetration problems.

More information about the project can be found in [1].

4.2 Innovations in pedagogy

The key innovative aspects of the project rely on the use of pedagogical approaches favouring learning. Active learning (or *learning by doing*) is a technique demonstrated to lead to student engagement and consequently improved learning [1,2]. The synchronous sessions are thus mostly based on specifically designed activities that the students must participate in. Learning the various theoretical concepts is done via the asynchronous learning elements provided ahead of the synchronous sessions. The asynchronous and synchronous learning sequence often referred to as a flipped classroom [1,3,4], is summarized in Figure 4.

It consists of the following elements implemented on a Learning Management System (LMS):

- *Handbooks* covering the theoretical aspects of the covered topics.
- *Pre-recorded lectures* (or *webcasts*) are available for on-demand viewing and extracting the main features, results, and concepts of the handbooks. Voice and/or video are available.
- *Online quizzes* associated with the webcasts focus on conceptual understanding, with immediate feedback to the students on their learning. The quizzes are designed to develop high-order cognitive skills among the students.
- The possibility to *pose questions* to the teachers while watching the lectures.
- *Active learning sessions* in the forms of wrap-up and tutorials live-broadcasted with synchronous interactions between the students and the teachers.
- Use of *discussion fora* monitored by the teachers. The fora are utilised as a pre- and post-class activity to maintain engagement, favour collaboration between students, and are also used for providing additional feedback and help to the students.

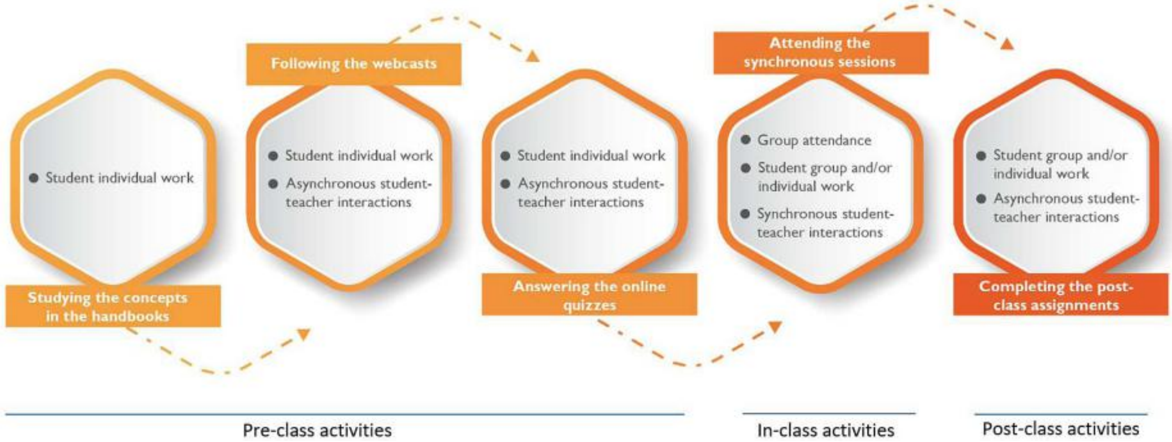

Fig. 4. Illustration of the learning sequence.

As earlier mentioned, the synchronous sessions are offered in a hybrid format, which represents another innovation of the project.

The use of the above hybrid set-up makes the courses attractive to any student, anywhere, without any need for the students to travel, in an increasingly competitive market. Likewise, the teaching staff does not necessarily need to travel for all course elements, even when several teachers contribute to the same course. Finally, offering short-period courses also fits attendees from the industry, without compromising a deep learning approach to the covered topics. The project thus contributes to both maintaining competencies and skills for the industry and life-long learning.

4.3 Key achievements

Since the start of the project, the contents of all handbooks and hands-on exercises have been decided. The writing of the handbooks is ca. 90% complete. The pedagogical method to be used by all teachers was decided and training/discussion sessions on the implementation of the methods were organized. An inventory of the infrastructures required for carrying out the project was performed, and an LMS (SOUL – Smart Open Universe of Learning, from Tecnatom) was purchased specifically for the project. Guidelines for the production of the teaching materials were developed, in order to guarantee the highest possible coherence of the various teaching materials.

Moreover, a mapping of the competencies in the nuclear sector was carried out, together with an assessment of the future needs and skills requirements. This mapping was performed via a questionnaire that was sent to a significant number of nuclear professionals. This questionnaire targeted the different needs of the nuclear industry, to uncover the gaps in the different trainings. Targeted interviews were also conducted with selected stakeholders. Four areas with high foreseen demands were identified: decommissioning, nuclear operations, reactor physics, and new technologies. Furthermore, an assessment of the technical skills, knowledge skills, and critical core skills lacking in the existing curricula was made. Finally, the pedagogical methods used in those curricula were scrutinised. The purpose was to identify good examples to increase the efficacy of teaching/learning. The use of advanced educational techniques in nuclear science and engineering, as well as in other sectors, was benchmarked. Interviews with four teachers using innovative pedagogical methods were carried out. The outcomes of the mapping of competencies, skills, and pedagogical methods are summarized in [5].

4.4 Utilization and cross-fertilization

Since interactions with the various stakeholders (students, teachers, professionals, and the public at large) are essential to guarantee the success of the project, various communication means were implemented. This includes a website, a LinkedIn account, and Twitter account, and newsletters that summarise the results and updates of the project. The project also includes an Advisory Board and an End-User Group, made of utilities, fuel/reactor manufacturers, safety authorities, technical support organizations, engineering companies, training organizations, and international networks. Those organizations are key in guaranteeing the alignment between the teaching resources being developed and the needs of the community.

5 European nuclear experimental educational platform (ENEEP)

5.1 Challenges and motivation

An essential element in the implementation and safe operation of nuclear facilities is a knowledgeable and skilled workforce. It is widely accepted that the desired nuclear-specific skills and experience of a workforce cannot be built without an experimental hands-on nuclear education and training (E&T) requiring research reactors (RRs) of various types and designs. According to [6], a threefold categorization of the competencies necessary to run a nuclear power plant can be drawn, which includes nuclear personnel, nuclearized

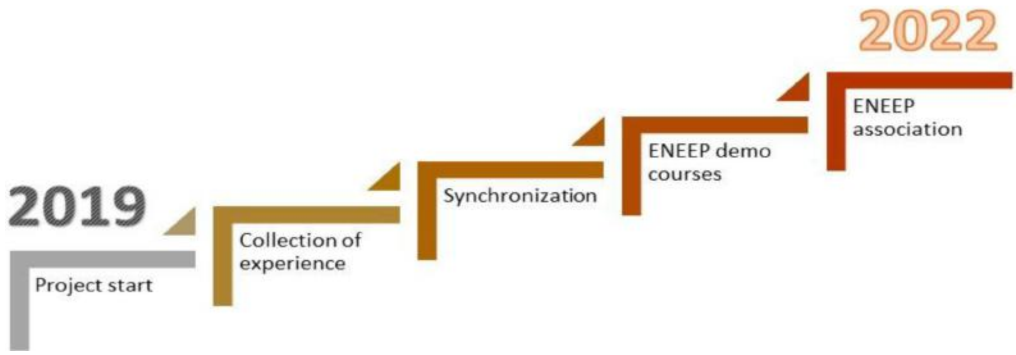

Fig. 5. Timeline of the ENEEP project.

personnel, and nuclear-aware personnel. For all the above-defined categories hands-on experience in the form of a high-quality tailored package need to be provided in the most effective manner. Nowadays it is difficult to enable access to RRs for students, trainees, and their instructors and to provide possibilities for performing nuclear reactor physics experiments. To address these concerns and to deliver high-quality tailored E&T packages and individual access to research infrastructure the European Nuclear Experimental Educational Platform (ENEEP) is being established using funds provided by the European Union under the topic NFRP-2018-7: "availability and use of research infrastructures for education, training and competence building" [7]. There are five ENEEP project partners, the Slovak University of Technology in Bratislava, Slovakia (STU), which is the coordinator; the Czech Technical University in Prague, Czech Republic (CTU); the Vienna University of Technology, Austria (TU Wien); the Jožef Stefan Institute, Slovenia (JSI) and the Budapest University of Technology and Economics, Hungary (BME).

5.2 Objectives and timeline

It is recognized that research programs, international initiatives, and the involvement of government, research centres, and the industry in the education of young professionals are the key to improving the overall level of education and attracting the best students across the EU to stay or to switch to nuclear [6]. Many international projects reflect these challenges, but in addition, the ENEEP project tries to bring nuclear education and training (E&T) closer to almost everyone. Although the ENEEP E&T activities are based on experiments utilizing research reactors and laboratories of nuclear physics, material science, and radiation protection, there are no specific limitations on the educational background of trainees and students. The timeline of the ENEEP project in Figure 5 is showing the sequence of necessary steps leading to the achievement of the project objectives.

The project started in June 2019 signing the consortium agreement between all five partners. Since each of the partners has been involved in nuclear E&T activities and has its established mechanisms, one of the very first steps in the project implementation was the collection of the experience of each partner. This phase was followed by the analysis of gaps and overlaps in the E&T activities, which lead to the synchronization of activities and processes and the definition of 60+ E&T experiments. In the meantime, the preparation of the ENEEP demo courses took place. These activities are the tools to prove the readiness of ENEEP to provide high-quality E&T activities in the field of nuclear and to cope with the current and potential challenges in the future. In addition, these courses provide a unique opportunity to collect feedback from the real users of the ENEEP infrastructure. This feedback is essential for the establishment of the ENEEP association, before the project end, in 2022.

5.3 Demonstration activities

As one of the most important objectives of the project, the demonstration of the educational and training capabilities of the ENEEP was carried out through dedicated educational activities, organised at the ENEEP partner facilities. The following group and individual education and training courses were organized:

- ***GA1:*** *Safe and secure operation of nuclear installations*
  - 2-week group activity,
  - STU, Bratislava, Slovakia and CTU, Prague, Czech Republic.
- ***GA2:*** *Experimental Reactor Physics*
  - 1-week group activity,
  - JSI, Ljubljana, Slovenia.
- ***IA1:*** *Experiments on the training reactor*
  - 1-week individual activity,
  - BME, Budapest, Hungary.
- ***IA2:*** *Experimental study of the TRIGA fuel characteristics*
  - 1-week individual activity,
  - TUW, Vienna, Austria.

The selected participants from EU member states were given an opportunity to attend the courses for free and were granted the ENEEP fellowship that covered the expenses related to travel, food, and accommodation. The preparation started in October 2021, the deadline

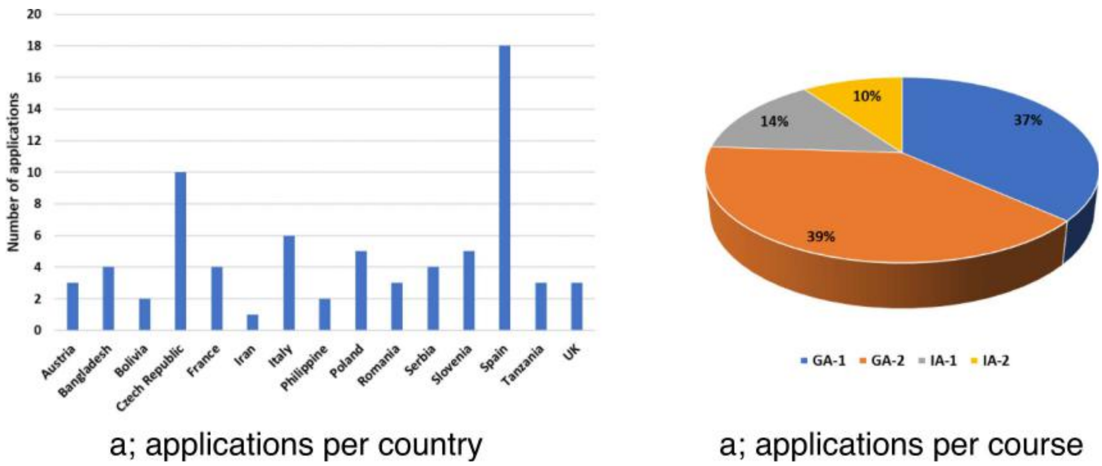

Fig. 6. Statistics of ENEEP demonstration courses.

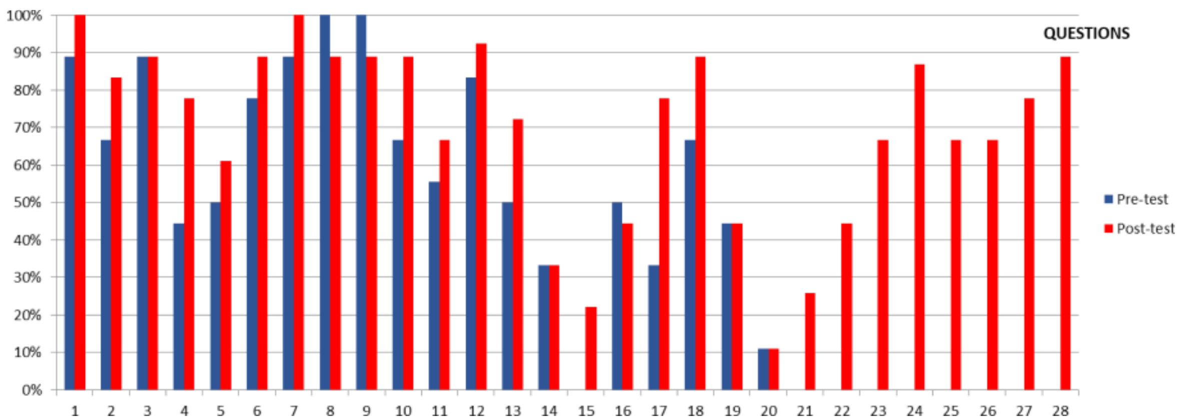

Fig. 7. Progress of the participants of the GA1 ENEEP training course.

for application was November 15, 2021, and the applications were evaluated by the project Scientific and Education Board based on their eligibility, relevance of background, Curriculum Vitae, clarity of motivation letter, recommendation, and the list of previous courses. For the four courses, 73 applications were received from 15 countries, among which 22 participants were directly qualified and 8 were put on the waiting list. 65% of the applicants were male and 35% were female, among which 83% were M.Sc. students, 13% were Ph.D. students, 2 were B.Sc. students, and 1 person was a young professional. The statistics of the training courses are shown in Figure 6.

The progress of students during the course was measured through pre-testing and post-testing, by asking the same questions. In the case of the GA1 training course, the average score of students in the pre-test was 60%, ranging between 28% and 78%. The results of the post-test (see Fig. 7) showed good progress since the average score increased to 69% and the range narrowed to 57%–79%.

The results are clearly showing the success of the GA1 course since we managed to minimize the difference between the participants and increase the knowledge level of each participant. In addition to testing, also feedback forms were distributed, in which the participants could evaluate the quality of the course, reaching the objectives, applicability, organization, and logistics as well as the quality of lectures on a numerical scale. The results showed that the overall score of the GA1 training course was 90.6% ± 5.2%.

5.4 ENEEP association

The main goal of the ENEEP project is to establish coordinated and sustainable access to the infrastructure of project partners also beyond the project duration. The choice made by the ENEEP project partners, as the most promising to achieve this goal, is to establish a non-profit association with the same name ENEEP. The ENEEP association will create a management, communication, and promotion umbrella above all participating institutions. Partial results of the ENEEP project, like the communication plan, evaluation processes, and course preparation procedures, will be directly utilized in the ENEEP association to follow up on the project activities. Moreover, the ENEEP association will represent all member institutions under one brand in the nuclear environment. The E&T activities of the ENEEP association will be based on standard, so-called "à la carte" courses (currently 60), which are the result of the long-term experience of the ENEEP founding members.

6 PIKNUS

6.1 Project objectives

The objective of the Administrative Arrangement PIKNUS (pilot action on knowledge management in the area of nuclear safety) between DG RTD and JRC as part of the Euratom Work Programme 2019–2020, is to define a concept of a knowledge management (KM) method and tool to improve the sharing and availability of Euratom research results for the European nuclear safety research community. A platform enabling access to the results of both indirect and direct actions from Euratom work programmes is under development. Within the pilot action, the work will focus on implementing the KM tool specifically for the area of materials ageing of currently operating nuclear power plant types. Later on, the KM tool could be further developed and extended according to needs.

6.2 End-user needs

One of the first steps in the project was to identify what information should be available on the platform. The sources of information can be classified into the following groups:

- JRC direct actions: these are descriptions and results of relevant research activities undertaken solely by the JRC during the observation period,
- Indirect actions: descriptions and results of Euratom research activities undertaken by multi-partner consortia during the observation period,
- Other relevant information: this is information concerning e.g. European research organisations and infrastructure, education and training, multinational organisations and networks on reactor safety, and JRC websites/repositories. Such information would be linked to the portal to an appropriate extent.

The results of the direct and indirect actions can be mostly retrieved from two sources: from CORDIS in the case of indirect actions, and from JRC Publications Repository PUBSY for the JRC direct actions.

The second step in the project was the identification of user needs. It was originally envisaged to organise a workshop involving a large group of potential end-users, but due to the sanitary crisis, the plans had to be changed. Instead, the following actions were taken:

- Discussions in PIKNUS Steering Group meetings (July and September 2020, February 2021),
- Project presentations of relevant H2020 coordinators at the NUGENIA TA4 meeting (December 2020),
- Survey for relevant H2020 coordinators (January 2021).

Table 1 shows the projects that were selected for the pilot, and their coordinators were accordingly considered as the best representatives of end-users. An online meeting took place in December 2020 with the coordinators of these H2020 projects, and they provided valuable information and feedback, which will be very useful for platform development. In addition, a survey was sent in February 2021 to the same project coordinators for further exploring the end-user needs. The survey comprised questions related to the ways the end-users would search for information, and what kind of use they would see for the platform. The end-users were also asked to express their availability to participate in (1) defining the features and testing the platform, (2) developing taxonomy, and (3) suggesting topics and contributing to the development of synthesis reports. Further, their opinion was asked about handing over project website contents after project closure.

Based on the end-user feedback, the platform should have the following main technical features:

- The core of the system should be accessible to CORDIS and PUBSY, supported with a good search engine,
- Access to other relevant outputs from Euratom- funded projects,
- Interactive part for a forum for exchanges,
- Linking of research institute's websites, infrastructures, international organisations, etc.

6.3 Proposed solution for the platform

The suggested approach to responding to the end-user needs in software development is summarised below.

Access to Euratom deliverables
JRC has developed a Semantic Text Analyser (SeTA) tool that allows document search and extraction over CORDIS and the JRC Publications Repository, the discovery of phrase meaning, context, and temporal development. It can recommend the most relevant documents including their semantic and temporal interdependencies. The tool has been thoroughly tested in real-life conditions in several domains.

The PIKNUS information system will integrate SeTA to retrieve Euratom-related information from CORDIS and the JRC Publications Repository, and continuous synchronisation with CORDIS and the JRC Publications Repository will be developed.

Access to other relevant outputs from Euratom-funded projects
A procedure for taking over relevant documents at the end of Euratom-funded projects needs to be established. This consists of practices for:

- Asking the permission from consortia for transferring documents from the project website at the end of the project,
- Selection of the documents,
- Transfer of the selected documents to the KM platform.

First contacts have been made to make a case study.

Table 1. H2020 projects included in the pilot.

H2020 Call	Shortname	Project full name
2014–15	SOTERIA	Safe long-term operation of light water reactors based on improved understanding of radiation effects in nuclear structural materials
2014–15	INCEFA-PLUS	INcreasing Safety in NPPs by Covering gaps in Environmental Fatigue Assessment
2016	ADVISE	ADVanced Inspection of Complex StructurEs
2016	ATLASplus	Advanced Structural Integrity Assessment Tools for Safe Long-Term Operation
2016	MEACTOS	Mitigating Environmentally Assisted Cracking Through Optimisation of Surface Condition
2016	NOMAD	Nondestructive Evaluation (NDE) System for the Inspection of Operation-Induced Material Degradation in Nuclear Power Plants
2016	TeaM Cables	European Tools and Methodologies for efficient ageing management of nuclear power plant Cables
2019	ENTENTE	European Database for Multiscale Modelling of Radiation Damage
2019	ACES	Towards improved assessment of safety performance for long-term operation of nuclear civil engineering structures
2019	INCEFA-SCALE	INcreasing safety in NPPs by Covering gaps in Environmental Fatigue Assessment - focusing on gaps between laboratory data and component SCALE
2019	STRUMAT-LTO	STRUctural MATerials research for safe Long Term Operation of LWR NPPs
2019	FRACTESUS	Fracture mechanics testing of irradiated RPV steels by means of sub-sized specimens
2019	El-Peacetolero	Embedded Electronic solutions for Polymer Innovative Scanning Tools using Light Emitting devices for diagnostic Routines

Interactive part of a forum for exchangess
In order to offer an interactive platform for the community of users, it is envisaged to use the tool developed at the European Commission, CIRCABC: *Communication and Information Resource Centre for Administrations, Businesses, and Citizens*. As the CIRCABC is accessible to any user inside or outside of the European Institutions, it was considered a practical solution for the collaborative part of the KM platform. The CIRCABC uses the EU Login, the European Commission's Authentication Service, as authentication. The same system is used for logging on to a whole range of websites and online services run by the European Commission.

In the CIRCABC, one can create collaborative spaces where users spread over the web can work together, sharing information and resources.

Linking of research institute's websites, infrastructures, international organisations, etc.
Even if the main aim of the KM platform is to improve the availability of Euratom research results for the European nuclear safety research community, it is advisable to provide links to other sources from the system for easy access to the most relevant external information. Such information is e.g.

- European research organisations,
- European research infrastructure,
- Multinational organisations and networks on reactor safety,
- JRC websites/repositories.

Further, EU legislation, such as the Euratom treaty and nuclear directives, and other cross-cutting knowledge can be linked to the platform.

Due to the sanitary crisis and delays in the IT process, the project duration has been extended until February 2023. The platform development has started with tailoring the semantic text analysis tool to the need of the platform. This will enable the retrieval of documents from CORDIS and PUBSY. This retrieval will not be limited to the pilot scope but allows access to all public deliverables of Euratom-funded projects and actions.

Front-end development has also recently started. This work comprises e.g. development of the user interface, visualisations, access tools, and the interactive workspace. The first version of the system should be available for testing in autumn 2022.

7 Summary and conclusion

Continuous and future-oriented education and training as well as knowledge management for young talents are required for the safe and reliable operation of nuclear reactors or nuclear facilities in Europe.

In the project ENEN+, several activities, such as summer camps, and specialized courses, have been carried out in order to attract, develop and retain young talents in the nuclear field. The most successful measure was the grant of more than 600 mobilities to B.Sc., M.Sc., Ph.D. and other young professionals to perform an E&T measure outside of their home country. This demand clearly demonstrates the European dimension of this action and the direct benefit to European citizens.

The A-CINCH project shows that cooperation in education among universities, research institutions, and end-users brings valuable outputs contributing to the solution of the identified gaps in education and combining classical and alternative/virtual teaching methods. There is much more work in the A-CINCH project, that has not been mentioned in more detail – RoboLabs (Remotely operated robotic laboratory) maintenance, Interactive Screens Experiments development and use in teaching, NucWik (nuclear wiki database of NRC teaching materials) updates, Open Educational Resources (OER) to be shared, or Citizen NRC MOOC preparation. Materials and tools are also analysed to identify missing parts through gap analysis, and quality assurance guideline is being prepared.

The project GRE@T-PIONEeR aims to close an E&T gap in reactor physics by means of developing and providing specialised and advanced courses in computational and experimental reactor physics at the graduate level (M.Sc. and Ph.D. levels) and post-graduate level, as well as the staff members working in the nuclear industry. New pedagogical approaches relying on active learning have been applied successfully.

The consortium forming the ENEEP project enables access to various research reactors and laboratories of nuclear physics, material science, and radiation protection. For four training courses offered so far at different research reactor locations, 73 applications were received from 15 countries, among which 22 participants were directly qualified and 8 were put on the waiting list. 83% were M.Sc. students, 13% were Ph.D. students, 2 B.Sc. students, and 1 person was a young professional. ENEEP could clearly demonstrate the European dimension of their E&T activities and the high attractiveness of the courses offered, which are also planned after the project end, through the ENEEP association.

In the PIKNUS project, a Knowledge Management platform is being developed to improve the accessibility to the results of various EURATOM-funded projects. The pilot focuses on recent "materials projects". An end-user group has provided valuable recommendations concerning the main features of the system. The website development has recently started, comprising e.g. tailoring the search and extraction of project results, and development of the user interface, visualisations, access tools, and interactive workspace. The first version of the system should be available for testing in autumn 2022. The start of operation is foreseen in 2023.

Conflict of interests

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– ENEN+: no associated data generated and/or analyzed.
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Author contribution statement

– ENEN+: Mr. Gabriel Lazaro Pavel and Joerg Starflinger contributed to the section describing the ENEN+ project.
– ENEEP: Mr. Stefan Cerba, contributed to the section describing the ENEEP project.
– Great Pioneer: Mr. Christophe Demaziere contributed to the section describing the Great Pioneer project.
– PIKNUS: Ms. Kaisa Simola contributed to the section describing the PIKNUS project.
– A-CINCH: Mr. Mojmir Nemec contributed to the section describing the A-CINCH project.

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Review Article

Open Access

Medical applications of ionizing radiation and radiation protection for European patients, population and environment

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Abstract. Medical applications of ionising radiation (IR) represent a key component of the diagnosis and treatment of many diseases, guaranteeing efficient health care. The use of IR in medicine, the largest source of general population radiation exposure, is potentially associated with increased risk of cancer and non-cancer diseases, which needs to be evaluated to provide evidence-based input for risk-benefit considerations. Efforts are also needed to improve the safety and efficacy of medical applications through optimisation. The EC Euratom programme enhances research in medical radiation protection. The four complementary multidisciplinary projects presented here contribute to (1) improving knowledge on exposure and effects of diagnostic and therapeutic applications and (2) transferring results into clinical practice. The common aim is to optimise use for individual patients, enhance education and training, ensuring adherence to ethical standards, particularly related to technologies based on artificial intelligence. MEDIRAD, SINFONIA and HARMONIC focus on improving exposure estimation and studying the detrimental effects of diagnostic and therapeutic medical exposures in patients and staff using different endpoints. EURAMED rocc-n-roll brings together the results of the projects and the recommendations generated by them to build, in collaboration with the EU Radiation Protection research platforms, a strategic research agenda and a roadmap for research priorities.

1 Introduction

Medical applications of ionizing radiation (IR) play a crucial role in the efficient health care, diagnosis and treatment of many diseases. There are, however, also risks associated with the medical application of ionizing radiation, including an increased risk of cancer and non-cancer diseases. As medical IR applications constitute the largest human-made source of radiation exposure to the European population [1], it is particularly important to optimize their use and the doses they entail. In addition, there is a historical radiation protection (RP) culture in Europe, well-illustrated by the Euratom directives, the Basic Safety Standards [2] being the most recent one.

In recent years, with the growing awareness of risks from such applications, EURATOM has funded four large-scale projects (MEDIRAD, HARMONIC, SINFONIA and EURAMED rocc-n-roll) which all contribute, in a complementary fashion, to improve estimates of the detrimental effects of medical applications, and to provide evidence-based input and new approaches to optimise their use, the resulting doses, to reduce associated risks to patients and medical professionals and ultimately to provide evidence for further updating of the current BSS. These projects were chosen because they contribute to optimising medical applications of IR and improving our understanding of radiation effects. Based on these contributions, they aim at generating evidence-based recommendations to the main stakeholders (including funders, RP authorities, medical societies and researchers as well as clinicians),

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fostering collaboration between the radiation protection and medical scientific communities. They are particularly pertinent to the issue of RP in medicine since they cover the most important sources of diagnostic and therapeutic medical radiation to patients and workers, as well as one of the most sensitive patient groups for radiation protection: children (see Tab. 1).

The current paper provides a cross-cutting description of the four projects and their achievements to date, stressing commonalities and highlighting the challenges encountered, research needs and the need for a future overarching strategy in medical RP research.

2 Ongoing European research in RP

The four projects together (Tab. 1) target all applications of radiation in medicine:

- Cancer treatment: HARMONIC (paediatric cancer patients), MEDIRAD (thyroid cancer patients and cardiovascular changes after radiotherapy (RT) for breast cancer) and SINFONIA (patients and workers);
- Cardiology: HARMONIC (paediatric cardiology) and MEDIRAD (patient and workers in fluoroscopy-guided procedures); and
- Diagnostic exposures: MEDIRAD (Computed Tomography (CT) scanning) and SINFONIA (Diagnosis of brain tumour and lymphoma).

SINFONIA also considers the impact on humans and biota from the release of radiopharmaceuticals by hospitals.

All of these aspects are considered in the strategic research agenda (SRA) to be developed in EURAMED rocc-n-roll.

The goal of all the projects is to contribute to better safety and efficacy for medical applications of IR. This implies the need for transferring the research results into clinical practice and daily medical use. To allow this, education and training is a fundamental prerequisite, which is addressed by all four projects. Successful transfer to clinical practice will not only result in better healthcare and improvement in RP for individual patients and medical professionals throughout Europe but also allow the development of potential socio-economic benefits for the European Union as a whole.

The success of all four projects relies on a well-integrated interdisciplinary approach, essential not only to ensure the quality of the research results but also, very importantly, for their translation to the efficient and safe use of IR in clinical practice, supported by professional/regulatory guidance and recommendations. A further shared component of these projects and all research in medical RP is the importance of ethical considerations throughout the implementation of the projects, as well as in the medical uses of IR.

2.1 Optimisation for medical radiation safety

A major focus of all selected research projects is research to improve the assessment of organ doses from medical procedures, the registration of these doses in real-time in the clinic, and to use them for the estimation of the adverse effects of exposure and quantification of risks (Tab. 1).

Real-time assessment of appropriate dose quantities is essential for the adequate protection of patients. Indeed, though dose estimates are provided routinely for diagnostic procedures using external photon radiation and for RT, they are measurable quantities that characterise the external radiation field, useful to assist in managing the patient dose, but not appropriate for evaluating the potential health effects of the exposure. For this, estimates of absorbed dose to organs and tissues of interest are more relevant but not currently available routinely. Thus, the projects focus on research, to estimate relevant dosimetric quantities in real-time in the clinic for different types of procedures and to establish dose biobanks in which they can be registered for research on potential health effects but also for evaluation of the cumulative doses received by patients to improve their radiological protection. In imaging applications, optimisation has always been based on guaranteeing a sufficient image quality, for which determination methods are developed.

Managing and potentially reducing staff doses is of utmost importance and is addressed in MEDIRAD and SINFONIA, in particular during nuclear medicine and fluoroscopically-guided procedures, where dose optimisation together with appropriate use of protective equipment contribute to workers safety.

The overarching objective of the projects is to identify where optimisation of doses and uses is needed to minimise health risks while maintaining the benefits to the patients. MEDIRAD has now delivered its evidence-based recommendations. The detailed recommendations can be found on the project website (www.medirad-project.eu) and are summarized below with a focus on optimisation:

- Reco 1 – Consolidation of patient data repositories across Europe, in particular:
  - Develop an interconnected and sustainable system of image and dose repositories at the European level.
- Reco 2 – Optimisation of radiation-based protocols for medical diagnostics or therapy, specifically:
  - Develop robust tools for optimisation of CT scanning and multimodality imaging.
  - Develop dosimetry-based protocols for molecular RT across Europe.
  - Actively promote good practices aimed at reducing cardiovascular risks after breast RT.
  - Deploy an EU-wide strategy to better predict and reduce secondary cardiovascular risks in breast cancer patients treated with RT.
  - Accelerate the generalised use in clinical practice of modelled total delivered doses to individual patients within Europe.

Table 1. Summary table.

	MEDIRAD	HARMONIC	SINFONIA	EURAMED rocc-n-roll
Objectives	Enhance the scientific basis and clinical practice of radiation protection in medicine.	Investigate the relationship between early-life exposure to ionizing radiation and development of cancer and non-cancer effects Provide the infrastructure for long-term follow-up of pediatric cancer and cardiac patients	Appraisal of detrimental effects of medical exposure for treatment of lymphoma or brain tumours.	Develop a European consensus on research needs and priorities in medical radiation application and RP to optimize the use of ionizing radiation in medicine, thereby improving its benefit to Europe's patients.
Optimisation	Improve organ dose estimation and registration to optimise doses for CT scans and nuclear medicine (NM) applications. Develop tools for real-time dose estimation. Develop a dose and imaging biobank.	Improve estimation of patient-specific organ doses, and non-targeted organs in radiotherapy (RT). Real-time dose estimation and augmented reality tools.	Develop novel personalised dosimetry methods and tools to estimate the radiation burden to brain tumours and lymphoma patients undergoing radiological, NM and RT procedures. Estimation of staff doses in proton therapy. Development of a simulation software tool for optimisation of staff doses in NM.	A common approach bringing together the disease diagnosis and treatment perspective and the radiation protection perspective is needed to improve the benefit/risk balance in the medical use of IR.
Risk	Evaluate and understand the effects of low-dose medical exposures, focusing on the two major endpoints of public health relevance: • Cardiovascular effects of low to moderate doses of radiation from RT in breast cancer treatment, including early markers of damage; • Cancer risk of low doses from CT in children. Develop a protocol for the follow-up of patients treated with radioactive iodine for thyroid cancer. Conduct research on factors that increase susceptibility to radiation-induced cancer.	Investigate the late health effects of low, moderate and high radiation doses from modern RT using protons or photons with focus on cancer and non-cancer effects (endocrine, neuro and cardiovascular, QoL). Investigate the relationship between early-life exposure to ionising radiation from X-ray-guided procedures and development of cancer in paediatric patients with cardiac defects. Investigate radiation-induced cellular responses and the mechanisms involved in the processes that may lead to cancer and vascular diseases.	Development of a risk appraisal tool that will consider, (a) the best radiation-induced cancer risk models, (b) accurate patient organ dose data based on personalised dosimetry methods developed within the project, (c) age-at-exposure and sex-related differences in radiation risk, (d) radiation quality, and (e) SINFONIA results related to variations in radiation susceptibility between individuals. Evaluation of risk to the public and the environment associated with the management of radiopharmaceuticals used in NM.	Risk will be considered as part of an intensive risk/benefit analysis for which criteria are to be developed within the project. Different research fields are integrated to identify unanswered research questions.
Interdisciplinarity	Clinicians (pediatric oncologists, radiation oncologists, cardiologists), epidemiologists, biologists, medical physicists, and sociologists; patients and regulators in stakeholder groups.	Clinicians (pediatric oncologists, radiation oncologists, cardiologists), epidemiologists, biologists, medical physicists, and sociologists.	Clinical dosimetry, medical physics, NM, radiology, radiation oncology, radiation biology, computing and artificial intelligence.	Clinicians (oncologists, neurovascular and cardiovascular doctors, paediatricians), medical physicists, experts in biology, physics etc., educators, ethicists, regulators, industry and patient representatives. Integrate the digitisation research community in addition to the health and radiation science communities.
Translation into practice	Set of science-based consensus policy recommendations for the effective protection of patients and staff were prepared, discussed with stakeholders and issued – Deliverables 6.5–6.8.	Provide guidelines on optimization techniques to guide treatments.	Science-based recommendations on radiological protection for the development of new applications of radiation in medical care, per category and per procedure.	The SRA will ultimately impact patients throughout Europe with better high-quality and safe healthcare. It will enable the European industry to better orientate their products towards clinical needs.
Education	The importance of education and training is highlighted in various elements of the science-based MEDIRAD Recommendations targeted at policymakers and the scientific/medical communities.	Training of pre-and post-doctoral students within the partners institutions.	Dedicated work package on education and training with implementation of various specific courses on radiation biology, AI applications etc.	Provide an education and training guidance system to foster the concepts for medical application of IR and corresponding medical RP. Design and pilot an education and training framework for health professionals and researchers to foster the transfer into clinical practice.

Table 1. continued.

	MEDIRAD	HARMONIC	SINFONIA	EURAMED rocc-n-roll
Ethics	Ethics approvals have been obtained from the appropriate authorities. Informed decisions of patients. Data Protection.	Ethics approvals are obtained from the appropriate authorities. Informed decisions of patients. Data Protection.	Ethics approvals have been obtained from the appropriate authorities. All data managed in the repository are stored in a secure manner and are de-identified.	Ethics and data protection of AI applications in diagnosis, personalized therapy, and digitalization in healthcare. Stakeholders' understanding of radiological risk and decision-making in medical procedures involving IR related to new medical applications.

- Reco 3 – Further optimisation of radiation protection for patients and medical workers:
  - Optimise systems for quantitative imaging irrespective of imaging system manufacturer or model.
  - Encourage harmonisation of practices through active engagement of health professionals, researchers, health authorities and patients.
  - Optimise the use of protective equipment to improve radiation protection of medical workers in interventional settings.
- Reco 4 – Future research on medical radiation protection in Europe, specifically:
  - Investigate new and optimise existing medical imaging procedures to improve benefit/risk ratios and personalised approaches.

In this respect, EURAMED rocc-n-roll is currently working on identifying research gaps to set up a new strategic research agenda (SRA) and a framework for the transfer of research results into clinical practice.

2.2 Radiation-induced risk

The potential health impact of the application of IR is important to appraise at the moment of choosing the particular modality for diagnostic and therapeutic purposes, particularly in sensitive populations such as children, and when introducing new IR applications and optimising existing ones.

Work in the research projects (Tab. 1) includes evaluating and understanding the effects of medical exposures:

(1) in children, from CT scanning (the largest diagnostic contribution to medical radiation dose) (MEDIRAD), from X-ray guided procedures for the diagnosis and treatment of cardiac defects, and cancer treatment, in particular from modern RT techniques using protons and photons (HARMONIC). As IR exposure in childhood is known to infer a greater risk of some cancer [3] and possibly non-cancer effects than exposure later in life, and as children have a longer life expectancy, it is particularly important to adequately understand the effects of these exposures and quantify them in order to minimise the long-term effects of IR on health and wellbeing of the patients;

(2) in adults, in particular, cardiovascular effects of external beam radiotherapy for breast cancer (the most prevalent cancer type in women in Europe); and feasibility of studying effects of molecular radiotherapy for thyroid cancer (less frequent, but for which little research has been conducted either in terms of actual doses delivered to the target and surrounding tissues or in terms of long-term sequelae of the exposure). As both breast and thyroid cancer have a good prognosis, there are large numbers of long-term survivors at risk of adverse effects from the treatment in Europe, hence understanding and minimising the long-term consequences of the treatment is of utmost importance;

(3) as well as on factors (genetic or environmental) which may confer increased sensitivity to radiation-induced cancer and non-cancer effects.

In addition to the work on specific populations and outcomes, SINFONIA aims to develop a novel radiation risk appraisal tool, including estimation of uncertainties, to support research not only on patients with suspected or diagnosed brain tumours and lymphomas undergoing radiological, nuclear medicine and radiation therapy procedures for diagnosis, staging, treatment response and follow-up but also on staff, comforters, the public and the environment.

Finally, MEDIRAD has issued a number of recommendations for future research on health effects:

- Recommendation 4 – Future research on medical radiation protection in Europe, specifically:
  - Conduct further research into the adverse effects of ionising radiation on healthy tissue;
  - Develop biologically-based models to evaluate radiation-induced disease risk;
  - Conduct large-scale clinical epidemiological follow-ups of patients to assess the late health effects of radiation in particular high-risk populations.

2.3 Interdisciplinarity of the projects

As shown in Table 1, the four projects rely on an integrative approach for RP research, strengthening the multidisciplinary collaboration between researchers, the medical community, and relevant stakeholders including patients. The multidisciplinary consortia in all four projects bring expert knowledge in a wide range of medical and scientific disciplines including, but not restricted to, radiologists, oncologists, cardiologists, paediatricians, medical physicists, radiographers, epidemiologists, biologists, computing and artificial intelligence experts and social scientists including those dealing with ethics. Such multidisciplinary collaboration will enhance the interaction between the relevant communities to integrate clinical, biological and epidemiological investigations and promote the identification of biological mechanisms strengthening the understanding of health effects. Collaboration between medical physicists and IT specialists will contribute to determining relevant image quality parameters and develop optimisation tools while dose reconstruction, an essential aspect of radiation epidemiology, results from a strong collaboration between (medical) physicists, radiologists, epidemiologists and statisticians.

The European RP research community relies on existing RP research platforms including MELODI, EURAMED and EURADOS which have developed and regularly update their SRAs to prioritise research topics for the European research community. All four projects carefully consider these priorities and are strengthening privileged relationships and integration within and between the platforms. EURAMED rocc-n-roll will develop, in collaboration with these and other platforms, an SRA for medical applications of IR and the corresponding radiation protection integrating the SRA of EURAMED as well as a corresponding roadmap. The development of such a coordinated and systematic European approach to research and innovation in medical applications of IR aims to improve patient care and quality of life of EU citizens, support growth and jobs in the EU and improve the EU's position on the global market.

2.4 Translation of research results into clinical practice

A commonly expected impact of the four research projects is the translation of the research results into improved practical measures for the effective protection of people in the medical sectors, leading to a more robust system of protection of patients, workers and the general public. Scientific evidence is to be comprehensively translated into procedure and practice guidelines as well as into policy recommendations, beyond the classical exploitation of scientific publications. MEDIRAD recommends the implementation of guidelines to help European countries (and the scientific community) implement European regulatory requirements on ethics (including compliance with the GDPR Directive) to strengthen the multinational epidemiological framework. Collectively we contribute to producing science-based recommendations for the protection of patients and staff and guidelines on optimization techniques to guide diagnosis and treatments. As an example, two follow-up projects aiming to bring investigated methods into clinical practice have recently been launched: EU-JUST-CT on the justification of CT examinations within Europe and i_Violin on implementing image quality assessment in oncological imaging. Where relevant, tailored material for patients and the public is or will be generated in the framework of the projects (see Fig. 1). We are building the infrastructures for harmonized patient data collection from different disciplines and treatments to account for the mechanisms leading to health detriment and to enable improved diagnosis and treatment. Ultimately, our contribution to understanding the health effects of ionizing radiation in all aspects of medical use intends to promote improved medical protocols, personalization of treatment, applied research and development of safer diagnostic and treatment modalities.

Finally, the main common objective is to impact patients throughout Europe with increased benefits from a better, high-quality and safe healthcare system toward equal access to medical applications using IR for diagnosis and treatment throughout Europe which could serve as a model for a more international approach.

2.5 Education and training

Education and training of the new generation of scientists and healthcare professionals devoted to RP in Europe are embedded in each of the four projects with the involvement of pre-and post-doctoral students in most participating institutions. In addition, SINFONIA and EURAMED rocc-n-roll have dedicated WPs devoted to analysing the current offer of academic and professional study programmes in the field of RP research and medical applications (including radiology, nuclear medicine, radiation oncology, medical physics, and other health care disciplines as well as epidemiology, biology, modelling, artificial intelligence (AI) and machine learning methods and applications in medicine). Based on these analyses, proposals for training programmes will be made to ensure high-level future research but also more harmonised patient care throughout Europe.

2.6 Ethical issues

Research involving patients, in particular children, and patient data sets and images raises a number of ethical issues which are systematically foreseen and addressed in the research protocols in MEDIRAD, HARMONIC and SINFONIA (GDPR compliant protocols that need to be approved by all appropriate ethics committees before any data collection or analysis can start). Informed decision of patients is a central aspect of today's diagnostic and especially therapeutic approaches, which definitely holds for the medical use of ionizing radiation, and is an important pre-condition for any radiation protection research project. Research for optimisation of the use of IR for individual patient care also raises ethical issues in particular when harmful effects are expected. The use of AI in medical applications, and its associated ethical concerns, is an important aspect of current and future projects. AI will help to develop diagnostic and treatment approaches that are better tailored to the specific characteristics of the patient to improve therapeutic outcomes and minimise short and long-term adverse effects of radiation. AI will therefore be applied to clinical data (patient history, treatment and follow-up) to provide individualized recommendations for treatment. As such, AI brings ethical challenges associated with, for example, the potential for bias and gender issues and access to sensitive personal information as well as questions of software-based treatment decisions.

Fig. 1. MEDIRAD recommendations.

In EURAMED rocc-n-roll all ethical aspects of research and medical use of ionising radiation are systematically reviewed in a number of different tasks dedicated to the patient perspective, data protection issues, databanks, and evaluation of the societal impact of the applications, and, in particular with a dedicated evaluation of the ethical aspects of AI-based approaches.

3 Discussion

3.1 Why research in medical RP is needed

To maximise the potential benefits and minimise the potential adverse effects of IR exposure, the growing use of medical applications of ionising radiation requires more research than ever in the field of radiation protection. The following examples give an overarching vision of what is still needed.

Patient A has a tumour in the left breast and must undergo RT, the standard treatment. RT has demonstrated that it can shrink the tumour and lengthen the life expectancy of the patient. Despite the best precautions, however, RT induces damage to the neighbouring organs and in particular the cardiovascular system, resulting in a significant risk of coronary disease and cardiac failure. Research needed in this context would address the development of new technologies and methods to maximise RT effects but minimise damage to healthy tissue. Also, the development of new tools for the detection and prediction of complications are potential consequences of a better understanding of the biological mechanisms of IR effects, and ethical issues must be examined for a proper benefit-risk balance of RT.

Patient B has cancer that requires regular follow-up of the tumour response during chemotherapy. Today this is done with recurrent CT examinations, although the total cumulative dose could easily exceed 100 mSv, a level beyond which stochastic complications are supposed to occur. In this context, the number of examinations should not matter because the benefit of a precise tumour response outweighs the hypothetical risk of IR. Since this is under debate [4], a better understanding of low-dose effects on human tissue must be developed. Biological approaches combined with epidemiological studies are still needed as well as personalised dosimetric methods in a wide context beyond oncology. In addition, the development of dose-reduction systems remains as crucial as other optimisation techniques for developing appropriate metrics and interoperability with the IT environment.

These two examples connect the four projects discussed here and will need to be addressed in the future to improve the benefits of IR applications to patients as well as the radiation protection of staff for such procedures.

3.2 Issues/challenges

Developing interdisciplinary approaches, especially between the radiation protection community and the health community as well as the digitisation community is critical, especially when referring to the rapid developments and new possibilities. In this context, the need of developing European-wide interconnected dose data repositories has to be stressed and would need a specific effort, in parallel to developing sustainable infrastructures for long-term clinical epidemiological follow-up of patients.

The transfer of research results into industrial products as well as into clinics in a harmonized way is a key element for future EC projects and needs a new framework which should be considered in future calls. Ensuring dissemination and uptake of MEDIRAD recommendations as well as from all projects and the EURAMED rocc-n-roll SRA by policymakers and scientific/medical communities and scientific exploitation will remain challenging and should be encouraged and supported as such.

3.3 Impacts

Our four projects impact radiological protection in the medical community by developing improved dosimetry and optimization tools which aim at providing, in the real-time, more accurate and personalised assessment of doses and lead to a more precise estimation of the dose-risk relationship for the benefit of the patients, staff and the general population.

The RP and medical communities are joining forces to understand the relationship between exposure to ionising radiation from diagnostic or therapeutic procedures and the development of cancer and non-cancer effects in specific populations integrating the identification of biomarkers of sensitivity to identify patients with a potential higher risk of short, medium or long-term radiation-induced effects.

The results of our research are to be translated into new/updated guidelines to assist clinicians, practitioners and medical physicists in properly balancing the risks and benefits of ionising radiation procedures and developing dose optimisation strategies for the protection of the patients and reduction of late toxicities. Guidelines for the protection of comforters, carers and medical staff are also developed. Our main objective is to promote high-quality healthcare minimizing side effects to reduce the overall burden of diseases.

3.4 Recommendations

The research in the current projects outlines the need for an overarching strategy for prioritising and implementing medical radiation protection research in Europe, to optimise diagnostic and treatment procedures and benefit European patients. Following up on the MEDIRAD recommendations, EURAMED rocc-n-roll aims to provide this strategy and to prioritise research needs to improve medical applications of IR, ensure the best medical practice and protection of patients. It will help to integrate the different approaches and will emphasize the importance of the patient-centred view, promoting better and harmonized patient care throughout Europe while allowing socio-economic benefits including industrial welfare.

4 Conclusion

Medical use of IR is currently the largest human-made source of exposure to ionising radiation in the population in Europe and use and applications are growing. It contributes greatly and effectively to health care in terms of diagnosis and treatment of patients. The four European projects described have in common to rely on interdisciplinary consortia with partners from different regions to integrate regional differences, establishing close collaboration between the different disciplines to achieve reliable and meaningful results. Their achievements have the potential to be transferred into clinical practice and daily medical use as they include the generation of easily applicable tools as well as corresponding education and training recommendations. Overall, research on medical applications of ionizing radiation and the corresponding radiation protection has been proven to have a great potential for better and more safe healthcare for individual patients within Europe. Further research, in particular into new applications, will be important to continue in order to improve medical care and the quality of life of patients. Special consideration should be given to data protection, especially considering the potential benefits of safely used AI applications in radiation-based medicine.

Conflict of interests

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

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Data availability statement

Within MEDIRAD, a matrix of historical doses associated with diagnostic radiological procedures has been generated and could be found at https://radiation.isglobal.org/medirad/2022/10/21/36/. Within EURAMED rocc-n-roll various surveys for example regarding the translational challenge and the current situation on education and training had been performed. The main results are published elsewhere, dedicated data can be made available on request. Within the SINFONIA project, radiation doses and other data associated with radiological procedures are currently being generated. Data associated with the HARMONIC project cannot be disclosed due to legal and ethical reasons. However, dosimetric tools and software will be made available.

Author contribution statement

Isabelle Thierry-Chef and Elisabeth Cardis took the leading role in proposing the strategy and overall organisation of the manuscript. They wrote the main text which has received very valuable inputs and comments from John Damilakis, Guy Frija, Monika Hierath, and Christoph Hoeschen.

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REVIEW ARTICLE

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RadoNorm – towards effective radiation protection based on improved scientific evidence and social considerations – focus on RADON and NORM

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Abstract. RadoNorm aims to manage risks from exposures to radon and naturally occurring radioactive material (NORM) to promote effective radiation protection based on improved scientific evidence and social considerations. It supports the European Member States and the EU Commission (EC) in implementing the Basic Safety Standards for protection against ionising radiation hazards at the legislative, executive, and operational levels (Directive 2013/59/EURATOM). The project is grounded on (1) implementation of multidisciplinary and innovative research and technologies, (2) integration of education and training, and (3) dissemination of project results targeting a broad stakeholder community including the public, regulators, and policymakers. The objectives are achieved through scientific research-related topics (exposure, dosimetry, biology, epidemiology, societal aspects), cross-cutting topics (education and training, dissemination, ethics) and project management. The project will yield guidelines at legal, executive and operational levels. It will enable consolidated and harmonised decision-making in the field of radiation protection, considering societal aspects and sustainable knowledge transfer. The project contributes to EC activities to strengthen radiation protection in a consistent and joint manner, as has already been done through the establishment of radiation protection platforms, the promotion of projects (e.g., DoReMi, OPERRA) and the partnership CONCERT-EJP. The outcomes may also impact future recommendations.

1 Introduction

The European Basic Safety Standards Directive 2013/59/EURATOM widens the application of radiation protection practices to previously not affected fields, such as exposures to radon, thoron (including their progeny) and exposures to naturally occurring radioactive material (NORM), and demands that they are regulated in the same way as artificial sources. Implementing new regulations and related guidelines must be based on sound, scientifically based evidence currently missing. Many open questions remain regarding dosimetry, effects and risks of radon and NORM when occurring alone or in combination with other stressors such as smoking. Also, the increased awareness of radon and NORM hazards calls for better risk governance.

1.1 Objectives

The RadoNorm project, funded by EURATOM H2020 from August 2020 to July 2025, aims to provide the required knowledge and to significantly reduce scientific as well as technical uncertainties in all steps of the radiation risk assessment and management cycle for radon and NORM exposure situations, as illustrated in Figure 1. This calls for research and technological developments, education and training, as well as dissemination actions targeted to the public as well as regulators. RadoNorm

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thus provides a holistic umbrella framework for integrating all aspects of radon and NORM protection, including underpinning science, past experiences and societal needs that might be relevant for implementing effective practical actions to optimise the protection of humans and the environment as well as to further develop them in a holistic way. RadoNorm supports the implementation of the European Basic Safety Standards (BSS) and helps to cope with the new requirements on radon and NORM. It would also help to improve recommendations on an international level through the ICRP. The holistic approach by RadoNorm covers risk assessment and risk management, development of tools, methods and best practices to cope with the issues related to radon and NORM, as well as research on societal aspects, thus making major impacts on society and helping the decision-makers and authorities in regulation and guidance.

Thus, RadoNorm provides science-based recommendations and guidance on how to best implement the BSS. The focus is put on innovative and practical solutions that significantly improve the radiological situation and radiation protection practices by all stakeholders involved.

1.2 Implementation

The project is designed to initiate and perform research and technical development in support of European Union Member States, Associated Countries and the European Commission (EC) in their efforts to implement the European radiation protection BSS. It has a highly multidisciplinary and inclusive character, which targets all relevant steps of the radiation risk management cycle for radon and NORM exposure situations. RadoNorm aims to reduce scientific, technical and societal uncertainties by (i) initiating and performing research and technical developments, (ii) integrating education and training in all research and development activities, and (iii) disseminating the project achievements through targeted actions to the public, stakeholders and regulators. Steps addressed are the characterisation of radon and NORM exposures (WP2), improving dosimetry (WP3), assessing effects and risks for humans and the environment (WP4), refining mitigation technologies (WP5), raising the understanding of societal aspects (WP6), and disseminating achievements (WP8). Furthermore, an ambitious pan-European E&T programme contributes to competence building and sustainability of the project findings (WP7). Figures 2 and 3 demonstrate the relationship between work packages and how they intertwine to answer the question of radon exposure as an example.

At the start of the project, several risks were identified, the most significant of which were changes in beneficiaries, BREXIT, poor visibility and delays in work. The COVID-19 pandemic also presented an unforeseen risk. Measures have nevertheless been taken to avoid bottlenecks in work, where the coordination team has diligently worked to actively engage partners, foster healthy communication and ensure that deliverables and milestones are timely met.

2 Key areas (WORK PACKAGES; WPs)

2.1 Coordination, management and administration (WP1)

The RadoNorm project is a multinational and multidisciplinary project, spanning 57 partners across 22 European countries and collaborating with groups in the US and Canada. The project engages both the natural sciences and social sciences.

This enormous effort to improve radiation protection based on scientific evidence and social considerations for radon and NORM can only be competently realised with the help of a central coordination system. Therefore, the smooth and efficient running of the project is being managed by the project coordinator (PC), who is the single point of contact for the project as a whole for all exchange of information, reporting requirements and financial aspects.

2.1.1 Objectives

The main objectives of WP1 are mainly administrative, i.e., to ensure the smooth running of the project, establish smooth communication within the project and with external entities, and ensure that the scientific goals of the project are being reached.

Responsibilities of the PC include monitoring progress using milestones and deliverables, ensuring compliance with the Grant Agreement and Consortium Agreement and the collection and collation of reports and their subsequent handover to the EC. The PC is also tasked with maintaining clear lines of communication between participants and governing bodies in the project so that research is properly guided and arising issues are quickly resolved. Moreover, it is the PC's duty to administer the disbursement of funds to the consortium and subsequently monitor and report financial compliance.

2.1.2 Achievements

WP1 has successfully compiled the project's first periodic report to the EC and has so far ensured that the project's deliverables and milestones are on track.

To provide a medium for coordination and management of internal documents among project participants, a secure internal web-based workspace was integrated with the project's public website. This was done in collaboration with WP8, responsible for dissemination and communication activities. The workspace allows the exchange of various types of information, such as datasets, results, coordination decisions, timetables, presentations, materials, and reporting among partners. It allows each partner, the work package leaders, and the coordinator to regularly monitor progress in data collation, analysis, and accomplished deliverables.

A system of RadoNorm internal cascade communication was set up, which allows the PC to communicate directly with members of the Executive Board (ExB), consisting of all WP leaders, to further communicate with task leaders and personnel within their work packages. Meetings of the PC with the ExB are held regularly every

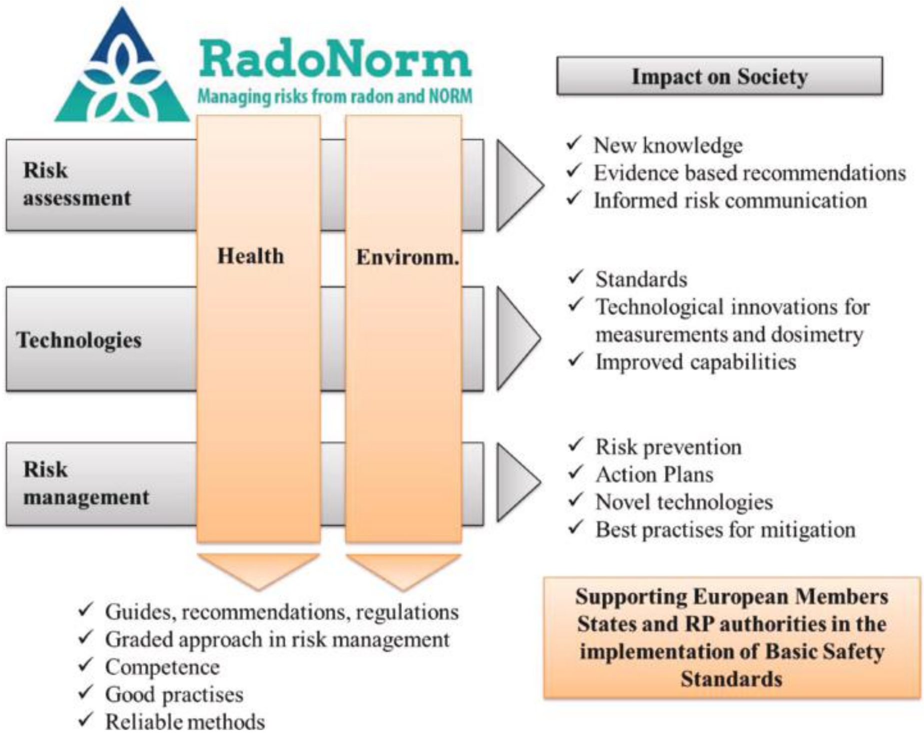

Fig. 1. Impact of RadoNorm on radiation protection.

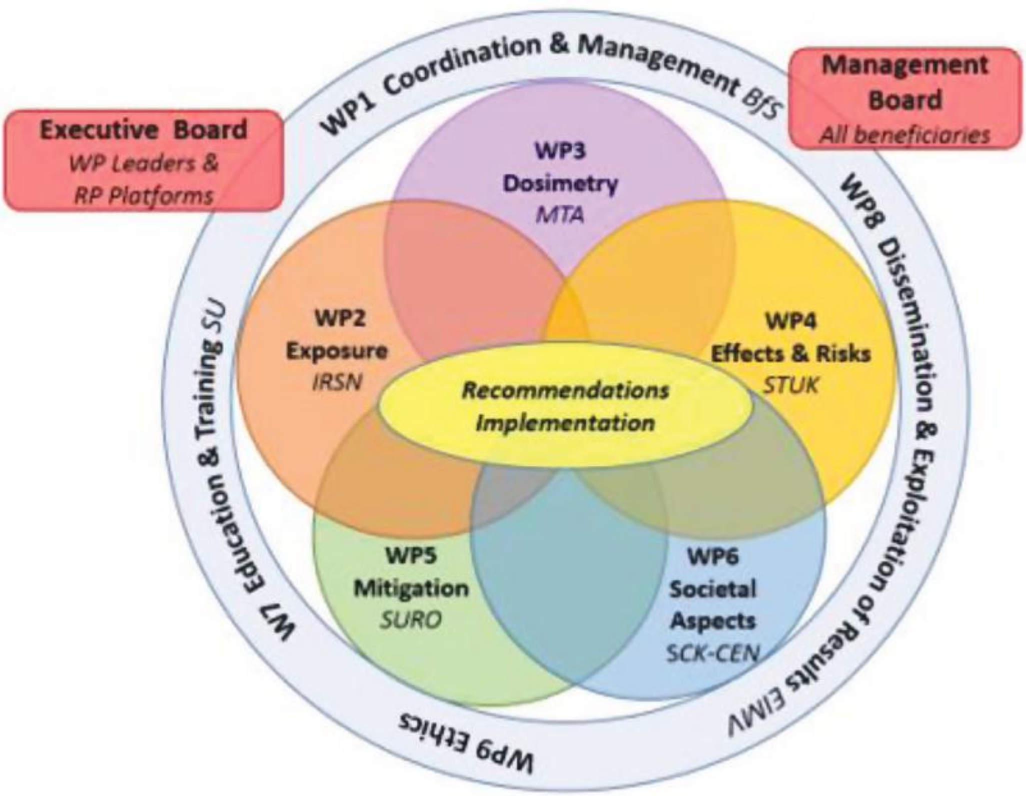

Fig. 2. Work package organisation in RadoNorm.

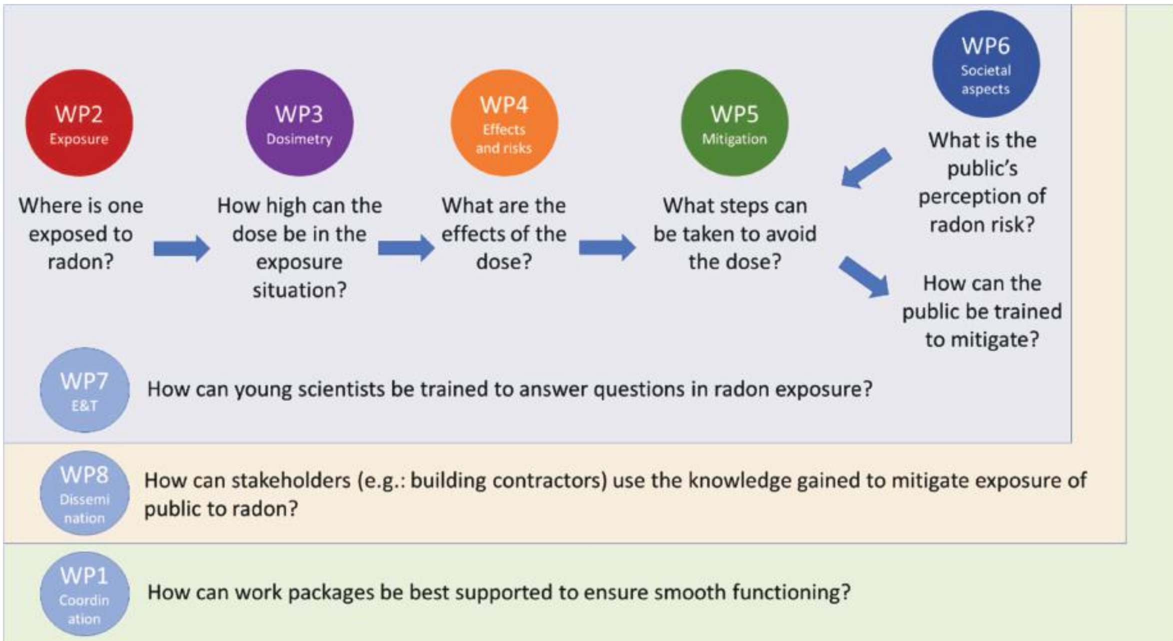

Fig. 3. How work packages contribute to the scientific process using radon as a case study.

three months. Moreover, the dissemination of information and results within the project was done through meetings of the General Assembly (GA) in the form of the Kick-Off Meeting and the 1st Annual Meeting. Due to the COVID-19 pandemic, both meetings had to be organised as online events.

Furthermore, the PC has clarified the ethics requirements of the project and made sure the necessary clearances have been obtained for the research to be carried out. This was done in the form of ethics reports that were submitted to the EC.

2.1.3 Perspectives

Another pillar of this work package is identifying project topics and results which could contribute to the Strategic Research Agenda (SRA) of the European Radiation Protection Platforms (RPPs). The PC has been in close contact with members of the European RPPs to identify relevant topics for research, especially as members of these platforms are part of the RadoNorm project. The research for RadoNorm is mainly based on their input, which is available to members of the platforms. Thus, the new findings benefit EU efforts not only in the development of BSS but also in the development of operational responses to local radioactive contamination, as well as aid the ongoing decommissioning of nuclear power plants across Europe and the subsequent storage of radioactive waste. It also increases public awareness of radiation protection measures.

2.2 Exposure situations (WP2)

When it comes to characterising and assessing the exposure of people and biota to radon and NORM, there still remain many uncertainties. As of now, there is great difficulty in radon metrology in determining (i) the average radon concentration level, which can be compared to the reference level, (ii) the fractionation between radon/thoron and their short-lived decay products, as well as (iii) the fraction of progeny attached to aerosols; which are all needed to assess the risk to radon exposure. Moreover, peculiarities in measurement can present themselves for specific sites (for example, in underground workplaces). Regarding exposure to NORM, the main uncertainties lie in understanding the different scenarios that can lead to an exposure event, not only due to the wide range of activities that use NORM but also due to the existence of natural areas with high background radioactivity, such as legacy sites. There is also difficulty in assessing the dispersion and transfer of NORM in the environment. Studying NORM dispersion and transfer is mainly done through the use of radioecological models, whose uncertainties can be reduced by a better understanding of the biological and geochemical processes governing the dispersion and transfer to various compartments of the environment.

2.2.1 Objectives

WP2 aims to provide a better characterisation of the exposure of people (public and workers) and biota to radon and NORM by fillings gaps of knowledge identified in previous European or National projects and those outlined as research priorities in SRAs of the European RPPs. Characterisation of exposure is to be done from the initial quantification of the radionuclide of concern at a given place and its contribution to the dose received by the people or the biota, to its dispersion and redistribution in the environment and finally to our capability of using models to predict this dispersion and transfer to assess the risk. For radon exposure situations, WP2 aims to improve upon detection and measurement methods for radon, thoron, and their progeny, assess the contribution of various natural and anthropogenic sources to radon exposure, aid in setting up workplace-specific radon measurement protocols and improve understanding of the processes and factors that contribute to the variability of outdoor amounts of radon, thoron and their decay products. For NORM exposure situations, WP2 will provide a systematic overview of exposure sites across Europe, investigate conditions and processes at NORM exposure scenarios that influence effects and risks, identify biological, chemical and geochemical parameters controlling the NORM migration in soil and transfer to plants, reviewing exposure pathways considered in radioecological models, and applying the new knowledge of exposure situations to models.

2.2.2 Achievements

Over the first 18 months, significant progress has been made. Methodologies and protocols have been established to compile or acquire new data for the (i) characterisation of temporal and spatial uncertainty of indoor radon measurement, (ii) characterisation of radon aerosols in underground workplaces, (iii) assessment of radon exposure in workplaces, (iv) assessment of building materials as a source of indoor radon exposure, (v) improvement of methods to identify high indoor radon levels, and (vi) assessment of radon and thoron outdoor concentrations and exhalation rate.

To collect information on NORM exposure sites at the European level, questionnaires and e-surveys were developed in collaboration with WP5. The initial experimental studies and the first set of field campaigns were started to better understand the influence of speciation, organic matter degradation, plant metabolites, earthworms or microorganisms on the mobility of uranium and radium in soils. These investigations would shed light on NORM transfer to plants and support the development of new modelling approaches to predict their reactivity in soils.

Finally, critical reviews of exposure pathways were carried out for dose assessment of public and biota at NORM industrial/legacy sites for three selected topics: (i) conventional waste disposal, (ii) the groundwater exposure pathways and the consideration of leaching and (iii) the use of sludge from sewer depuration systems of liquid effluents as fertiliser in agriculture.

2.2.3 Perspectives

This new scientific knowledge gained in WP2 will provide pragmatic and feasible recommendations or guidelines for radon-radon progeny measurements and workplace type-specific measurement protocols for the realistic assessment of radon exposure of the workers. Moreover, it will provide methods to support the EU Member States in the identification of high indoor radon levels at the European level, as well as give recommendations to support the revision of EC Radiation Protection guidelines (such as RPs guidance 122 and 135) in consideration of new types of industries involving NORM, processes, environmental standards and types of releases. WP2 outputs will also complement the risk assessment research for humans and biota as performed in WP4, as well as the assessment of remediation strategies in contaminated areas as in WP5.

2.3 Dosimetry (WP3)

Assessment of any dose-effect relationships requires reliable dose estimation. Therefore, it is highly important to obtain reliable data on doses, dose distributions, and their uncertainties in order to characterise the health and biological effects of radon exposure. These include data on absorbed doses and their uncertainties in epidemiological studies and on doses at different levels of biological organisation in biological experiments.

2.3.1 Objectives

Besides providing reliable dose estimation in different exposure scenarios, this area aims to identify specific human subpopulations potentially more sensitive to radon exposure than the general public since there are no two people alike. The effects of severe asthma on absorbed doses and dose distributions in the lungs have been quantified by computer models of airways of diseased patients considering anatomical, physiological, and histological differences.

While smoking increases lung cancer risk, it also induces changes in lung morphometry and respiratory physiology, affecting the deposition and clearance of radon progeny. In this way, the same environmental radon concentration may result in different absorbed dose rates in the lungs depending on smoking history. The final goal is to distinguish between smoking-induced and radon-induced lung cancers considering the differences in the spatial distribution of bronchial carcinomas and deposition patterns upon exposure to cigarette smoke and radon progeny.

While the highest fraction of a dose is absorbed in the lungs, other organs are also exposed to radon progeny and other sources of ionising radiation. Annual absorbed doses arising from exposure to radon gas, radon progeny, long-lived radionuclides (LLR) to the lung and to other organs will be calculated in individual miners. Calculations will be performed with standard biokinetic and dosimetric models published.

Another aim is to gain insights into the uncertainties arising from model parameters, which affect the dose attributed to cohort members, to define better the uncertainties affecting the dose-effect relationship. Biokinetic and dosimetric models will be applied in the dose calculations and uncertainty analysis. Uncertainties arising from exposure, biokinetic and dosimetric models will be studied separately and then combined.

It is an important question whether in vivo and in vitro experiments can mimic the real-life exposure scenario and to what extent. Therefore, computational microdosimetry will be performed in order to support the preparation and evaluation of biological experiments.

2.3.2 Achievements

Because of the widely differing experimental information on the effects of smoking, a thorough review of the existing literature was performed in order to establish reasonable modelling scenarios. A thorough review has been performed in order to develop a comprehensive model for the dose to embryo and foetus, considering a placental transfer, lactation, and age of children, among other factors. A literature review of the models and their parameter values has also been performed to quantify uncertainties deriving from prior distributions from which parameter values will be sampled for Monte Carlo simulations. In vivo dose distributions in human lungs (Fig. 4) have already been quantified in order to provide realistic exposure conditions for in vitro experiments with cell cultures and organotypic tissue models. Specific energy and hit distributions have also been quantified in the case of in vitro experiments with cells and organotypic tissue models exposed to solid alpha sources and charged particle microbeams.

2.3.3 Perspectives

The results of this WP will contribute significantly to the Multidisciplinary European Low Dose Initiative (MELODI) research platform by improving understanding of dose-response relationships for radiation-induced health effects and organ-specific cancer risk assessments, as well as to the European Radiation Dosimetry Group (EURADOS) platform by helping to refine, validate and implement new biokinetic models.

WP3 also address the question as to whether a new dose concept can be developed accounting for spatial dose inhomogeneity by generating new knowledge related to the role of spatial dose distribution in radiation risk, and exploring how intra-organ dose distribution can be considered in the system of radiation protection.

In order to explore ways how differences (if any) can be considered in the system of radiation protection, the consideration of the effects of spatial variation in dose delivery at other spatial scales has been reviewed. To complement that, the existing epidemiological and biological data about the biological and health effects of hot particles and other heterogeneous exposures, including exposure to radon progeny, will also be reviewed. In addition, particular attention will be paid to experimental results on the effects of spatially inhomogeneous dose distributions in state-of-the-art organotypic lung models. A biophysical model capable of predicting the relative biological effectiveness of various radiation types will also be applied to describe the carcinogenic potential of complex radiation fields in dependence on the dose. This will lead to an estimate of the effect of weighted dose dependent on the composition of the radiation field for carcinogenesis-related endpoints. Based on these studies, recommendations can be made on how to improve the system of radiation protection.

In the end, the results of this WP will contribute significantly to the MELODI research platform by improving understanding of dose-response relationships for radiation-induced health effects and organ-specific cancer risk assessments, as well as to the EURADOS platform by helping to refine, validate and implement new biokinetic models.

2.4 Effects and risk assessment (WP4)

2.4.1 Objectives

The general objective of WP4 is to generate new knowledge related to biological effects and responses after exposure to radon and NORM that have implications for risk assessment and radiation protection of humans and the environment. It also aims to reduce the existing uncertainties in risk assessment. To achieve this goal, WP4 is structured into tasks addressing major knowledge gaps in human health risk assessment of radon and NORM, such as the interaction between radon and smoking in lung cancer, risks of radon outside of the lung, risks associated with radon exposure during childhood, risks from radon and NORM in drinking water, mechanisms of radiation action in the disease processes, and quantification of various sources of uncertainties in risk inference. In addition to human health effects, we address the major knowledge gaps for the risk assessment of non-human biota with respect to the combined effects of NORM and other stressors and determine adverse outcome pathways (AOPs) leading to such effects.

2.4.2 Achievements

The methods used in WP4 include epidemiological studies and simulations based on epidemiological datasets, risk modelling, molecular epidemiology, experimental studies on combined effects carried out in realistic co-exposure conditions and determination of AOPs linking the mechanisms and effects after co-exposures. During the first 18 months of the project, all studies have been successfully initiated. Smoking risk models with temporal exposure window have been developed to include intensity and duration of smoking and time since quitting smoking, and geometric mixed models for interaction between cumulated radon exposure and smoking have been developed.

To study radon-related risks other than lung cancer among adults, detailed specification of analysis plans regarding outcomes, risk models and subgroups have been carried out. Aiming at pooled analyses of national studies on the association of radon and childhood cancers, leukaemia and brain cancer, studies on national cohorts have been continued. Moreover, mechanisms of radiation action in lung cancer are being studied among never-smokers exposed to radon. In addition to the molecular characterisation of non-small-cell-lung-cancer among 1000 patients, the genetic alterations found with the molecular phenotype in animals (rats) and humans exposed at work (miners) are being investigated.

Various sources of uncertainties in radon-induced lung cancer risk inference are studied. Developing and fitting Bayesian hierarchical models based on survival disease models and shared error structures may alleviate uncertainties in exposure and dosimetry. Biologically based models on lung carcinogenesis are being developed that

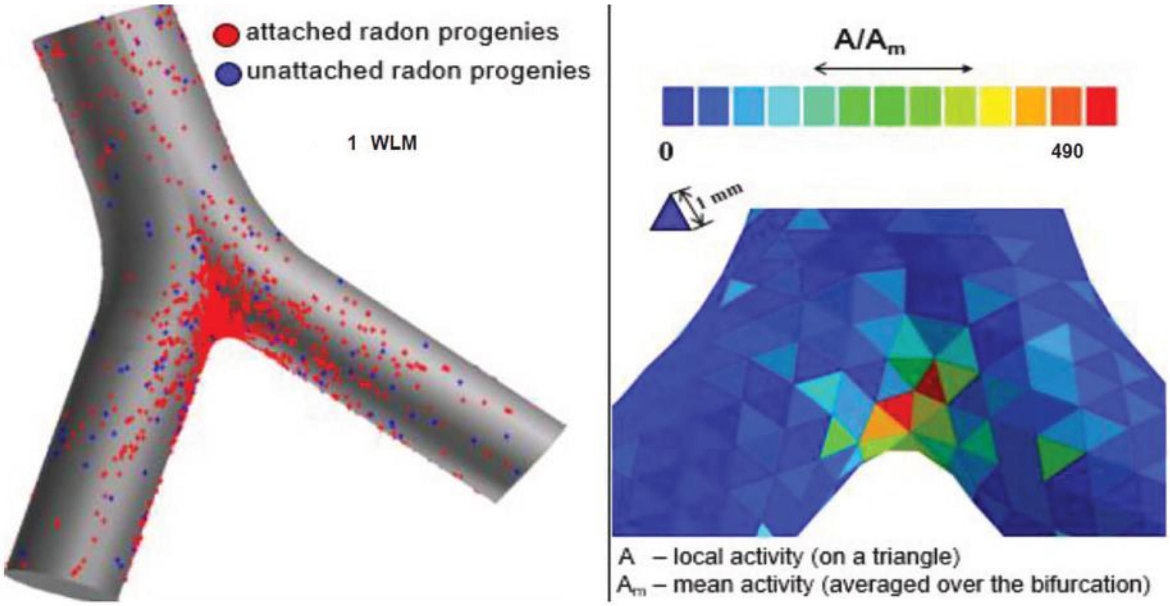

Fig. 4. Deposition pattern of the inhaled radon progenies in a central bronchial airway bifurcation (left) and colour map of the deposition enhancement factors (right).

integrate molecular data, calculate lifetime risk and contribute to the AOP development.

2.4.3 Perspectives

Even though it is well known that radon causes cancer, there are still major gaps in knowledge. Much less is known about the possible association between radon exposure and diseases other than cancer, like cardiovascular diseases. Furthermore, studies on radon risks have been carried out among adult populations, like uranium miners, and we need more information on the risks after exposure during childhood. The interaction of radon and smoking is also a major public health question. Smoking increases the lung cancer risk from radon, and in fact, quitting smoking is an effective way to reduce the risk of radon. We address this question by analysing datasets that have information on radon exposure and smoking, looking into the trends in smoking by age groups and experimental studies to gain a further understanding of the molecular mechanisms involved in the interaction of radon and smoking.

There are few studies focusing on the risk from ingestion of naturally occurring radionuclides such as radon, uranium and radium, and to this effect, better exposure characterisation from different drinking water sources is needed, which is planned to be undertaken during the course of the project.

Radon detectors that are sensitive to thoron (^{220}Rn) can over-estimate radon (^{222}Rn) exposure. This leads to an underestimation of lung cancer risk per radon exposure. To study this, the detectors used in previous epidemiological studies are being tested for their sensitivity to thoron.

Experimental studies on the effects and mechanisms of action of combined exposures to radon or NORM and other stressors relevant in true exposure situations of humans and biota have been started by reviewing and setting up co-exposure systems (cells, rodents, aquatic organisms). Based on the experimental data, predictive models will be established for the combined effects of multiple stressors for lung cancer caused by radon/tobacco and ecotoxicological relevant endpoints. Other stressors being considered are nanoparticles (e.g., carbon, silicate) and other NOR substances (e.g., U, Ra, Po-210).

In the end, the concerted effort of all tasks within the work package will help develop new methods for risk modelling, in particular, quantification of uncertainties for risk inference. It could potentially shed light on elucidating driver mutations for radon-induced lung cancer, which would be a major breakthrough in radiation carcinogenesis. But it would more likely be that several radon-related pathways leading to lung carcinogenesis are discovered. Contribution to public health will also be profound by providing predictive models on radon exposure and predictions on future lung cancer rates. Through its findings, WP4 is poised to close several knowledge gaps addressed in the MELODI, ALLIANCE and EURADOS research platforms.

2.5 Mitigation (WP5)

2.5.1 Objectives

The main goal of WP5 is to improve and optimise radiation protection of workers, the general public and the environment against the harmful effects of ionising radiation caused by the presence of natural radionuclides in nature and the work environment utilising innovative mitigation techniques, systems and strategies. In order to achieve the main goal, several key objectives were identified, and corresponding research activities were defined.

One main objective is the improvement of the efficiency of radon mitigation systems and their sustainability through the new developments and optimisation of current radon control systems. The innovative design of preventive measures and corrective actions applied in dwellings and workplaces involving NORM industries will use new knowledge on radon sources and radon entry pathways gained through experimental and theoretical work carried out specifically in WP2 and WP5 in close collaboration. The ongoing research is focused on the modification and optimisation of existing ventilation systems, such as described in Figure 5, the application of radon-resistant construction techniques and materials and the utilisation of continuous radon monitors for control of active operation elements of preventive measures and corrective actions.

Analysing information on lessons learned and experience gained during implemented actions for mitigation in buildings, workplaces and NORM industry facilities in the EU Member States is also undertaken as part of WP5. This information enables us to improve regulation tools and procedures, leading to a reduction of occupational and public exposures to ionising radiation reflecting the variety of exposure scenarios.

Another objective is the development of strategies for final treatment of NORM residues/waste based on preventive actions and mitigation methods with respect to existing circumstances corresponding to specific NORM-involving industries, technological processes, legacy sites and environmental conditions. This is based on the evaluation of remediation options using radioecological models from the legal perspective and general radiation protection principles (justification, optimisation, and dose limitation) based on industry-specific BATs (best available technologies) and/or LCAs (life cycle assessments).

2.5.2 Achievements

The methods used in WP5 include measurement campaigns in dwellings, workplaces, NORM industry facilities and legacy sites; field radiation surveys and environmental sampling and measurement; laboratory measurement and analysis; proficiency testing programs in radon/thoron calibration facilities; in situ comparison measurements; radioecological modelling and utilisation of case studies in specific NORM and legacy sites; radon-resistant construction techniques and materials testing; data processing and analysis software tools; information and data collection methods.

Over the course of the first 18 months, several questionnaires have been formulated and distributed. Two were done to get an overview of regulatory approaches and international standards for systems and methods (preventive measures, corrective actions) to control radon in workplaces and dwellings, formulated and distributed among relevant stakeholders. A third, more general questionnaire, in collaboration with WP2, was to gather specific information related to NORM aspects that would be needed later in the project. Other questionnaires are currently in preparation, such as collecting information about the measurement of radon and radon progenies and other relevant parameters that might be important from the point of view of dose from radon calculation and the evaluation of radon mitigation systems.

For radiation risk mitigation measures applied in NORM-involving industries and remediation of legacy sites, a workshop was organised with industry representatives and relevant authorities dealing with radioactivity in water. The workshop comprised invited introductory presentations on a legal context, research examples, case studies, already applied solutions and follow-up panel discussions.

A review of building materials and technologies with significant impact on indoor radon levels was also conducted. This was done by literature searches and asking partners about their experience with the material with elevated content of natural radionuclides or including residues of NORM industries.

Two specific NORM situations have been determined as case studies: (i) mixing of NORM residues with other residues during underground coal mining activities or for reuse/recycling and (ii) a NORM-affected legacy site in Norway. Key parameters needed for modelling and collation of relevant datasets for model application were carried out. The foreseen outcome of this would be a methodology and a procedure tested on the aforementioned cases for addressing solution effectiveness and identifying possible issues to obtain an appropriate, well-justified decision.

Laboratory experiments have commenced on exhalation rate measurement from a building material sampled during radon diagnosis. Additionally, other experimental and theoretical studies are underway on testing various methods of radon diffusion coefficient determination in radon-proof membranes.

The selection of active and passive dosimeters for testing purposes is also underway. This is done in order to prepare a large in situ inter-comparison measurement campaign focused on a dose assessment of workers from radon and radon progeny in selected underground workplaces. Measurement campaigns in dwellings and underground workplaces before and after the implementation of corrective actions and comparing measurement techniques are also planned. Installation of preventive measures based on a sub-slab depressurisation system for further testing purposes is also being carried out.

2.5.3 Perspectives

New findings will eventually lead to better software and measurement tools for air exchange rate determination and radon diffusion coefficient determination, among others. It will also help improve water treatment technologies by reducing the level of natural radionuclides and non-radioactive contaminants. Furthermore, it will strengthen mitigation efforts in NORM industries and legacy sites using site-specific radioecological models.

2.6 Societal aspects (WP6)

Radon, NORM and the risks they entail for humans and the environment are important societal issues. In this

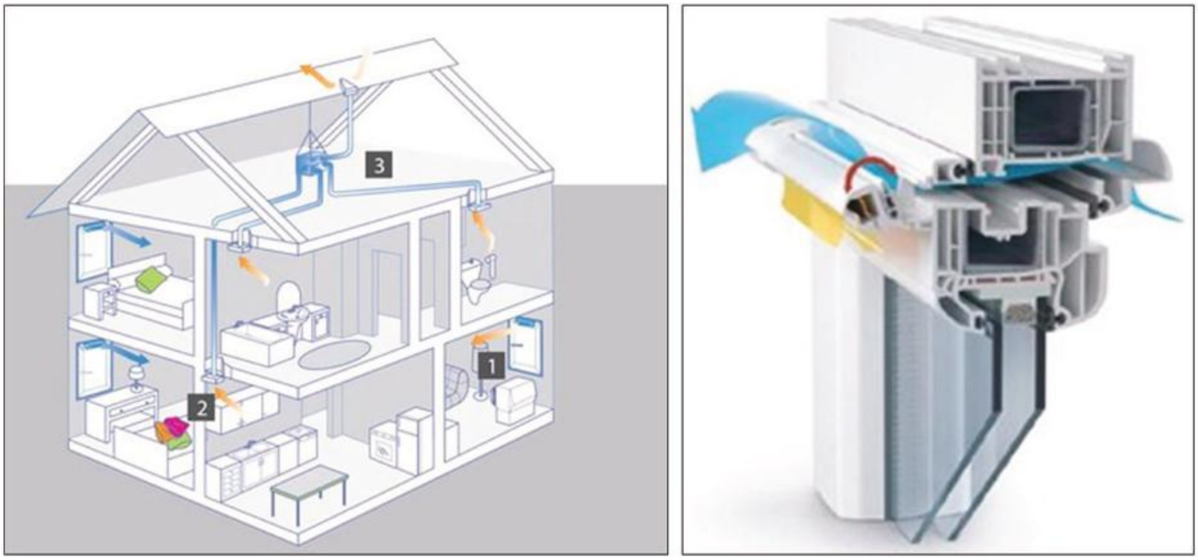

Fig. 5. Radon corrective measures – a hybrid ventilation system.

respect, they should not only be approached through a technical lens, but attention should equally be directed at the ways in which individuals, groups, organisations and institutions in society are perceiving, thinking about, and acting upon radon and NORM. When focusing on the societal aspects of radon and NORM, important questions arise, such as “what barriers are people experiencing to radon remediation?”, “how can citizens be more actively engaged in radon measurement and remediation?” and “what factors influence companies’ (un)willingness to use NORM-containing by-products in the production of construction materials?”.

2.6.1 Objectives

Through a focus on the societal aspects of radon and NORM, WP6 aims to contribute to strategic, innovative, theory- and evidence-based governance of radon and NORM. Building on and addressing the gaps of past research, it proposes systematic and methodologically sounds social scientific approaches to study radon and NORM. More specifically, WP6 aims to improve public awareness of radon and NORM, evaluate methods to achieve behavioural change, and contribute to science-based policy support for radiation protection from Radon and NORM. This is done through five tasks, covering the development of a strong methodological base and toolbox for studying stakeholders’ perceptions, attitudes, behaviours, motivations and opinions related to radon and NORM; the development and testing of health communication tools focused on achieving behaviour change; establishing and supporting citizen science initiatives on radon remediation; studying societal aspects in specific and understudied exposure situations; and formulating consolidated recommendations for science and policy. Integrating a work package dedicated to societal aspects, which builds on insights from social science and humanities research, demonstrates the strong holistic and multidisciplinary character of the RadoNorm project.

2.6.2 Achievements

In the first 18 months of the project, each task has been initiated with tangible outputs for all of them. With regard to the development of a strong social scientific methodological base and toolbox for studying radon and NORM, an elaborate literature review was conducted on methods used in published articles ($n = 142$) on the subject. Besides uncovering a strong underrepresentation of NORM as a subject in social science studies (being studied only in 19 articles), this review highlighted a dominant geographical focus on the US, the use of rather ‘traditional’ quantitative and qualitative methods, and the (lack of) reliability and validity of a range of variables and scales used in the past. Building on this state-of-the-art, a range of quantitative and qualitative methods have been selected, adapted and tested in various national and local contexts, gaining insight into how different publics perceive and act with regard to radon and NORM exposure. This will result in a database and methodological toolbox to be consulted and used by researchers and policymakers.

Some of the first results of WP6 have been published in various articles. Regarding citizen science, a paper titled “Evaluation of citizen science contributions to radon research” was published in the Journal of Environmental Radioactivity in October 2021. In that same journal, an article was published in April 2022 titled “Societal aspects of NORM: an overlooked research field”. In that same month, the International Journal of Public Health published the article “Cure or Carcinogen? A Framing Analysis of European Radon Spa Websites”.

Finally, various events have been organised in the context and with the support of WP6. A webinar titled “expert consultation on investigating the potential of citizen science for effective radon measurement and mitigation” was co-organised by RadoNorm, the Social Sciences and Humanities in Ionising Radiation Research (SHARE) platform and the International Atomic Energy Agency (IAEA) in the framework of the RICOMET 2020 conference in September 2020. During that same conference, a webinar on "Societal aspects and marketing challenges of NORM in building products" (co-organised by SHARE, the European NORM Association (ENA) and the RadoNorm project), and a webinar on "Radon air pollution: communication and protective behaviour" (co-organised by the Environment and Resources Authority (ERA), IAEA, the RadoNorm project and SHARE) was organised. A one-day hybrid conference on transdisciplinarity titled "Beyond scientific disciplinary boundaries: the future of radiation protection research and practice?" was organised by SCK CEN, MERIENCE, NMBU and the SHARE platform in September 2022.

2.6.3 Perspectives

These insights serve as a sound basis for developing communication strategies and tools, which might be used to tackle the identified gap between people's attitudes and values on the one hand and their actions on the other (e.g., knowing that radon is an issue and perceiving it as problematic, while not taking remediating actions). Through pinpointing behavioural objectives and change objectives for specific stakeholder groups and gaining insights into determinants of these behaviours, communication tools are developed and tested, both in the laboratory and 'field' settings. This hence provides a hands-on, scientifically consolidated means to achieve behaviour change, which is an important route towards increased radon testing, mitigation and/or remediation (Fig. 6).

An additional but partly complementary route to such an increase in testing, mitigation and/or remediation is also being investigated through setting up and testing a range of citizen science initiatives, where citizens take an active role in conducting measurements and designing strategies for increasing radon remediation. Through building on citizen science principles defined by the European Citizen Science Association and exchanging with previous radon-focused citizen science projects, four pilot initiatives have been prepared, of which the first (in Ireland) was launched in Spring 2022. Towards the end of 2022 and building on insights gained through the pilot studies, a call for citizen science initiatives on radon will be launched across Europe, thus establishing a network of initiatives and citizens engaged in radon governance.

One particular interest of WP6 also lies in investigating the understudied societal aspects related to specific radon and NORM exposure situations. These specific situations are radon and NORM in the context of geothermal projects, the use of NORM-containing industrial by-products in the construction industry, and the existence of radon spas in different European countries. Related to the first context, a socio-technical investigation is undertaken to describe radiological and chemical characteristics of geothermal by-products, uncover perceptions of workers and other stakeholders with regard to radiation issues, and identify – with the help of stakeholders – potential management strategies for these by-products. For the second context, interest is taken in the use of alternative cementitious binders made with NORM-containing by-products and how both industrial actors and end-users perceive the use of such binders in the construction industry. Finally, with regard to radon spas, a frame analysis has uncovered how such spas in their public communication frame radon is significantly different (and sometimes contradicting) ways from the framings encountered in public health communication, a finding which in the coming months will be further explored through interviews and/or observations with relevant stakeholders.

Overall, WP6 emphasises that radon and NORM are situated in complex and continuously dynamic societies and hence stresses that effective governance strategies should also uncover the interplay between the technical and natural aspects of radon and NORM on the one hand and their societal aspects on the other. As such, it contributes both to state-of-the-art research and to science-based policymaking.

2.7 Education and training (WP7)

2.7.1 Objectives

WP7 aims to organise the education and training program of RadoNorm focusing on Ph.D. students and early career researchers (ECRs). To this end, WP7 monitors and supports the progress of Ph.D. and ECR projects and contributes to their professional development by organising targeted courses and exchange visits.

2.7.2 Achievements

Approximately 24% of the project budget is dedicated to the salaries of Ph.D. students and ECRs. During the first 18 months of RadoNorm, 20 Ph.Ds. and 14 ECRs were recruited. A virtual meeting for Ph.D. students and ECRs was organised in 2021, where each young researcher presented his/her project and answered questions. Such meetings will be repeated regularly in order to foster collaboration between Europe's future radiation researchers. The coming meetings are intended as face-to-face events, where the researchers can get to know each other personally, this being an important element of team building.

Five courses were held in 2021: "Interdisciplinary radiation research on radon" organised by BfS (Germany), "The art of public opinion survey analysis: surveying the public on Radon and Norm" organised by the University of Antwerp and SCK-CEN (Belgium), "Naturally occurring radionuclides in work and natural environment – establishing the problem definition, finding sources and exposure assessment" organised by GIG (Poland), "NORM impact assessment toolkit: from microorganisms to human cells" organised by the University of Aveiro and University of Porto (Portugal) and "Cellular effects of high and low LET ionising radiation – introduction to radiation biology" organised by Stockholm University (Sweden).

Eleven travel grants were awarded in 2021, which was quite low and presumably due to the COVID-19 pandemic.

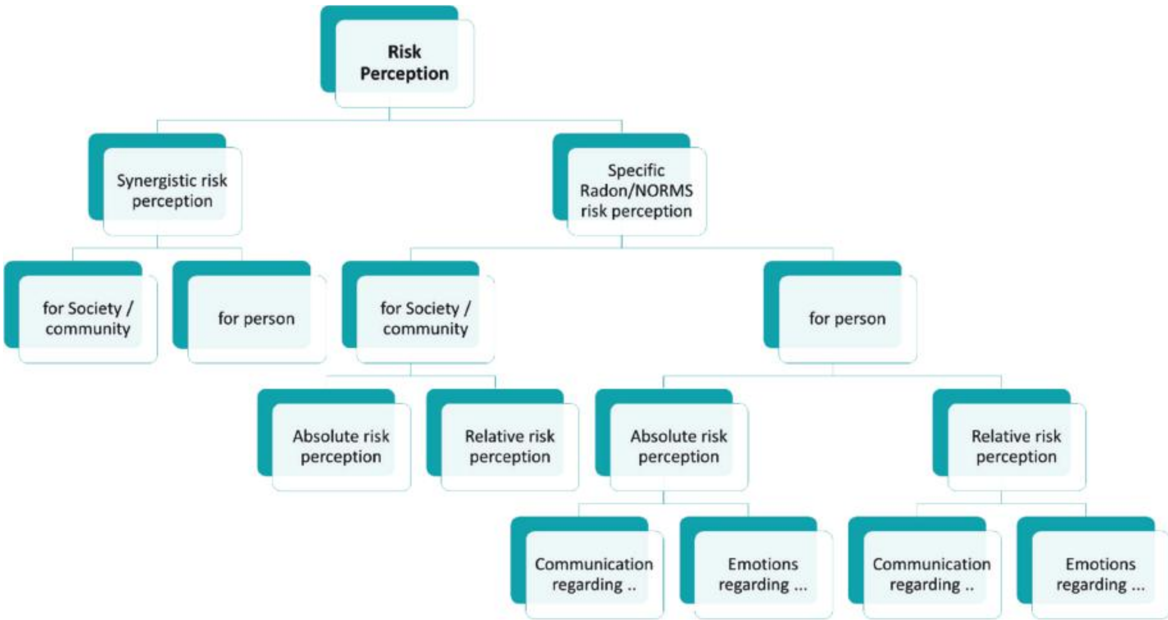

Fig. 6. Systematic overview of Radon/NORM risk perception.

2.7.3 Perspectives

There are still Ph.D. and ECR positions to be filled at a later stage, in accordance with the work planned for each task. Training and courses for these young investigators will also be conducted in the coming years, with various courses already planned for 2022. We expect that as the pandemic restrictions ease, we will be able to fund more travel grants to encourage young investigators to pursue scientific exchange in person.

At the end of the project, a new generation of scientists would be well-trained and willing to take on the challenges of radiation protection in their respective fields.

2.8 Communication, dissemination and exploitation of results (WP8)

2.8.1 Objectives

Among the aims of RadoNorm is also to disseminate the project achievements through special actions targeted at the public, other stakeholders including regulatory authorities and policymakers. In addition, one of the objectives of the project is to exchange and communicate with stakeholders, including the general public, affected populations, professional and regulatory organisations across Europe, as well as international communities of scientific, technical, legal, and other professional experts in radiation protection. Therefore, a specific cross-cutting work package in RadoNorm is devoted to communication, dissemination and exploitation of the RadoNorm results in the most effective way with the highest impact throughout the project lifetime and also beyond. To achieve the best results, all work package leaders are involved and contribute to the activities. The PC ensures resource optimisation to ensure consistency of the dissemination activities and maximise public outreach. The work package on communication, dissemination and exploitation objective is to: (i) enable two-way communication about the project and its results to multiple audiences and show its impact and benefits by addressing and providing possible solutions to challenges of radon and NORM exposures; (ii) make the results transferable for audiences that may use the new knowledge, data and information in their own work, enable use and uptake of results and maximise the impact of EU-funded research; (iii) utilise the RadoNorm results in developing, creating and marketing products, processes, services or other activities (policymaking) to effectively exploit the project's results for society.

2.8.2 Achievements

In order to achieve these objectives, the project adopted the strategy and plan for communication, dissemination and exploitation of results with the overview of stakeholders, their needs and expectations, different tools and channels for communication and dissemination and for involvement of target groups. Different means have been outlined for online communication and feedback, specific materials to promote key messages, events and participation in other relevant actions. Also support for other work packages in communication and dissemination of their research to scientific and non-scientific audiences is provided. The report of the strategy and plan provides the basis for both external and internal communication, dissemination activities and approach to the exploitation of results. RadoNorm's outreach activities aim at communicating and disseminating the project results during the project lifetime and increase the impact after the end of the project.

The external communication and dissemination strategy uses a synergetic combination of several channels and

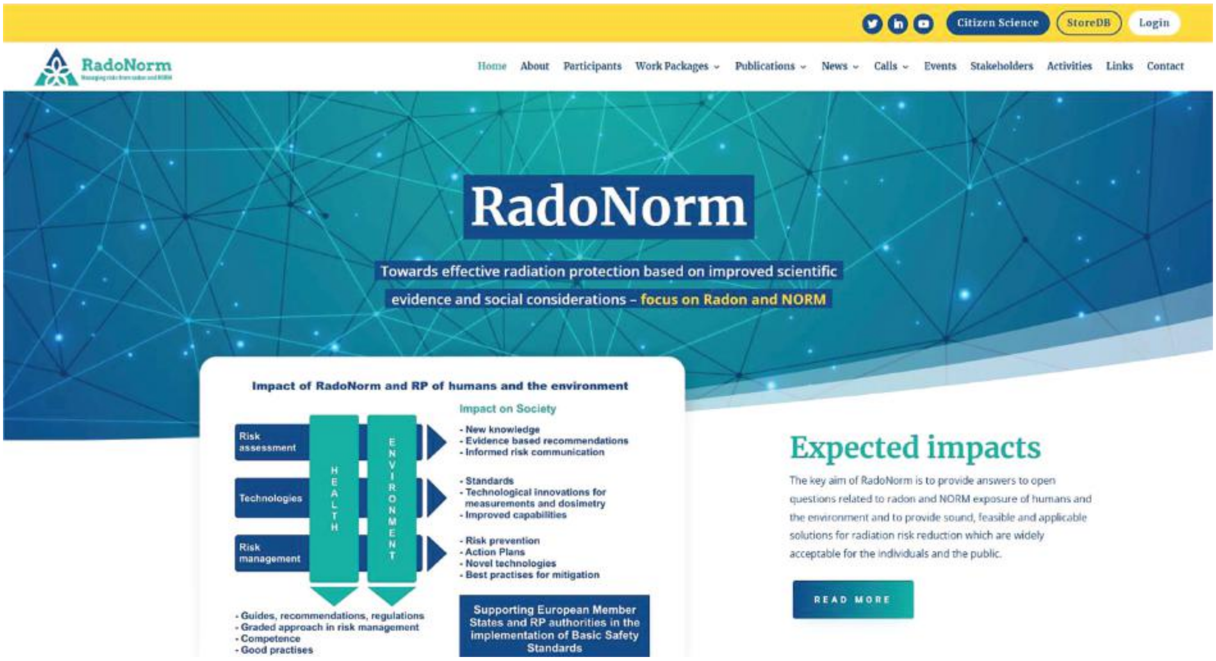

Fig. 7. RadoNorm website on public domain.

tools, such as a project website (Fig. 7) linked with social media networks, newsletters and other information materials, two-way interaction tools and channels with different stakeholder groups established in the project, conferences and other event opportunities and publications in various media including peer-reviewed scientific journals and popular science publications. All this information is available on the RadoNorm website https://www.radonorm.eu/ and is regularly updated.

The internal communication and dissemination plan defines responsibilities among project partners and consortium bodies and describes internal communication flows and monitoring instruments. Internal communications are conducted via emails sent out by the PC and work package leaders and periodic electronic or face-to-face meetings. Project communication and documentation (including project minutes, deliverables, etc.) are stored and shared in the internal repository on the RadoNorm webpage. The internal communication plan also provides information on templates made available to all partners.

2.8.3 Perspectives

The RadoNorm results will include reports, recommendations, new skills and knowledge, educational materials, publications, Ph.D. theses, new collected data and prototypes (like new pre-standards and measurement methods). RadoNorm uses the STORE^{db} platform (https://www.storedb.org) for secure storage of data and sharing and dissemination of data and information. In general, the RadoNorm results are public unless the decision to protect the outputs is taken (such as patenting or other forms of intellectual property protection). Green open access to the website's online project repository is assured, and also gold open access for a limited number of publications. Thus, the international guidelines for open data (FAIR) and transparent publication (TOP) are respected, and the availability and reuse of the primary scientific data further increase the value of RadoNorm output. It also assures that the public-funded RadoNorm output can become available to the broader research community. Published results would also be exploited by the scientific community and various stakeholders involved in radiation protection.

3 Conclusions

The RadoNorm project had a successful start and showed considerable and tangible output over its first 18 months, despite the COVID-19 pandemic. 12 out of 85 deliverables and 20 out of 99 milestones have been achieved. The project objectives have been fulfilled, especially in addressing knowledge gaps through scientific investigation, training personnel in radiation protection research, disseminating its findings to a broad audience, engaging and educating the public, and bringing together the radiation protection scientific committee at an EU level to coordinate research efforts.

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

Ulrike Kulka is the project coordinator, and Mandy Birschwilks is a member of the coordination team. Laureline Fevrier, Balázs Madas, Sisko Salomaa, Aleš Froňka, Tanja Perko, Andrzej Wojcik and Nadja Železnik are work package leaders. All authors contributed to the writing of this manuscript.

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EUROPEAN RADIATION PROTECTION RESEARCH FOR THE EFFECTIVE PROTECTION OF PEOPLE AND THE ENVIRONMENT

Hildegarde VANDENHOVE (SCK-CEN, BE)

MEENAS

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Abstract

Radiation protection research and innovation is quintessential for medical applications, sustainable energy and economy development, emergency preparedness especially in today's challenging geopolitical context, and for supporting regulation and standards.

The six European radiation protection research platforms MELODI, EURADOS, EURAMED, NERIS, ALLIANCE, SHARE established the MEENAS association.

MEENAS intends to enforce radiation protection research and innovation in Europe and beyond and operates as single-voice towards third parties such as the European Commission. To this end, a vision document was created under guidance of MEENAS and key radiation protection entities and in close interaction with the entire European radiation protection community, which formed the basis of the PIANOFORTE partnership, set up in response to the HORIZON-EURATOM-2021-NRT-01-09 call. PIANOFORTE aims to provide a European scientific and technological basis for a robust system of protection and consolidated science-based policy recommendations to decision makers. In the long term, these efforts will translate into new and improved practical measures and better outcomes for the effective protection of people (public, workers, patients) and environment. This paper presents the history, highlights and importance of the PIANOFORTE partnership, its interlink with the Horizon Europe objectives, clusters, missions, programmes and with other international initiatives. Radiation protection research, more than before, needs to be part of a global collaborative reciprocal network.

1 INTRODUCTION

Radiation protection (RP) aims at protecting people and the environment from detrimental effects of ionising radiation, while maintaining or even improving the benefits of its use. Radiation protection is an enabler. An effective RP system must be based on scientific knowledge including the disciplines of radiobiology, epidemiology, radiation physics, dosimetry, emergency management, radioecology, medicine and sociology. Radiation technologies are used widely and protection based on state-of-the-art scientific evidence is an important requirement for development in the fields of medicine, industry and protection of the environment. The public, occupationally exposed personnel and patients are rightly concerned about possible consequences of exposure to radiation, both from planned, accidental and medical scenarios. An accurate balancing and clear communication of risks and benefits is needed. However, many knowledge gaps exist. Does the current system provide sufficient protection? Complete avoidance of radiation exposure is not possible so the inevitable question is what level of exposure is justified? Our radiation protection system, even today, is mainly based on (cancer) effects following nuclear bombing experiences and high dose or dose rate exposures, which are extrapolated to low dose exposures inherently assuming the same mechanisms of effects take place at these low doses. This is one of the (main) reasons why R&I is still needed. New technologies evolve that lead to exposure of people and the environment to different sources of radiation and isotopes, requiring understanding of dosimetry and effects. Radiation accidents provoke public attention and democratic societies must ensure a sufficient level of competence not only to cope with the consequences but also to provide reliable information for action. The aim of this paper is to highlight the importance of radiation protection, the development and innovation needs in radiation protection, the requirement of mutual interconnectivity within the broad Horizon Europe programme and the pivotal role that and the PIANOFORTE Partnership and the MEENAS association plays in this.

2 DEALING WITH CHALLENGES OF RADIATION PROTECTION RESEARCH AND INNOVATION

Research and innovation in radiation protection enhance basic knowledge and enable the development of new ideas, designs, services and products and contribute to the advancement of radiation protection rules and guidelines for better life and health. Radiation protection is of importance in a plethora of exposure contexts. Medical therapy and diagnosis using ionising radiation, though beneficial, lead to exposure of patients, medical staff and public, and requires the production and manipulation of sources/radiopharmaceuticals and radioactive waste. Nuclear energy applications result in exposures over the entire nuclear fuel cycle; other industrial applications of ionising radiation not related to medical applications include industrial and scientific applications of ionising radiation and military uses. Many natural resources contain naturally occurring radionuclides (Naturally Occurring Radioactive Materials or Technically Enhanced NORM), which potential of exposure during the whole life cycle and which is an issue to consider in the context of renewable energy production. Last but not least natural radiation is responsible for about half of the population's exposure to radiation and requires attention in high background areas, but also includes cosmogenic radiation relevant in aviation and humans in space.[23]

The purpose of radiation protection is to provide an appropriate level of protection for humans and environment without unduly limiting the beneficial actions giving rise to radiation exposure. Therefore research and innovation is essential to allow to define the correct balance. To do so without being perceived as a purely regulatory obstacle radiation protection research should be connected to these innovation processes early on. Since techniques, technologies, activities, perspectives change, radiation protection and radiation protection research and innovation should be in pace with the evolutions in society. There is actually a high social demand for better protection of humans (and the environment) from hazards generated by modern technologies that include ionising radiation.

2.1 The rapid development of applications making use of ionising radiation is beneficial for the improvement of medical diagnosis and treatments, but also quality and safety need to remain a high priority

In parallel to the development of nuclear energy, non-power applications of ionising radiation have become key tools for exploring matter and improving health (SAMIRA Council Conclusions[24]; EC DG ENER[25]). Over the years, health has become the most important non-power application area routinely using ionising radiation in imaging and therapeutic applications with actual developments paving the way for personalised and targeted medicine. Medical procedures account for nearly all (>95 %) human exposure to man-made radiation[26],[27].

23 https://www.concert-h2020.eu/deliverables/integrating-activities#anchor-d3 – D3.7
24 https://www.consilium.europa.eu/en/press/press-releases/2019/06/06/the-council-underlines-role-of-non-power-nuclear-technologies/
25 https://ec.europa.eu/energy/studies/european-study-medical-industrial-and-research-applications-nuclear-and-radiation-technology_en?redir=1
26 https://remon.jrc.ec.europa.eu/About
27 https://www.nrc.gov/about-nrc/radiation/around-us/doses-daily-lives.html

Ionising radiation is an essential component of modern healthcare as part of the diagnosis and management of many diseases and medical conditions. It is used primarily in diagnostic and interventional radiology, nuclear medicine, and radiotherapy but also in other settings such as cardiology. Nuclear medicine provides huge benefits as it yields a.o. more precise information than exploratory surgery and offers the potential to identify disease in its earliest stage, yet the significant rise in the use of computed tomography (CT) and hybrid imaging over recent decades also raises concerns. In particular, concern relates to the potential for improper utilisation and suboptimal justification and optimisation practices. The rise in high dose interventional radiology and cardiology procedures performed outside of imaging departments also poses challenges from an occupational protection perspective. The increase in complexity of equipment and techniques in radiotherapy and the increasing access to high-level equipment has increased the number of patients who access radiotherapy as a key component of their treatment approach; tailoring of optimal treatment requires a high level of accuracy and is dependent on sufficient numbers of appropriately trained and educated staff. Theranostics is an emerging diagnostic and treatment technology. In order for such novel combination strategies to become part of the everyday treatment routine, substantial advances are needed in understanding the interactions between radiation and treatment modalities, especially regarding potential toxic effects of normal tissues. Another example where cutting-edge know-how across multiple disciplines is required is the justification of large-scale prevention programs where the benefits of earlier detection must be continuously balanced with the added “harm” that is created by the large-scale application of ionising radiation diagnostics (e.g., large scale mammography programs or emerging breast cancer prevention systems).

The potential risks of ionising radiation for patients and staff require the utmost concentration on good and safe clinical practice in the field. Radiological protection ensures justification and optimisation of medical applications and balances the expected benefit of the use of ionising radiation for the patient with the protection of their health from harmful effects of ionising radiation. Therefore, it allows optimising the benefit/risk ratio for medical use of ionising radiation including the possibility of personalised medicine. The optimisation of existing clinical applications and the development of new applications using ionising radiation must be driven by clinical needs and radiation protection must be considered right from the beginning.

Meaningful developments of medical radiation technologies should rely on cutting edge know-how in the fields of medicine, radiation physics and radiation biology. Successful examples include the PODIUM[28] project of CONCERT[29] and new detector designs for nuclear medicine based on the MADEIRA[30] project or optimisation tools developed within the MEDIRAD[46] project.

We should assess and address barriers for the transfer of bench developments into clinical practice and minimise differences throughout Europe.

[28] https://podium-concerth2020.eu
[29] https://www.concert-h2020.eu/
[30]https://cordis.europa.eu/project/id/212100/reporting/it

There is need for further research to increase the safe use of radiation in medicine. We should define standards for justification of applications and benefit-risk evaluations of procedures guaranteeing the best possible radiation protection for patients and staff everywhere in Europe based on dedicated R&D. This will also be contributing to the European objective of emerging as a global leader in the use of ionising radiation in medicine through innovation. Patients will benefit from the improved safety of medical radiation applications and improved knowledge on potential radiation side effects will contribute to higher degree of confidence in the process of shared decision making regarding the choice of optimal medical interventions.

A wide range of skilled personnel (researchers, engineers and technicians, radiographers, radiologists, medical physicists, dosimetry specialists, nurses, etc.) are needed to implement medical applications. The medium-term threat of a skilled-personnel shortage is shared by European Institutions, as well as by health, industry and research stakeholders, all echoing the same finding in the nuclear-energy field. Thus education and training challenges need to be addressed.

2.2 The protection of human health and the environment against the dangers of ionising radiation is at the heart of Global and European strategies and an integral part of a sustainable economy

There is growing concern among European citizens about human and environmental health and we should provide answers to these concerns as it is done for other stressors (like chemical toxicants). Since exposure to radiation and radionuclides has a potential impact on human and environmental health alongside other known stressors, radiation protection should not be considered in isolation but with a holisitic view, using the "exposome" concept[31].

The 8th Environmental Action Programme (EAP) conclusion "Turning the Trends Together" note that the EU is committed to a high level of protection of the environment and human health and to the improvement of the quality of the environment. The field of environmental health research has undergone important changes recently, driven part by 1) the unifying vision of the exposome which aims to consider all environmental exposures from conception to death, and 2) the One Health concept which aims to promote a more integrated, systemic and unified approach to human and ecosystem health. A major outcome is the current development of the Health Environment Research Agenda for Europe (HERA). As part of this agenda, environmental and occupational exposures to low doses of ionising radiation, including from (but not limited to) radon and medical exposures have been clearly identified. Radiation protection research and innovation needs to be in line with these international and European strategies.

[31] https://www.humanexposome.eu/

In December 2019, in parallel with the Green Deal Communication, a political agreement between the European Parliament and the Council on the creation of the world's first-ever "green list" classification system for sustainable investment was endorsed. The 'Taxonomy' regulation provides a general framework to allow the progressive development of an EU-wide system for sustainable economic activities. Through innovative research on the impact of ionising radiation on humans and ecosystems, we can provide scientific input to the extensive technical work called for by the Technical Expert Group. This will be of particular importance in assessing potential environment or health impacts related to the use of nuclear energy, particularly in future developments (e.g. small modular reactors) but even more so in context of other sources of energy (e.g. rare earth mining and ore handling for green and renewable energy technologies[32], geothermic energy production) where workers, public and the environment may be exposed to NORMs.

2.3 Emergency preparedness needs continuous sustained cross border efforts and innovations

The nuclear power plant accidents in Chernobyl (1986) and in Fukushima-Daiichi (2011) remind us that a combination of multiple low probability events can lead to disaster. While all the Sustainable Development Goals (SDGs) are relevant for building a sustainable and resilient world, several have targets directly or indirectly related to disaster risk reduction. Implementing the SDGs also contributes to achieving the goal of the 2015-2030 United Nations Sendai Framework for disaster risk reduction. This Framework outlines four priorities: (1) understanding disaster risk; (2) strengthening governance to manage disaster risk; (3) investing in disaster risk reduction for resilience and; (4) enhancing disaster preparedness for effective response and to "Build Back Better" in recovery, rehabilitation and reconstruction. Although much has been done since the Chernobyl and Fukushima-Daiichi accident to improve preparedness in case of a nuclear or radiological accident, much more has to be achieved in this field in relation to new threats or new installations and devices using ionising radiation. Harmonisation efforts in risk analysis and mitigation for cross-boarder accidents and risks are essential as seen in the current Ukrainian crisis. The rapidly and unexpectedly changing geopolitical context and the threat for use of tactical or strategic nuclear weapons call for an unprecedented European emergency preparedness readiness level.

As the world seeks low-carbon replacements for (ageing) fossil-fuel-fired plants in the context of combating climate change, interest in next generation reactors, such as SMRs and micro-reactors, as part of a hybrid energy system, is growing. We need to consider aspects specific to the design, deployment and operation including handling of waste of these new technologies, from both a nuclear safety and nuclear security perspective, to better inform decisions on both operational and emergency arrangements and on human and environmental protection. Keeping societies informed of new developments and new needs will be essential to ensure public acceptance.

[32] https://hir.harvard.edu/not-so-green-technology-the-complicated-legacy-of-rare-earth-mining/

2.4 Easy access to research infrastructures, education and training (E&T) are key to maintaining and developing excellence in radiation protection research

European excellence in the field of radiation protection research is internationally recognised. One reason is that Europe was able, across time and thanks to national and European efforts, to maintain and develop specific infrastructures that are of prime importance for research activities. These infrastructures include so-called large infrastructures e.g. lab and field exposure facilities for animal and plant experiments; epidemiological cohorts; clinical cohorts; biobanks and imaging biobanks; databases and analytical platforms. The inventory of European infrastructures and future needs established during the CONCERT EJP revealed that most infrastructures required for tackling current radiation protection challenges are available within Member States and Associated Countries. We need to ensure their continued access by maintaining visibility and assuring sustainability beyond national short-term constraints and, last but not least, to support cross-border exchange of students and researchers for their optimal use. This will be tackled both by PIANOFORTE (see 4) and OFFERR (see 5).

2.5 Research and innovation is key for improving radiation protection science-based regulation and standards and meeting stakeholders´ expectations

Exploitation of research takes place via various routes and impacts in numerous ways including the development of recommendations and standards and providing new methods, models, products and services to support radiation protection practices in industry, hospitals etc. Radiation protection standards in Europe and elsewhere are highly dependent on scientific knowledge that is reviewed in cycles by UNSCEAR, by international committes (ICRP, IAEA, IRPA), European committees (e.g., EURATOM Article 31 Groups of experts). The acquisition of new scientific knowledge through research is therefore a crucial element in improving radiation protection standards for the public, the environment, radiation workers, and persons in the medical field (patients and staff). Although current radiation protection standards are generally judged to be acceptably robust, there remains considerable scientific uncertainty regarding human health risks at low doses and/or low dose rates, and to the ecosystem health now recognised as strongly interconnected with human health[33].

The system of radiation protection is based not only on science but also on values and experience. Values are addressed by the ethical and societal principles for protection with the three principles of protection being: justification, optimisation and limitation. The communication of risks, risk assessment and management of protective strategies with the public, workers and among stakeholders is crucial.

Science underpins the European BSS. While supporting the implementation of the BSS requirements, continuous research is also needed to test the adequacy of the requirements and to propose improvements to such requirements and their implementation. In this sense, radiological protection is an essential component of the EURATOM program. It enables technology development, good professional

[33] https://www.who.int/publications/i/item/9789241565196

practice and effective regulatory supervision through the EURATOM BSS Directive and links scientific experts across Europe and beyond on a cost efficient basis.

3 LINKS WITH PREVIOUS PARTNERSHIP AND ROLE OF MEENAS

About ten years ago, a major concern in the field of radiation protection research was the fragmentation of research activities and the decline of research resources at the European level. Since then, a remarkable reorganisation of the European radiation protection research landscape has taken place. Platforms in different fields of radiation protection were established: MELODI[34] for low dose effects, ALLIANCE[35] for radioecology, NERIS[36] for nuclear and radiological emergency response and recovery, EURAMED[37] for radiation protection in medical applications and SHARE[38] for social sciences in radiation protection research, EURADOS[39] for dosimetric aspects had already been established before. Strategic research agendas (SRAs) were developed together with roadmaps. While the individual platforms have brought together European scientists and consolidated their strategies, there has been in parallel an increased collaboration between the platforms within the integrative work packages of the CONCERT EJP[29] to develop priorities and, as a final product, a joint roadmap[23] (JRM). More than 200 organisations are members of the six thematic platforms and more than 90 entities were involved in CONCERT. They have joined their forces to create and update the strategic agendas.

The JRM reflects the broad spectrum of societal and scientific issues requiring consideration by the radiological protection research community and presents a view of the collective challenges in the context of existing and potential exposure scenarios,. Eight Joint Research Challenges were identified: 1) Understanding and quantifying the health effects of radiation exposure; 2) Improving the concepts of dose quantities; 3) Understanding radiation-related effects on non-human biota and ecosystems; 4) Optimising medical use of radiation; 5) Improving radiation protection of workers; 6) Integrated approach to environmental exposure and risk assessment from ionising radiation; 7) Optimise emergency and recovery preparedness and response; 8) Radiation protection in society.

The research challenges cover many disciplines, requiring collaboration of researchers from different platforms. Within these research challenges, the joint roadmap presents 'game changers', defined as research issues that, when successfully resolved, have the potential to impact substantially and strengthen the system and/or practice of radiation protection for man and/or the environment through 1) significantly improving the evidence base, 2) developing principles and recommendations, 3) developing standards based on the recommendations and 4) improving practice. The JRM provides a solid basis to define priority areas and strategic objectives for mutual cooperation and a vision and role for a European radiation protection research programme to 2030 and beyond. This will also be reflected in the SRA and the roadmap currently

[34] https://melodi-online.eu/
[35] https://radioecology-exchange.org/
[36] https://eu-neris.net/
[37] https://www.euramed.eu/
[38] https://www.ssh-share.eu/
[39] https://eurados.sckcen.be/

developed for research on medical uses of ionizing radiation within EURAMED rocc-n-roll project[45].

In order to improve further the coordination of radiation protection research, the six European Radiation Protection platforms are now structured under the MEENAS[40] umbrella structure. This structure, formalised in 2020 by the signing of a Memorandum of Understanding by all platforms, aims to 1) promote the integration and the efficiency of European R&D in radiation protection to better protect humans (public, patients and workers) and environment; 2) advance scientific excellence; 3) maintain and develop European research capacity; 4) encourage scientific education and training and foster key research infrastructures in the field of radiation protection; 5) foster international collaboration and collaboration with organisations and networks in a non-exclusive manner by open interaction with the wider research community and stakeholders.

4 PIANOFORTE

The EURATOM dynamics during the past decade in the field of radiation protection research demonstrate the increasing capability of the scientific community to use the development of thematic platforms as well as the use of European funding instruments, including with national co-funding mechanisms for the required inter- and multi-disciplinary work. A multi-annual programme is required for an optimised implementation of the research activities to tackle the highly multidisciplinary challenges which call for a supra national coordination and collaboration in order to improve efficiency and to avoid duplication. A vision document was created under guidance of MEENAS by some national organisation in charge of radiation protection and in close interaction with the entire European radiation protection community. A co-funded Partnership established for several years was presented as the best approach to ensure an efficient coordination and optimised planning of research activities through a long-term call planning system to address and realise the challenges[41]. This long-term vision also demands introducing some flexibility as the JRM (and associated challenges) should be considered as a living document regularly up-dated considering, on the one hand, advances and developments that affect the research needs and, on the other hand, the apparition of new scientific challenges (e.g. development of new radiopharmaceuticals or radiotherapy and imaging techniques, AI based methodologies or new nuclear reactor technology such as small modular reactor) which may need specific research actions or societal concern. The instrument of a co-funded partnership ensures that the European member states are heavily involved in aligning their national research and funding priorities with the overall ambitions and challenges of radiation protection research.

The bundling of necessary resources could only be achieved via a European co-fund Partnership and project and a EURATOM call for a partnership in radiation

[40] https://eu-meenas.net/doku.php

[41] https://eu-meenas.net/lib/exe/fetch.php/vision_doc_v1.4.pdf

protection research was launched (NRT-01-09). By building further on the remarkable RP integration effort, a Partnership could tap into all available national expertise and stakeholders in the field of European radiation protection research. The call was answered by the PIANOFORTE partnership which was reviewed very positively and that will kick-off in June 2022.

4.1 Ambition of the PIANOFORTE partnership

The PIANOFORTE Partnership will consolidate an EU-wide research and innovation community in the field of radiation protection, to support EU and national authorities and to ensure progress with new knowledge, innovative methods and technologies and skills to address current knowledge gaps, societal concerns and emerging issues[24]. An integrated approach to radiation protection research, exploiting synergies between various areas of expertise, including cancer diagnosis and treatments, is required to realise maximum benefits and outcomes. The Partnership will enable coordination and more efficient research efforts, in particular, those regarding the risks associated with medical, industrial or environmental exposure, and on emergency management in relation to accidents involving radiation. The vision is to provide a pan-European scientific and technological basis for a robust system of protection and advance science-based policy recommendations to decision makers. In the long term, the efforts will translate into novel or improved practical measures to give better outcomes for patients suffering from cancer and for a better protection of people (public, workers and patients) and the environment.

PIANOFORTE builds on a history of integration and consolidation in the European radiation protection research landscape. The experience acquired when implementing several FP7 projects (DoReMi[42], OPERRA[43] and COMET[44]), the H2020 CONCERT EJP[29] and the on-going H2020 research programmes (EURAMED rocc-n-roll[45], MEDIRAD[46], HARMONIC[47], RadoNorm[48], SINFONIA[49]) is assuring the capacity and quality of many national radiation protection programmes and supporting national research schemes.

PIANOFORTE seeks to have an impact on radiation protection of humans and the environment in many ways. For example, the results of the research activities will support the implementation of the European Basic Safety Standards (BSS), to manage new requirements and harmonise practices throughout Europe. The holistic approach covers both fundamental science for exposure and effects, risk assessment, perception and management, as well as development of measurement techniques, innovative tools, methods and best practices to cope with the existing and emerging issues related to radiation exposure, thus creating

[42] https://melodi-online.eu/doremi/overview/
[43] https://melodi-online.eu/operra/
[44] https://cordis.europa.eu/project/id/604974
[45] https://roccnroll.euramed.eu/
[46] http://www.medirad-project.eu/
[47] https://harmonicproject.eu/
[48] https://www.radonorm.eu/
[49] https://www.sinfonia-appraisal.eu/

a major impact for society. Research is needed for risk prediction in specific situations and for foresight, to anticipate potential exposures.

Young, well-trained experts in the radiation protection research field are needed to supply the society with well-grounded expertise, leading to improved social capital in the EU. Critical infrastructures need to be supported and access to these infrastructures should be possible for the whole radiation protection community.

Additionally, PIANOFORTE aims to coalesce and combine national efforts by all Members States to guarantee an optimised radiation protection level of its citizen and at the same time provide other services that are enabled by ionising radiation, especially in the field of medicine. In that sense, part of the Partnership will be dedicated to support the "Europe's beating cancer plan" - a main priority of the von der Leyen Commission and a key pillar of a strong European Health Union. Indeed, it is of the utmost importance for the system of radiological protection to optimise medical applications of ionising radiation and to harmonise practices throughout Europe, especially to balance the protection of human health from harmful effects of ionising radiation with the potential benefit of the use of ionising radiation for the individual patient. This is especially true for the diagnosis and treatment of cancer. The ultimate goal is to optimise the use of ionising radiation for the diagnosis and treatment for each patient on an individualised approach based on individual risk and sensitivity in a standardised way throughout Europe.

Through this Partnership, EURATOM will strengthen radiation protection communities across academia, national research institutes, industry, hospitals and authorities and will multiply the success been made in the last decade. It will better serve communities across all Member States, and a strong stakeholder and end-user-based focus in the co-funded research will enable scientific innovations to translate rapidly into improvements of quality of life and health for European citizens.

4.2 Research needs addressed by PIANOFORTE

In line with NRT-01-09, research needs addressed by PIANOFORTE are as follows:

Priority 1: To improve the prevention, detection and safe treatment of cancer in contribution to "Europe's beating cancer plan" the Horizon Europe "Cancer" Mission.

PIANOFORTE, through its research activities will provide inputs to at least two recommendations by the recent "Report of the mission board for cancer" namely: "advance and implement personalised medicine approaches for all patients in Europe" and "develop an EU-wide research programme on early diagnostics and minimally invasive treatments". Bridges with Partnerships "ERA for health", "Personalised medicine", "Artificial intelligence, data and robotics" and "Metrology", and their associated social and ethical dimensions would also be beneficial. Links with ongoing projects like EURAMED rocc-n-roll[45] and the SAMIRA initiative will be established and further institutionalised to maintain a close sustainable connection. R&I needs in radiation protection associated with this overarching challenge consist of:

- Developing a knowledge base and analytical tools for major features of variability in the radiation response, including radio-sensitivity, radio-susceptibility and radio-degeneration, radio-induced immune-response, in humans and ecosystems;

- Paving the way to personalised medicine, including factors of gender and age as part of individual radiation sensitivity, susceptibility and degenerative fragility;

- Harmonising practices throughout Europe especially with respect to the protection of human health from the harmful effects of ionising radiation and with respect to the potential benefit of the use of ionising radiation for the individual patient;

- Optimising protocols to improve patient protection also by use of AI techniques;

- Developing science-based recommendations procedures and tools for improving radiation protection of patients and staff and assuring transfer of new and optimised medical procedures into medical practice

- Robust consideration of patient concerns, trust and limitations to personalisation.

Priority 2: To consolidate regulations and improve practices in domains using ionising radiation by capturing low-dose research advances in support of the BSS implementation and of the EU Green Deal objectives, specifically to ensure the sustainable transition "while also protecting citizens' health from environmental degradation and pollution, and addressing air and water quality". This ambition is shared again with the "Health" cluster. Radiation protection R&I needs are:

- Improving risk estimates for justification of practices and optimisation of radiological protection of members of public, patients, workers, environment in all exposure situations;

- A better understanding and quantification of low-dose effects on human health and ecosystems through mechanistic approaches as well as new instruments and tools for the radiological monitoring of the environment;

- Advancing state-of-the-art understanding of link between exposure characteristics and cancer and non-cancer effects, including optimised detection and dosimetry;

- Advancing integrative radiobiology from basic mechanisms to clinic and epidemiology, to further characterise and evaluate ionising radiation effects;

- Facilitating uptake of research results by decision makers and regulators to improve protection of workers, public, environment by science-based policy recommendations.

Priority 3: To improve the anticipation and resilience in case of radiological or nuclear event and the management of legacy sites by providing a scientific basis to recommendations, procedures and tools in support of the Action plan on the Sendai Framework for disaster risk reduction.

This challenge contributes to the EU objective of creating "a resilient and more stable Europe that protects" and research performed during the Partnership will be closely connected to the Horizon Europe "Civil security for society" cluster that is aimed at an "improved disaster risk management and societal resilience" through better understanding of natural and man-made disasters and by the development of novel concepts and technologies to counter these risks or alleviate the consequence. It will also be closely connected to activities developed in the "food, natural resources, agriculture, and environment, biodiversity" cluster one of the objectives of which is "reducing environmental degradation and pollution". Links with the Partnership on Metrology will be established. R&I needs in radiation protection associated with this challenge are:

- Development of robust prediction models of radiological contamination in the environment for an integrated dose and risk assessment;

- Optimisation of emergency and recovery preparedness and response using AI;

- Improvement of stakeholder's involvement strategies; including the communication of results of radiological protection to non-specialist audiences;

- Optimisation of processes and values such as reasonableness and tolerability.

4.3 General, specific and operational objectives

The general objective of PIANOFORTE is to improve radiological protection of members of the public, patients, workers and environment in all exposure scenarios and provide solutions and recommendations for optimised protection in accordance with the BSS. This objective will be reached by multidisciplinary research, innovation and citizen involvement activities in a collaborative approach of scientists, regulators and stakeholders. Research projects focusing on identified research and innovation priorities will be selected through competitive open calls. The general objective will be reached through the achievement of six specific objectives (four scientific and two integration specific objectives) that are presented below. The four scientific specific objectives are aimed at tackling the three priorities defined in 4.2.

Scientific specific objectives

- Innovate in ionising radiation based medical applications combating cancer and other diseases by new and optimised diagnostic and therapeutic approaches improving patient health and safety, by new AI and ML based technological developments and supporting transfer of the R&I outcome to practice.
- Improve scientific understanding of the variability in individual radiation response and health risk of exposure.
- Support regulations and implementation of the BSS and improve practices in the domain of low dose exposures of humans and the environment by better understanding and reducing uncertainties in risk estimates.
- Provide the scientific basis to recommendations, procedures and tools for assuring better preparedness to response and recovery from a potential radiological event or nuclear accident and to improve the know-how to manage legacy sites thereby exploiting AI and big data technologies.

Integration specific objectives

- Maintain a sustainable expertise capability on radiation protection issues across the EU by fostering the availability, the use, and the sharing of existing state-of-the-art infrastructures at European level and beyond, and conducting education and training activities.
- Involve all relevant stakeholders at the different stages of the implementation of research projects and assure efficient dissemination, knowledge management and uptake of results.

4.4 Main concept of PIANOFORTE

The objective of this Partnership is to conduct research activities that address current and future scientific and technical challenges to improve radiation protection practices, enable better implementation of BSS and ultimately ensure better protection from ionising radiation. As recommended by the EURATOM STC, more than 75% of the Partnership's budget will be dedicated to research with the remainder allowing for better access to national infrastructure, education and training and dissemination and exploitation of results. The methodology of the partnership is summarised in Figure 1 and is based on a five-step iterative process:

Step 1 – Prioritisation. This step defines priorities for an open call for proposals. Priority setting will be done in a comprehensive, transparent process involving both the scientific community and wider set of radiation protection stakeholders/target groups.

Step 2 – Open Call for proposals allowing entities inside and outside consortium to respond (third parties).

Step 3 – Research project implementation emphasising shared infrastructures deploying education and training programs, with involvement of stakeholders.

Step 4 – Outputs. The projects and integration activities will produce outputs including: peer-reviewed publications, reports, codes, experimental data, protocols, etc.

Step 5 – Outcomes. A crucial point of the projects will be the transfer from outputs into outcomes that will have impacts on the different target groups.

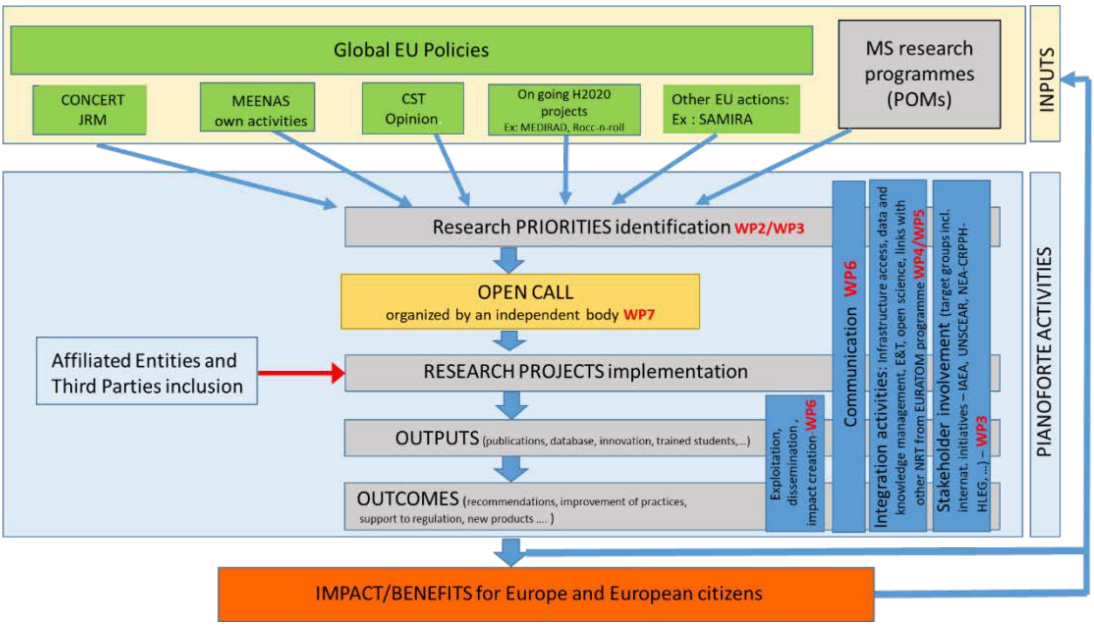

Figure 1: Methodology of PIANOFORTE Partnership and interaction between the different work-packages (not further detailed here)

4.5 Impact

Through the implementation of research projects selected through the open call system, PIANOFORTE will create outputs in various forms such as publications, reports, database, innovation, training packages, prototypes, trained students, infrastructure network, protocols, models, tools, codes, etc. It will be a main task of PIANOFORTE to exploit and disseminate all knowledge in the most appropriate form to the different target groups, including government authorities, experts in radiation protection and related disciplines, National Program Owners / Managers (POMs), civil society and affected communities.

5 MAXIMIZING INTEGRATED RADIATION PROTECTION R&I

5.1 Collaboration opportunities within EURATOM Work programme 2021-2022

The need to establish links between different strands of the EURATOM 2021-2022 work programme was explicit and contact was made with coordinators of several proposals to various NRTs, including NRT-01-01: Safety and operating nuclear power plants and research reactors; NRT-01-07: Development of tritium management in fusion and fission facilities; NRT-01-10: Safe use and reliable supply of medical radionuclides; and NRT-01-12: European facility for nuclear research; NRT-01-13: Towards a European nuclear competence area.

Several successful outcomes have followed from these early-stage contacts. For example, MEENAS is involved in the user group of OFFERR (NRT-01-12). The objective of OFFERR (eurOpean platForm For accEssing nucleaR R&d facilities) is to support the SNETP Association to establish a scheme facilitating access for R&D experts to key nuclear science infrastructures ("User Facilities"). The beneficiaries of the scheme will be (i), the User Facilities - funded directly from OFFERR for their services and (ii) the research teams that successfully applied through open calls to access the User Facilities. MEENAS representatives within the consortium will assure integration of crucial radiation protection and medical applications facilities.

Other example, MEENAS partner SHARE is centrally involved in ECOSENS - Economic and Societal Considerations for the Future of Nuclear Energy in Society, a reply to NRT-01-14 - Socio-economic issues related to nuclear technologies.

The European Radiation R&I community is also, via SHARE, involved in the EC project HARPERS – Harmonised practices, regulations and standards in waste management and decommissioning in reply to NRT-01-08 (Towards an aligned harmonised application of international regulatory framework in waste management and decommissioning)

MEENAS will act as stakeholder in the SNETPFORWARD project (call NRT-01-16 Support for the Sustainable Nuclear Energy Technology Platform to address cross-sectoral challenges and non-power applications of ionising radiation). Objectives are threefold: (1) Reinforce SNETP Committees structuration and processes; (2) Strengthen SNETP cooperation activities with EU & international stakeholders, and (3) Foster innovation within EU nuclear community. We will further liaise with SNETP and its pillars (e.g. NUGENIA). The Sustainable Nuclear Energy Technology Platform is a research, development and innovation platform that supports and promotes safe, reliable and efficient operation of the civil nuclear systems by facilitating the cooperation among its members. SNETP is recognised by the European Commission to act as a key stakeholder in driving innovation, knowledge transfer and European competitiveness for all nuclear power and non-power applications. A cooperation scheme between MEENAS and SNETP is established.

At large, the radiation protection community will search for maximal integration within EURATOM. Liaising across EURATOM is important not only to increase our relevance, impact and network but also to increase the R&I revenue which is for the next 7 years so far only guaranteed with funding within PIANOFORTE. If this will be truly the case this might imply a decrease in total annual funding from ca 12 M€ per year in 2020-2024 to ca 7 M€ (including co-funding) thereafter.

The radiation protection research community needs to creatively apply its expertise, models, tool, techniques in tracer studies for monitoring climate change and its effects, monitoring environmental pollution or processes like sediment relocation, circular and sustainable energy resources and circular economy and associated environmental protection and monitoring, monitoring and evaluating radiological impact in REE exploration and exploitation (also in context of renewable energy technologies).

5.2 Links and collaboration opportunities with other EU programmes

As mentioned above, links should be established with several other EU programs, often partnerships, within the "Health", "Civil security for society" and "Food, natural resources, agriculture and environment, biodiversity" clusters. A particular effort during this partnership will be made to establish links, in the form of dedicated contact points or working groups, with the HEALTH cluster in order to create synergies in the field of the use of ionizing radiation in medicine and in particular in the field of better protection of the patients. One example for this is a specific stakeholder-oriented research question for the radiation protection community to address with respect to clinical guidelines for proton therapy. PIANOFORTE will make a substantial contribution in coming years to the 'Europe Beating cancer' plan and the implementation of the SAMIRA initiative. Most of the fundamental research questions arising in radiation protection need to be dealt by the Partnership. Any supplementary actions will be implemented in synergy with Horizon Europe's Health cluster, Mission on Cancer, and guided by the research roadmap (expected in 2023) as well as feedback from SAMIRA initiatives. Interaction with SAMIRA and the Health programme and DG SANTE is quintessential for European radiation protection.

The importance of interaction with these other programmes has to be highlighted. EURATOM and the radiation protection community (MELODI, ALLIANCE, NERIS, EURADOS) through EJP CONCERT enforced the (re-)integration of the medical radiation protection sector and invited the participation of social science and humanities because of the important contribution of medical applications using ionising radiation in diagnostics and therapy to the overall average radiation dose to the public (much higher contribution for individual patients and medical personnel), which is only increasing. EURAMED and many organisations involved in radiation protection research are already involved in the EU4H project I-Violin – "Imaging optimisation and standardisation, oncology diagnosis and treatment, computed tomography, equal access in EU healthcare, radiation protection and dosimetry, education and training", with the objectives to satisfy the need to optimise and harmonise oncologic imaging procedures in Europe and to disseminate the image quality assessment tool developed in MEDIRAD for chest

CT after adjustment of it for imaging procedures in the abdominal and pelvic regions in hospitals throughout Europe Together with dose evaluation tools this will allow meaningful optimisation of imaging procedures in oncological treatment in terms of optimised benefit risk ratios in the context of imaging procedures with relevant contributions to exposure especially in cases with repeated imaging in patients.

This Europe-wide multidisciplinary co-operation in radiation protection is critical to assure public (patient and medical personnel) health and welfare. Some other programmes of the health sector has been identified in which radiation protection research improving the risk prevention by better understanding of effects of ionizing radiation and better protection against it can play a significant role. Especially, as ionizing radiation can be seen as a cross-border threat to human welfare.

Apart from the health programme, our community will more strongly than in the past evaluate contributions to the Climate-Energy- Mobility programme, the Digital-Industry-Space programme and the Food-technology-Agri-Environmental programme and evaluate how we can contribute the space research, improving the benefit/risk ratios in medicine, (risk) communication and ethical aspects, quality assurance, control and management, valuating new technologies in all these fields plus AI.

5.3 Other international activities

Concerns about the fragmentation of radiation protection research and a decline in research funding is not specific to Europe. Similar concerns have arisen in Asia and in North-America, especially in the low-dose research domain. To overcome this fragmentation, Japan launched the Planning and Acting Network for Low Dose Research (PLANET) and the United States, the International Dose Effect Alliance (IDEA). OECD/NEA/CRPPH, has launched the High-Level Group for Low-Dose Research (HLG-LDR) to build a global network that facilitates collaboration among ongoing and planned low dose ionising radiation research programmes. A permanent dialogue between PIANOFORTE members and the HLG-LDR will be established in order to leverage European influence in this key area.

In the field of dosimetry, the Asian Radiation Dosimetry Group (ARADOS), which is a voluntary network launched by Korea, China and Japan, has the goal of promoting research and development among Asian countries in the field of ionising radiation.

In the field of emergency response and recovery, NEA has set up a standing working party with a focus on the organisation of the INEX exercises covering the different phases of emergency and recovery. WHO has established the collaboration network REMPAN, to share information and to advocate for the radiation-emergency related activities of the network member institutions. The IAEA supports effective emergency preparedness and response capabilities on a national and international level, through the development of safety standards, guidelines and technical tools and training. IAEA further has a well-established programme on environmental modelling and impact and risk assessment and on-site and environmental remediation (ENVIRONET) as well as a health care support programme. Collaborations with MEENAS' constituent research platforms have already been set up and will be further developed within PIANOFORTE. The PIANOFORTE Partnership, when appropriate, will establish collaborative and/or coordination actions with all these networks, thus further promoting scientific debate and optimisation of resources.

6 CONCLUSIONS

Radiation protection R&I is quintessential for medical applications, sustainable energy and economy development, emergency preparedness especially in today's challenging geopolitical context, and for supporting regulation and standards. Radiation protection is of importance in a plethora of exposure contexts. An effective RP system must be based on advances in scientific knowledge in pace with societal developments. This requires a multi-annual effort and programme for an optimised implementation of the research activities to tackle the highly multidisciplinary challenges which requires a supra national coordination and collaboration.

MEENAS was successfully established to enforce radiation protection research and innovation in Europe and beyond and operates as single-voice of the six platforms on radiation protection research in Europe. MEENAS and the over 200 organisations it represents strongly welcome the EURATOM-Horizon Europe Partnership for Research in Radiation Protection which will serve as a foundation for helping to ensure the achievement of the set goals with high priority dedicated to 1) medical applications, as medical exposures are by far the largest source of man-made exposure of the European population and the fight against cancer is a top priority of H-EU; 2) better understand and reduce uncertainties associated with health risk estimates for low dose exposure; 3) strengthen a science-based European methodology for emergency management and long-term recovery, unknown at the time of writing but extremely relevant given the current geopolitical context; 4) education and training of next generation experts and an optimal infrastructure (use) base. Innovation will be our mission since it is essential for the European economy and societal progress. The competitiveness of the economy can be only guaranteed by effective knowledge exchange between research and industry.

This Europe-wide multidisciplinary co-operation in radiation protection is critical to assure public health and welfare. Liaison within the EURATOM and Horizon Europe programme (e.g. Health Cluster, DG SANTE, DG-ENER) will therefore be essential to optimise and maximise our role in radiation protection R&I, also in context of energy and economy sustainability and climate change. Still today funding for radiation protection research and innovation is linked with the EURATOM programme yet the limitation of radiation protection R&I funding to EURATOM is can only be historically explained since radiation protection is ubiquitous and quintessential also for Health and medical applications, Energy and Electricity production (REE, NORM), Space exploration, … Enhanced collaboration, integration, networking among and between programmes is needed and is critical to assure public (patient and medical personnel) health, welfare and progress.

7 AUTHOR CONTRIBUTION STATEMENT

Hildegarde Vandenhove took the leading role in the overall organisation manuscript. She wrote the main text which was based on sections of mentioned vision document[19] and the PIANOFORTE proposal with main and key contributions by Jean-Christophe Gariel, Filip Vanhavere, Hildegarde Vandenhove, Florian Rauser, Andrzej Wojcik. Valuable inputs and comments were received from Christoph Hoeschen, Susan Hodgson, Nathalie Impens, Andrzej Wojcik, Filip Vanhavere, Boris Brkljačić, Kristine Leysen (SCK CEN), Jean-François Bottollier-Depois.

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Review Article

Open Access

SHARE: Stakeholder based analysis of research for decommissioning

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Abstract. The H2020 EU-funded SHARE project (Stakeholders- based Analysis of REsearch for Decommissioning) is a forerunner to the establishment of a framework for collaboration on research activities related to the decommissioning of nuclear facilities. SHARE aimed to provide an inclusive roadmap for decommissioning research, in both technical and non-technical areas, in the EU and abroad, to enable stakeholders to improve jointly safety, reduce costs and minimise environmental impact. SHARE has been built on a consultation process considering the needs and perspectives of different stakeholders all across the decommissioning value chain. The project also considered existing and emerging innovative technologies solutions as well as the international best practices in the field of decommissioning. After a three-year process, the project provides a Strategic Research Agenda and a Roadmap built on the participation of the international Stakeholder community in a multi-step process including a questionnaire survey, a state-of-the-art review, a gap analysis and multiple workshops. As the final output, the SHARE roadmap effectively set the framework for organizing the priorities identified in the SHARE SRA.

1 Introduction

In Europe, the boom of nuclear power generation in the second half of the 20th century, incarnated by the Euratom treaty, gave rise to a strong nuclear industrial environment. As of March 2022, 119 nuclear power plants are operating in the European Union (EU), Switzerland and the UK contributing around 24% of the total electricity production [1,2] with a greenhouse gas intensity comparable to renewables around the whole lifecycle [3]. Additionally, many research facilities and fuel cycle facilities are operating, contributing to a total of 1.1 million jobs in the nuclear industry. Despite these significant strengths, nuclear power production has declined by over 25% since its peak at 930 TWh in 2004. Current plans foresee 50 European nuclear power plants in shutdown by 2025, which will then be decommissioned. The European Nuclear Illustrative Programme estimates a total budget of 263 Mrd€$_{2014}$ up to 2050 for decommissioning operations (123 Mrd€$_{2014}$) and radioactive waste management (140 Mrd€$_{2014}$) [4]. For perspective, this corresponds to 2% of the total GDP of the former 28 Member States in 2014 and 24% of the EU budget in the period 2014–2020. These numbers underline the importance of future decommissioning activities.

Decommissioning nuclear facilities is a significant task with technical and non-technical challenges including many Stakeholders: facility operators, supply chain industry, research organizations, regulators, technical support organizations, waste management organizations, universities, international organizations and consultants. Technical challenges exist because, while a certain level of maturity has been reached for many technologies used for operations in rather "standard" nuclear facilities, there remains room for optimization/cost reduction in characterization methods, dismantling techniques and waste management. Furthermore, there is a need for the

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development of innovative technologies for less common facilities such as graphite reactors or legacy waste facilities. Non-technical challenges exist because the organization of work and regulation during decommissioning are significantly different from the operational phase and will last for 20–30 years. Thus, decommissioning activities require the retention of historical site knowledge and the recruitment and development of new competencies as well as good supply chain management and a solid education and training network. Many of these challenges require an investment that might exceed the capacities of individual entities. Therefore, multilateral and international development and research projects that are underpinned by confidence and the understanding of the common interest are key for effective decommissioning.

The European Commission, convinced by this importance, decided to fund the Coordination and Support Action called SHARE (Stakeholder-based Analysis of REsearch for decommissioning) in the framework of the EURATOM nuclear fission research programme. The ambition of SHARE is to organise international efforts towards collaborative research and co-financing in decommissioning research, development and demonstration. To this end, the main objective is to provide a roadmap for collaborative research over the next 10–15 years so Stakeholders can jointly work to improve safety, reduce costs and minimise the environmental impact during the decommissioning of nuclear facilities. The data for SHARE is acquired by the iterative consultation of the international Stakeholder community. This point of view is complementary to the classical approaches that identify key issues in a top-down manner [5,6].

2 Project structure and methodologies

The foundation for the bottom-up approach is the global stakeholder community of nuclear decommissioning. Indeed, the understanding of the consortium formed by the CEA, Enresa, IFE, In Extenso, JRC, KIT, LEI, NNL, SCK-CEN, SOGIN, and VTT [7] is to make explicit the needs originating from the stakeholders. The consortium aimed to create a thorough frame for stakeholders to be able to express their needs. The work structure of the project that was created to this end is displayed in Figure 1.

The work packages WP5 and WP6 are overarching the whole project and concern project management and dissemination and communication. The main results were obtained in the four work packages WP1 to WP4. The task of WP1 was to work on the methodology of the project data generation and data processing. WP2 consisted of, (i) conducting a questionnaire survey among the Stakeholders to determine the importance and urgency of their needs and, (ii) weighing and analyzing the results. Almost simultaneously, WP3 reviewed the state-of-the-art of available solutions. In the frame of WP3, several interactive workshops with the Stakeholders lead to the combination of the results from WP2 and the state-of-the-art review. The outcome, in the form of collectively consolidated activities, is the content of the WP3 "Gap analysis" deliverable. Based on these results, WP4 worked on the presentation of the obtained data by providing a strategic research agenda and a roadmap for future development. The international stakeholder community showed active support and commitment throughout the project duration. As shown in Figure 2, almost 1000 Stakeholders engaged in or followed the project.

The main outcome of the first work package was the collection of a representative list of Stakeholders and the initial structuring of the decommissioning activities in eight thematic areas comprising 71 sub-thematic areas. Among them were three *non-technical areas*: safety and radiological protection (Q1), project management and costing (Q2), and human resources management (Q3); and five *technical areas*: characterization (Q4), site preparatory activities (Q5), dismantling technologies (Q6), environmental remediation and site release (Q7), and radioactive waste management (Q8). A complete list of the associated sub-thematic areas is presented in appendix Table A.1. In anticipation of later chapters, it is important to note that this structure evolved as the project progressed.

2.1 Questionnaire survey

The questionnaire survey was conducted online between March and July 2020 based on the methodology defined in WP1. First, the Stakeholders from the representative list were invited to complete the questionnaire which consisted of rating, on a scale from 0 to 5, the importance and the urgency of the eight thematic areas and the 71 sub-thematic areas. Stakeholders were additionally provided with the possibility to add free format comments. For completeness, the Stakeholders provided some profile-relevant data such as their country, their type of organization (Industry, Operator, University, Consultant, International organization, Research Org., Regulator, Standardization Org., Technical Service Org., Waste Management Org., Other), the number of employees of their organization, the type of facilities treated in their organization (Power Reactor, Research Reactor, Fuel Cycle Facility, Other) and the status of their current decommissioning activities (None, Planning, On-Going, completed/nearly-completed). Then, the collected responses were analysed, first, by weighting the Stakeholder opinion by their profile data and, second, by defining rating categories for the prioritisation of the (sub-)thematic areas.

For the weighting, first, the Stakeholders were categorised by their type of organization to, then, make the respondent population match the invited target population. I.e., overrepresented organizations were weighted lower and underrepresented organizations were weighted higher. As Figure 3 shows, a minor adjustment was needed since the populations matched well.

Second, the relevance of the Stakeholder opinion for the EU project SHARE as collectively determined by the consortiums allowed the weighting of the results further. To this end three different methods of collective evaluation were used [8]:

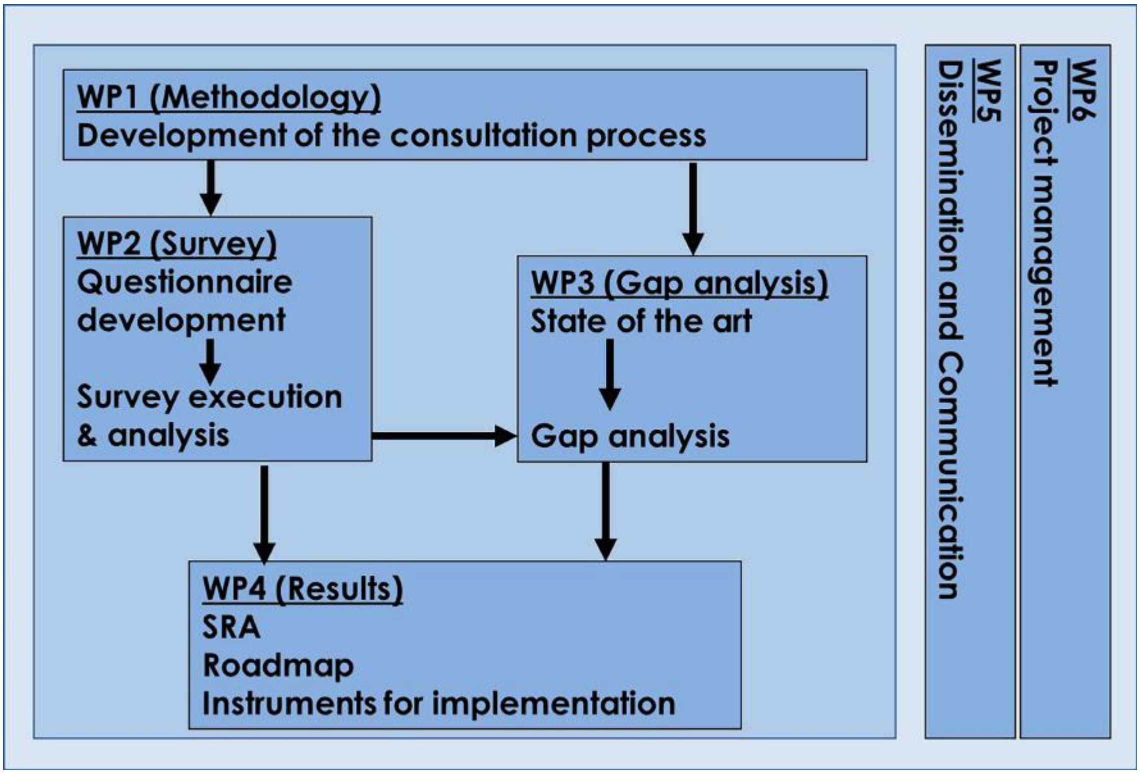

Fig. 1. Work structure of the SHARE project.

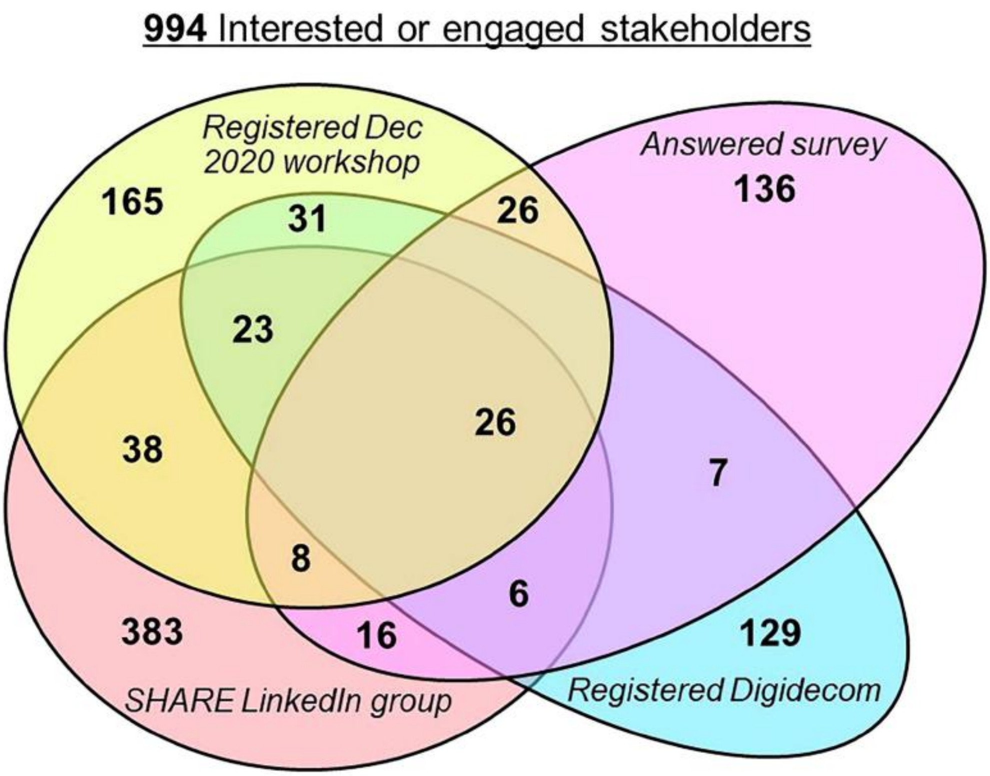

Fig. 2. Overview of the number of Stakeholder that engaged in or followed the project.

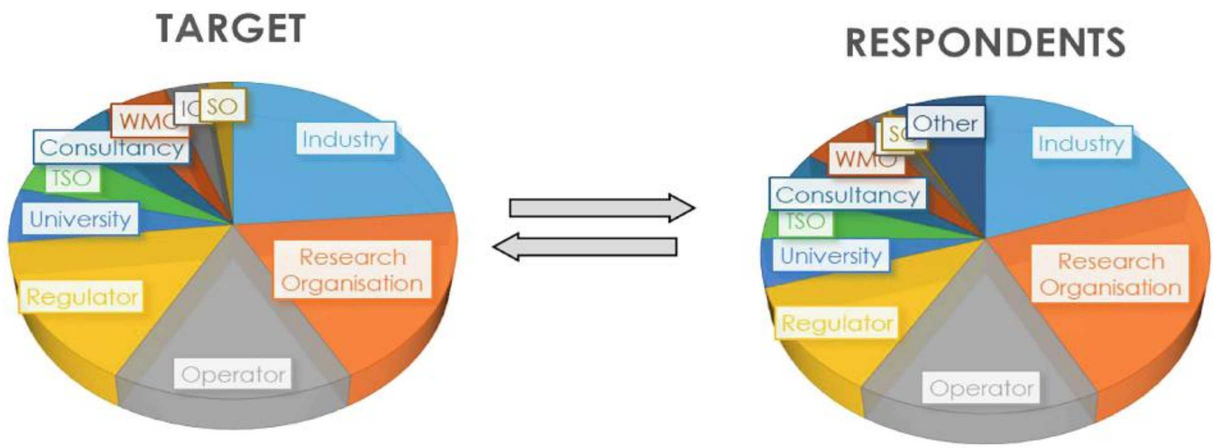

Fig. 3. The population of responding and targeted Stakeholders in the questionnaire survey by their type of organization.

- a pairwise comparison for the type of Stakeholder organization.
- The DELPHI method for the status of the decommissioning project.
- General Consensus for the regional factor.

Whatever the method, the maximum weighting factor was unity (1).

Then, the prioritisation of the (sub-)thematic areas required a pertinent method for categorizing the different ratings. To this end, three levels (low, medium, and high) were introduced for importance and urgency ratings. The (sub-)thematic areas are assigned to them depending on the share of "top 2 responses". This term refers to the sum of the shares of respondents rating a (sub-)thematic area either very important/urgent (rating "5") or important/urgent (rating ("4"). The threshold for medium importance and medium urgency was at 40% and 30% respectively and for high importance and high urgency at 50% and 40% respectively. For example, 46% of the respondents rated the thematic area "Q4 Characterization" "very important" and 33% ranked it "important" leading to a top 2 share of 79% and, thus, a high importance rating.

2.2 State-of-the-art

The state-of-the-art review was conducted to identify the existing and emerging techniques and solutions or best practices to meet the needs of decommissioning community. The method of analysis was to use the structure of the thematic areas established before and to look at each thematic area on four different scales as illustrated in Figure 4.

By reviewing journal articles, industry reports, conference proceedings and expert input, the consortium identified strategies and initiatives on the international, regional and national scale. A dive into available technologies was performed on the national and local levels. A dedicated two-day workshop in October 2020 allowed Stakeholders to engage with the content produced so far by reviewing and consolidating it.

2.3 Gap analysis

The previously obtained results served as the foundation for the gap analysis. In the December 2020 workshop facilitated by the consortium, the Stakeholders brainstormed to produce possible activities in 71 sub-thematic breakout sessions. For the Stakeholder's feedback, Mural was chosen as the online interactive brainstorming tool. The ideas were collected on digital post-its and were shared in real-time with the participants. Each session was dedicated to a sub-thematic area and involved a four-step process. First, Stakeholders identified needs, challenges and opportunities for the corresponding sub-thematic area. Second, a consortium member acted as a facilitator to group the identified needs. Third, the Stakeholders provided some insight into the available solutions and opportunities, which helped to identify the gaps. Finally, Stakeholders proposed activities to close those gaps. Afterwards, the consortium synthesised the outcomes of this workshop on the scale of the sub-thematic areas and, then, presented these at the DigiDecom 2021 conference. Here, the SLIDO live polls tool was used during the event and the Stakeholders provided further input in the form of feedback on the results of the gap analysis. The results of the gap analysis were categorised into four different "action types" for the gap analysis deliverable to provide a better overview [9].

In the same work package, relevant international collaborative research initiatives were also identified.

2.4 Strategic research agenda/roadmap

In the final work package, the consortium pushed the analysis of the project outcomes further by, first, modifying the previously assigned action type to facilitate the categorization of the activities.

The second step consisted of associating importance ratings from the survey with the activities from the same sub-thematic area. In this step, several rearrangements of the activities among the sub-thematic areas were made to ensure clear categorization. For the Strategic

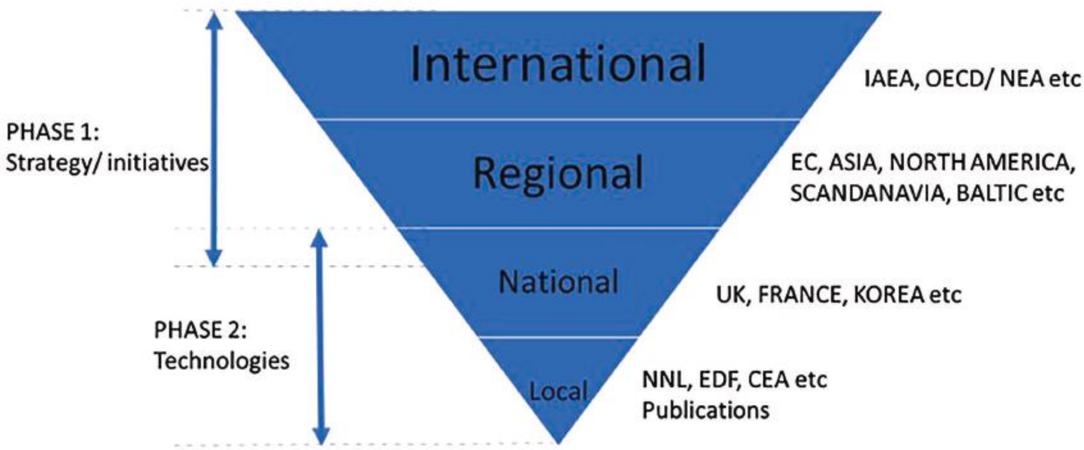

Fig. 4. Scales of the state of the art review.

Research Agenda (SRA), the sub-thematic areas were prioritised by the importance rating for each of the action types.

Finally, for the roadmap, the urgency rating was attributed to the activities of the corresponding sub-thematic area. This allowed the establishment of a time horizon for the activities going from <5 years (high urgency), over 5–10 years (medium urgency) to >10 years (low urgency). If possible, activities with the same time horizon were merged according to their content and action type. Lastly, some related thematic areas were merged.

Figure 5 emphasizes how the SHARE SRA and roadmap have been built through an iterative consultation process considering the needs and points of view of different stakeholders.

3 Results of the inquiry and discussion

3.1 Representativity of the collected data

The first data point to be noted is the participation of the Stakeholder community in the questionnaire survey. Out of the 650 invited Stakeholders, 224 fully completed the questionnaire which corresponds to a participation of 34%. This strong engagement confirms the interest of the community in this project and its premise. As mentioned above, the profiles of the respondents matched the profile of the invited Stakeholders. Care was taken to invite a representative average of Stakeholders to the survey, the latter fact supports the project's ambition to provide broad outcomes. This point is underlined when looking at the other profile factors of the responding Stakeholders. Figure 6 shows the four profile criteria “type of facility”, “type of organization”, “region” and “status of the decommissioning project”.

Indeed, the respondents come from organizations that are in various stages of their decommissioning process and operate different types of facilities. Furthermore, many different global regions are represented.

3.2 Data evaluation and results

Coming to the results of the survey, a thorough discussion of all results would be out of the scope of this article. This article intents to give an overview and then focus on the most salient results. First, Figure 7 shows the weighted results on the scale of the thematic areas, in terms of importance and urgency.

Red circles indicated the sum of the share of the top 2 rankings. Radioactive waste management or characterization is rated highest. Following are safety and radiological protection or project management and cost. The last group is formed of environmental remediation, dismantling, human resources management and site preparatory activities.

Figure 8 shows the weighted importance and urgency ratings of the sub-thematic areas.

Each circle corresponds to a sub-thematic area that is noted by a number (QXX) which relates to the survey question number. The question numbers can be found in appendix Table A.1. The different colours represent the different thematic areas. The size of the circle indicates the urgency category from low to high. The place on the x axis shows the importance category. Importance and urgency ratings for the same sub-thematic areas are correlated. Despite the appearance in this figure where some sub-thematic areas (e.g., Q35, Q45, Q33, Q19, Q25) with medium importance have high urgency, numerically, all sub-thematic areas have higher importance ratings than urgency ratings. The average difference between the importance and the urgency rating for the same sub-thematic is 11 points. This supports the categorization limits set by the consortium which differ by 10 points between importance and urgency. I.e., “High importance” is above 50 points and “high urgency” is above 40 points. The difference varies between the thematic areas. For example, Q2 and Q3 show the smallest average difference (7 points) whereas Q6 and Q7 show the highest average difference (15 and 16 points). For most thematic areas except Q5 and Q7, the thematic area rating is higher than the average of the sub-thematic area ratings. On average,

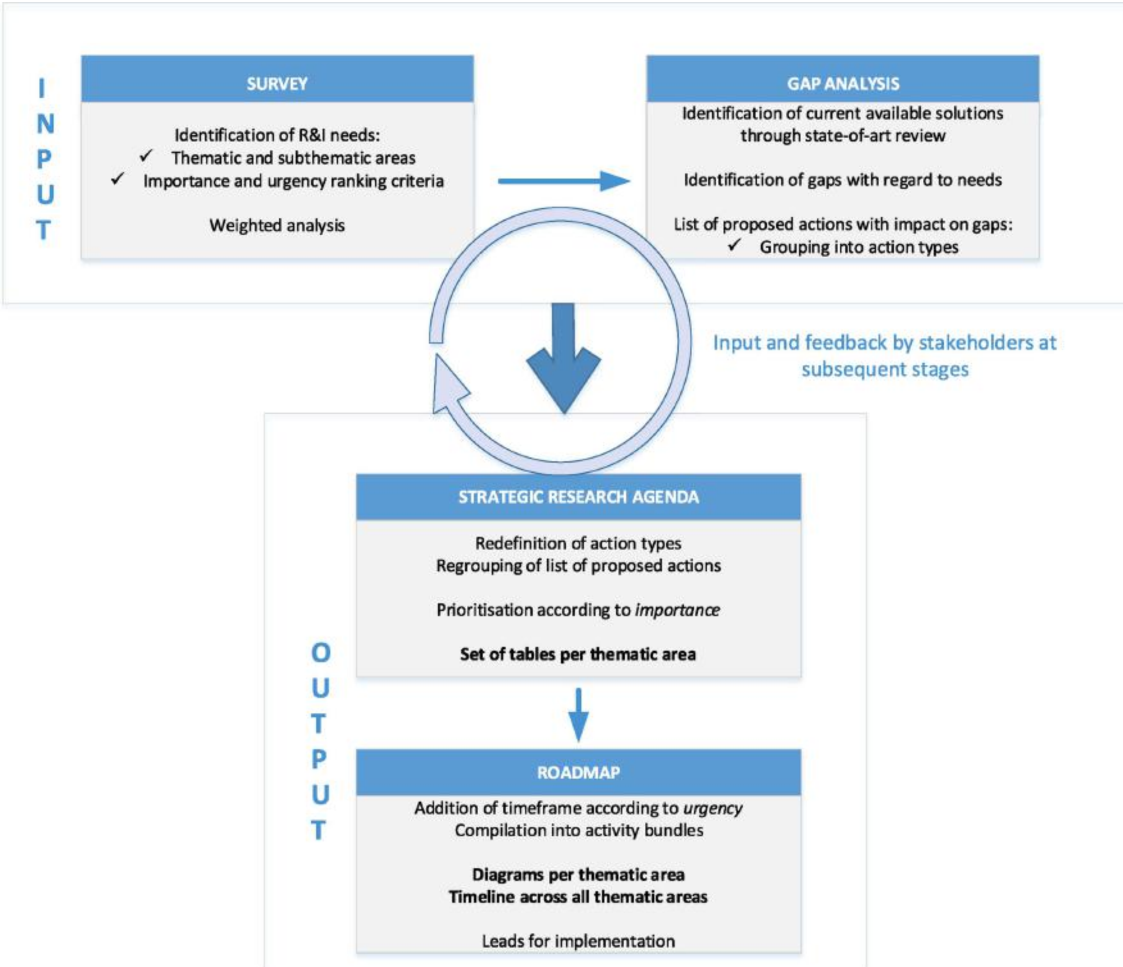

Fig. 5. SHARE methodology.

the difference is 19 points for importance ratings and 13 points for urgency ratings. The biggest gaps are found for Q4 with 30 points for importance and 22 points for urgency, and for Q8 with 30 points for importance and 28 points for urgency. The differences are smallest for Q3 and Q6 below 10 points. As mentioned earlier, for Q5 and the urgency rating Q7 the difference is reversed. However, a more profound analysis must be done carefully, since it involves many hypotheses and assumptions concerning the questionnaire formulation, interpretation and respondent population. Additional analysis can be found in the corresponding project deliverables [8,10,11]. In view of this heterogeneity, looking at the top 10 sub-thematic areas shown in Table 1 provides further insight.

Of the top 10, eight sub-thematic areas are common in terms of importance and urgency. Three (Q32, Q84, Q63) of the other four can be found in the top 20. Only Q62 is at place 31 in terms of urgency. A large number of sub-thematic areas in the top 10 concern characterization in some form (Q36, Q53, Q38, Q37, Q63). Other focus points are robotics (Q60, Q40), material clearance (Q13, Q62, Q84) and radioactive waste management (Q53, Q70). This confirms that the knowledge of the inventory and the existence of adapted solutions for waste management or clearance is key to the success of decommissioning projects. General education for decommissioning is also attributed to a very urgent position.

It is also noted that some of the needs in the sub-thematic areas are already addressed to some degree by available solutions and best practices already provided for in the community. To establish a vision of the current state of the art before moving to the identification of possible actions, the consortium reviewed the available literature and consulted experts [12]. This work laid the foundation for the gap analysis.

The combination of the questionnaire survey in its structure and results and the review of current best practices and technical solutions allowed the team to work out propositions for future activities together with the Stakeholders. The exchange platform for this collaboration was provided by two online workshops in December 2020 and dedicated sessions during the DigiDecom 2021 conference. Stakeholders showed significant interest and engagement in these workshops with participants from diverse groups in the community. Indeed, as Figure 9 shows, the 459 registered participants in these workshops represent the

Fig. 6. Profiles of the Stakeholders responding to the questionnaire survey.

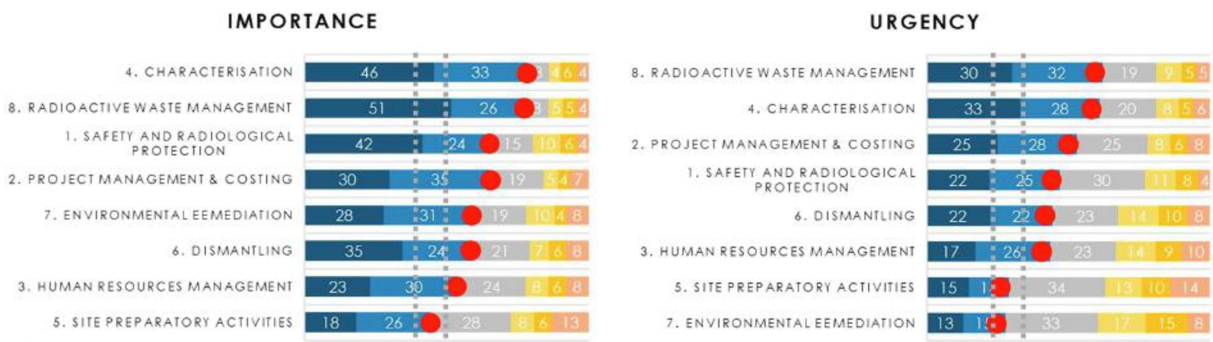

Fig. 7. Results of the questionnaire survey for the thematic areas.

decommissioning Stakeholder community from all over the world well.

The output of this process was published in the Gap Analysis Report [9]. The collective consultation structured by the facilitator action of the consortium gave rise to the proposition of around 220 activities to address the needs. For each thematic area, different key aspects were identified (Tab. 2).

3.3 The SRA and the Roadmap

The research needs highlighted by the SHARE survey were prioritised according to the survey-weighted analysis [8]. The following gap analysis highlighted the gaps in technology, best practices and crosscutting activities [9].

The proposed actions to fill the identified gaps were categorised into four types of activities:

- *implementation of RD&D:* the category includes research, development, demonstration and deployment activities. This also includes underpinning activities such as benchmarking. These research activities aim to create knowledge across all TRL (Technological Readiness Level) levels and to advance the maturation and adoption of new and innovative technologies.
- *Knowledge sharing:* this category of actions focuses on knowledge exchange, ranging from knowledge management to dissemination activities, such as sharing best practices and networking.
- *Education and training:* these activities aim to develop capabilities, skills and competencies for the "nuclear" workforce.
- *Harmonization of practices:* the activities in this category consider the opportunities and benefits of harmonization in the areas of regulatory frameworks and technology development. They are typically achieved by

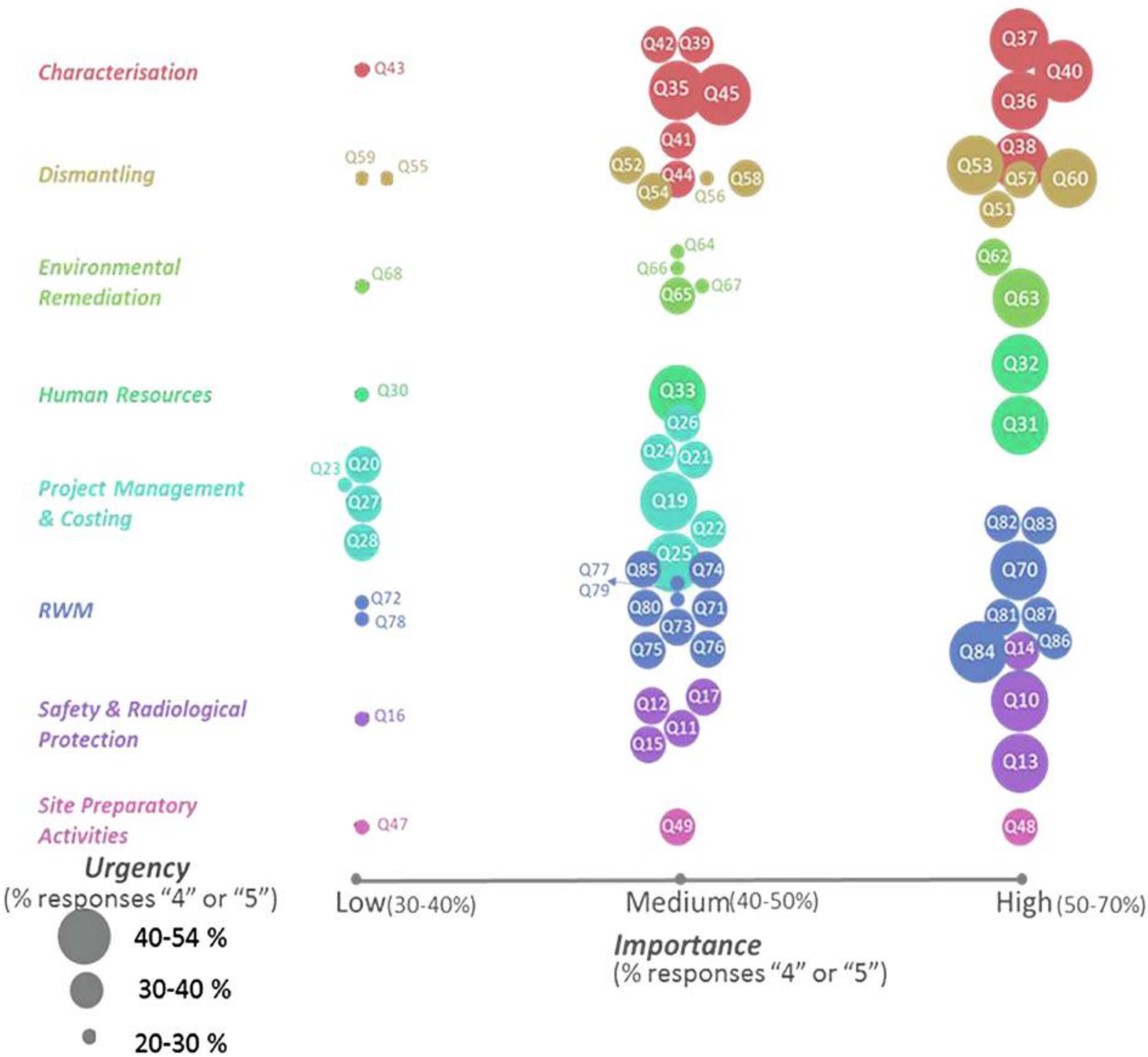

Fig. 8. Importance and urgency rating of the subthematic areas.

mutual agreement and are consolidated in recommendations, directives and guidelines.

This categorization was pre-defined for the Gap Analysis. However, the categories defined in the associated deliverable were ultimately revised. The new categories, being either RD&D or cross-cutting (knowledge sharing, harmonization, education and training) were deliberately chosen to reflect the nature of the desired outcome of the activity. For example, benchmarking requires pre-emptive knowledge sharing of harmonised knowledge. Categorization, at first, seems ambiguous. It was resolved by considering that benchmarking, ultimately, aims at creating knowledge and is, therefore, RD&D. Because progress was made in the field of the activities the consortium provided the updated status for the ongoing project per thematic area. The compiled and categorised actions, where further developments could lead to cheaper, faster and safer future decommissioning activities while improving safety, reducing costs and minimise environmental impact, are presented as main activities of common interest for the six thematic areas of the SHARE Strategic Research Agenda (SRA) [13].

Recent reports [14,15], on innovation in decommissioning identified the future, suggested R&D areas and focus [16] on new aspects, trends and innovative technologies. SHARE continues the work of identifying research and innovation needs and crosscutting activities based on stakeholder involvement, with an emphasis to strengthen international networking and complementarity between national research programmes for decommissioning. The SHARE SRA identifies and prioritises the activities needed to advance the decommissioning field in various thematic areas.

For the non-technological topics (safety and radiological protection, project management, costing and human resources management) in the first thematic area of the SRA, mainly crosscutting activities in the field of

Table 1. Top 10 subthematic areas in terms of importance and urgency.

Place	Importance		Urgency	
	Number	Title	Number	Title
1	Q36	Inventory assessment (Radiological and non-radiological)	Q36	*
2	Q53	In situ Radioactive Waste characterization and segregation	Q53	*
3	Q60	Robots and remote-controlled tools for dismantling	Q32	General education for decommissioning
4	Q38	Characterization of activated components and areas (Concrete)	Q13	*
5	Q40	Technologies for hard-to-access areas (high walls, embedded components, harsh environment...)	Q38	*
6	Q37	Characterization of activated components and areas (Metal)	Q70	*
7	Q70	Management routes for materials including radioactive waste streams	Q37	*
8	Q13	Development of National regulatory guidance for Decommissioning (Clearance of structures and materials)	Q40	*
9	Q62	Clearance of surfaces and structures (interiors and exteriors)	Q60	*
10	Q63	Characterization methods and technologies to identify subsurface contamination	Q84	Material clearance (methodology and procedures)

* indicate that the title of a sub-thematic area was already mentioned in the table.

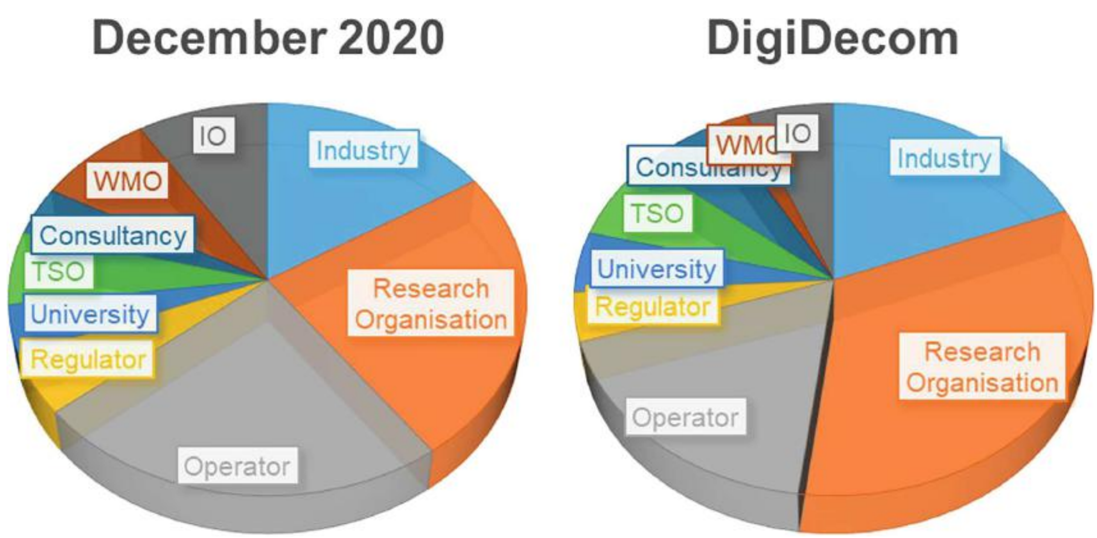

Fig. 9. Pie charts of the profiles of the participants to the two workshops organised for the gap analysis.

Table 2. Key aspects of the gap analysis by thematic area.

Thematic areas	Key aspects
Q1 Safety and radiological protection	Enhancement in international/national harmonization
	Homogenization of regulations
	Future coordination and collaborations
	Regulatory guidance
Q2 Project management and costing	Guidance on tools for cost management and digitization
	Development of IT tools for project management
	Enhance use of BIM (Building Information Modelling) and virtual software
Q3 Human resources management	Coordination among EU, IAEA, and NEA to update existing documents
	Harmonization of knowledge bases
	Enhance use of IT tools, training methods and education of employees
	Benchmarking on methods and tools for knowledge management
Q4 Characterization	Fast and cheap methods of radionuclide measurements
	Technology for digital methods and automation
	Developments towards knowledge management, training and standardisation
Q5 Site preparatory activities	Moved to Q8 "Radioactive Waste Management"
Q6 Dismantling technologies	Development of technologies for detection of contamination, decontamination and cutting of metals and concrete
	R&D towards automation and digitization
	Enhance the use of mobile systems and robotics for worker safety
	Experience sharing in dismantling technologies and benchmarking
	Standardization of autonomous systems
Q7 Environmental remediation and site release	Models, digital tools, multi-criteria analysis, and international guidance for remediation and site release
	Benchmarking of technologies and IT tools
	Experience sharing for harmonization
Q8 Radioactive waste management	Harmonization of best practices, waste minimization
	Enhance optimization opportunities
	Encourage the use of new technologies
	Simpler and cheaper processes for secondary waste handling
	Experience sharing for IT tools and specific waste forms (asbestos)
	Harmonization and standards for waste acceptance criteria

knowledge sharing, harmonisation of practices and education and training have been identified when compared to the technological RD&D topics. The needs that stand out most are the education and recruiting of the next-generation workforce, the development and dissemination of adequate digital tools to plan and follow-up decommissioning activities and the harmonisation of safety standards and waste criteria as enablers for collaboration.

The thematic areas of characterisation and material and waste management have been identified by the stakeholders as most important and urgent overall, with activities for technology advances formulated in the field of measurement optimisation and waste treatment and conditioning techniques, together with crosscutting activities.

Innovative processes, technologies and methodologies for dismantling, decontamination and environmental remediation with a focus on waste minimisation and a need for further development to enhance efficiency, mobility and/or automation are highlighted in the relevant thematic areas. The stakeholders also emphasised the need for sharing best practices and the development of guidance for certain topics.

Ongoing initiatives and recent activities in all thematic areas demonstrate continuous development and innovation, to Figure 10 ether with existing possibilities for the

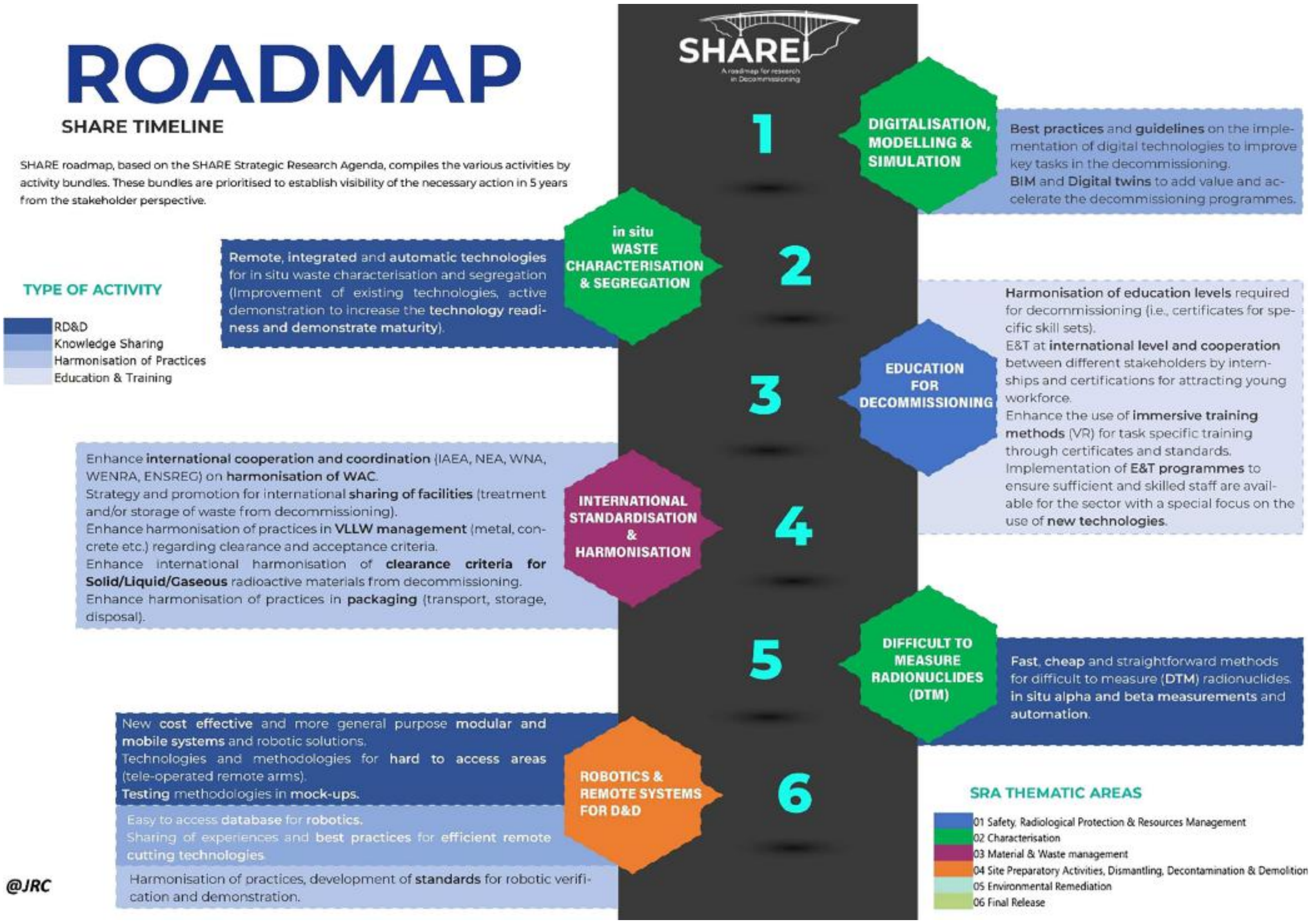

Fig. 10. SHARE Roadmap part I.

exchange of information and lessons learnt. There are opportunities for multinational projects co-financed by stakeholders with common challenges. To go further (and faster) to deliver cost-effective research and innovation, however novel "instruments for collaboration" need to be established to achieve this goal. Open science has a potential role to play, in supporting future coordination of R&I efforts.

Finally, the SHARE Roadmap [17] applies the urgency rating to the same activities. By allowing the moving and merging of similar activities inside an urgency rating, complexity was reduced and readability enhanced. Figures 10 and 11 show the SHARE roadmap compiling the most urgent activities by activity bundles.

4 Conclusion

The SHARE project has through extensive international stakeholder engagement and dialogue, produced a consolidated view of the opportunities to enhance the landscape of decommissioning and this is encoded in the Strategic Research Agenda (SRA) and the present Roadmap document. The activities range from RD&D for activities that create knowledge including benchmarking and technology development, Knowledge Sharing for activities that demand dissemination, Harmonisation of Practices for activities that require at least the adoption of best practices but can include regulatory measures, and Education and Training for activities that aim at creating and developing workforce competencies. The process was performed as a "bottom-up" approach by co-constructing the outcome with the international Stakeholder community. This approach is complementary to the usual top-down scheme found in roadmaps and strategic documents. To maximise objectivity, in all Stakeholder consultations, the consortium acted as facilitator and structured the frame of reference. Indeed, the consortium configured the discussions by establishing the thematic areas and reviewing the state of the art in the field of nuclear decommissioning. The structure of eight thematic areas was inspired by the phases of existing decommissioning programmes: there were three non-technical areas (safety and radiological protection, project management and costing and human resources) that span the whole project duration and five technical areas (characterization, site preparatory activities, dismantling technologies, environmental remediation and site release, and radioactive waste management) that intervene more or less at specific moments.

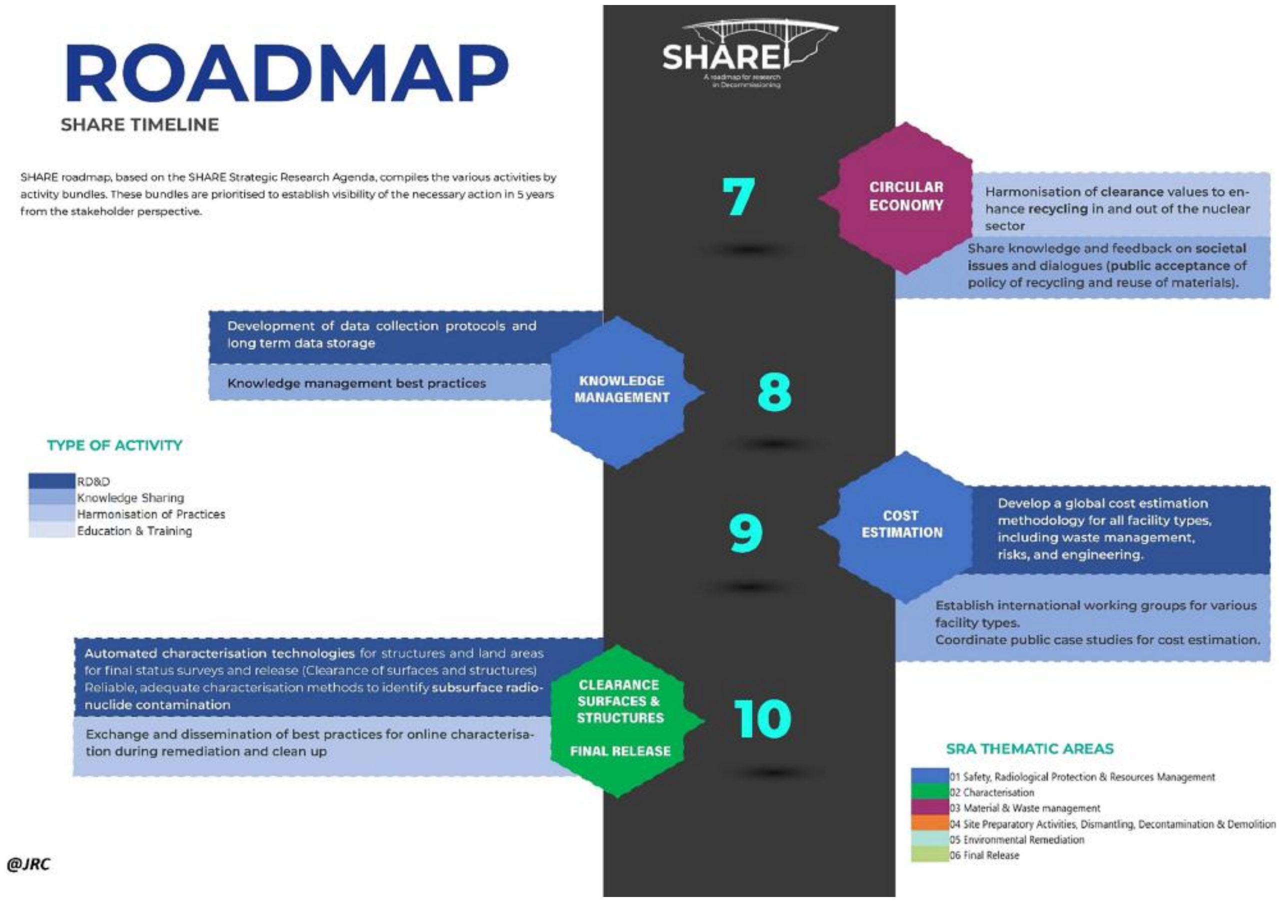

Fig. 11. SHARE Roadmap part II.

The SHARE consortium successfully fulfilled the project purpose by providing the SRA and the Roadmap for future collaborative activities in the decommissioning sector.

There are many advantages in collaboration to deliver these activities, notably, cost sharing of RD&D but also in the intellectual gearing of bringing the experience of different actors together to solve a problem. Collaboration and cooperation offer benefits for knowledge sharing, harmonisation and education and training. Within the SHARE project report, D3.3 [18] many instruments for collaboration were identified as relevant to the decommissioning context.

European instruments led by the European Commission such as Horizon Europe are likely to continue to be the key facilitating instruments for open collaborative Research, Development & Demonstration (RD&D) across Europe. Experience of EURATOM projects such as Theramin, PREDIS and CHANCE have illustrated how powerful these collaborations can be, benefitting from sharing of both expertise and national facilities to address technological challenges. On-going projects such as the European Joint Programming EURAD or Euratom H2020 HARPERS can, thus, now pick up on the knowledge created by SHARE

These collaborations can be aided and indeed initiated by strong European networks, notably SNETP, Nugenia and ETSON. A strong European network perhaps facilitated through SNETP-Nugenia has the potential to continue the stakeholder dialogue and networking achieved in SHARE, to inform policy, strategy, and the research agenda in decommissioning at a European level.

For regulatory issues that occur frequently in the roadmap, close interaction with regulator networks such as ENSREG or WENRA could be fruitful. The same is true for educational issues where several expert networks exist. Indeed, an expert insight provided by such groups is crucial for pertinent project development.

However, other international organisations including OECD-NEA and IAEA are also facilitating cooperation beyond Europe and remain important instruments for collaboration and networking in the nuclear sector, notably on knowledge sharing, harmonisation and education and training globally.

The effective implementation relies on strong collaboration based on shared drivers and goals, as embodied in the initiatives outlined above. However, bilateral or smaller regional (local) collaborations will also play an important role in driving innovation where incentives and drivers align, to make progress against common goals.

Appendix A

Table A.1. List of thematic and sub-thematic areas in the questionnaire survey.

Thematic area	Sub thematic area
Safety and Radiological Protection aspects	Q10 International harmonization of safety standards
	Q11 Development/National regulatory guidance for Decommissioning: Preparatory activities
	Q12 Development/National regulatory guidance for Decommissioning: Dismantling
	Q13 Development/National regulatory guidance for Decommissioning: Clearance of structures and materials
	Q14 Development/National regulatory guidance for Decommissioning: Final site release
	Q15 Methods and tools for nuclear safety
	Q16 Methods and tools for conventional industrial safety
	Q17 Development of radiological protection approaches and guidance for Decommissioning
Project management and costing	Q19 Methodologies and software tools for comparison of alternative decommissioning strategies
	Q20 Methodologies and software tools for project management and performance monitoring
	Q21 Tools for data collection in the field (e.g., for work monitoring)
	Q22 Digital transformation in decommissioning (big data, business intelligence)
	Q23 Supply chain management for decommissioning
	Q24 Methods and tools for communication (public)
	Q25 Methodologies and guidance for cost estimation
	Q26 Software for cost estimation (partly discussed in other sessions)
	Q27 Development of mechanisms for cost benchmarking
	Q28 Methods and tools for sensitivity and uncertainty analysis in cost estimation (partly discussed in other sessions)
Human resources management	Q30 Organization models (staff & resources)
	Q31 Methods and software tools for knowledge management (e.g., competence preservation)
	Q32 General education for Decommissioning
	Q33 Methodologies and tools for task-specific training
Characterization	Q35 Methodology for historical site assessment
Site preparatory activities	Q47 Adaption of auxiliary systems for decommissioning (ventilation, electrical, monitoring, etc.)
	Q48 Preparation of infrastructures and buildings for decommissioning (storages, capabilities for material sorting and treatment...)
	Q49 Systems decontamination (internal)
Dismantling	Q51 Segmentation of large irradiated metallic components (reactor vessel internals, etc.)
	Q52 Handling, segregation and loading of segmented elements and secondary waste
	Q53 In situ Radioactive Waste characterization and segregation
	Q54 Segmentation of large surface-contaminated components
	Q55 Dismantling of surface-contaminated piping and small components
	Q56 Segmentation of interior concrete structures (e.g., bioshield)
	Q57 In situ decontamination of building surface (concrete)
	Q58 Management (characterization, decontamination, removal) of radiological embedded elements
	Q59 Demolition of large, reinforced concrete structures
	Q60 Robots and remote-controlled tools for dismantling
Environmental remediation	Q62 Clearance of surfaces and structures (interiors and exteriors)
	Q63 Characterisation methods and technologies to identify subsurface contamination
	Q64 Modelling and statistical tools to analyse contaminant transport in subsurface soil and groundwater
	Q65 Soil remediation technologies (washing, bioremediation, contamination fixing)
	Q66 Remediation of contaminated groundwater (radiological)
	Q67 Methodologies and techniques for final release survey of the Site
	Q68 Tools for statistical analysis and management of survey data for site release
Radioactive waste management	Q70 Management routes for materials including radioactive waste streams
	Q71 Radioactive material decontamination (mechanical)
	Q72 Radioactive material decontamination (electrochemical)

Table A.1. continued.

Thematic area	Sub thematic area	Thematic area	Sub thematic area
	Q36 Inventory assessment (Radiological and non-radiological)		Q73 Radioactive material treatment processes (metals)
	Q37 Characterization of activated components and areas (Metal)		Q74 Radioactive material treatment processes (concrete)
	Q38 Characterization of activated components and areas (Concrete)		Q75 Radioactive material treatment processes (aqueous liquids)
	Q39 Characterization of activated components and areas (Graphite)		Q76 Radioactive material treatment processes (non-aqueous liquids)
	Q40 Technologies for hard-to-access areas (high walls, embedded components, harsh environment…)		Q77 Radioactive material treatment processes (organic materials)
	Q41 Development of modelling and simulation software for characterization of irradiated components		Q78 Radioactive material treatment processes (VLLW)
	Q42 Standards for statistical sampling		Q79 Radioactive material treatment processes (LLW)
	Q43 Geostatistical software applications		Q80 Radioactive material treatment processes (ILW)
	Q44 Sample analysis technologies		Q81 Radioactive waste conditioning
	Q45 Alpha and beta non-destructive measurements		Q82 Radioactive waste packaging and logistics
			Q83 Characterization and survey of containerised radioactive waste
			Q84 Material clearance (methodology and procedures)
			Q85 Material clearance (instrumentation and logistics)
			Q86 Management of hazardous and toxic materials (asbestos, lead in paint, etc.)
			Q87 Conventional and cleared materials recycling (circular economy)

Conflict of interests

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

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Data availability statement

GDPR was respected. All published data from the project is publicly available in the deliverables on the project homepage.

Author contribution statement

Robert Winkler was project coordinator of SHARE and drafted the manuscript. Laura Aldave de las Heras was work package leader (WP1 "Methodology"). Development of the methodology used in the project, including the survey analysis, the gap analysis and SRA and roadmap setup. Federica Pancotti contributed to all work packages and was the author of the state of the art (3.1) and the questionnaire explanatory deliverable (2.5). Anthony Banford was the leader of work package 3 and contributed to the state-of-the-art analysis, the gap analysis, leading stakeholder engagement workshops and the subsequent needs analysis. He participated to the Work Package 4 Strategic Research Agenda and Roadmap Team doing preparation of, co-authoring and dissemination. Reka Szoke reviewed the paper. Kurt van den Dungen was leader of WP4 and coordinated and authored the SRA and the Roadmap. Gintautas Poškas is the author of the deliverables D2.3 and D2.4 and contributed to the article by reviewing and coauthoring chapter 2. KIT participants (Angelika Bohnstedt and Muhammad Chaudhry) have been involved in all WPs, with strong input in WP 1 as task leader being responsible for "Inventory of relevant actors within stakeholder's profile by country" and in WP 2 "Questionnaire on innovation needs for decommissioning". They put in a lot of effort was done in the gap analysis on identified needs and available solutions, which included literature research as well as stakeholder workshops with the final outcome in the Strategic Research Agenda.

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Review Article

Open Access

European collaborative efforts to achieve effective, safe, and cost-controlled dismantling of nuclear facilities

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Abstract. This paper aims to give an overview of very recent European coordinate efforts to implement technologies of the “4.0 Industry” in the nuclear deconstruction sector. This objective aims to benefit from the lever of efficiency and reliability represented by innovative technologies on all the value chain of the dismantling, from early characterization to the dismantling operations themselves through engineering studies, waste management, project management and coordination of multiple stakeholders of each project. The outcomes of five projects (INNO4GRAPH, LD-SAFE, PLEIADES, CLEANDEM and INSIDER) are summarized here. They result in a unique data and knowledge common base, as well as in a significant sharing of experience based on dismantling projects already carried out or to come. They also result in designing new tools or methods natively taking into account the needs of a maximum of dismantling operators, as well as new test facilities. This will allow the undertaken joint work and collaboration to be continued. All of this paves the way to further collaborative projects and developments, in order to continue to implement reliable new technologies and processes in European dismantling projects to make future dismantling operations more efficient, safer and more cost-effective.

1 Introduction

Due to the energetic political choices of some European countries to phase out nuclear power such as Germany or more recently Belgium on the one hand, and industrial choices regarding the extension or not of their lifetime, on the other hand, an increasing number of nuclear installations and power reactors, in particular, are to be dismantled in the coming decades. Except for graphite reactor dismantling, which remains a technical challenge, the general feasibility of dismantling many reactors (PWR, BWR, HWR, ...) is established. Still, these operations can be optimised in terms of dismantling processes, waste generation, costs and lead times.

The reliability and safety requirements imposed on dismantling sites make it necessary to use mature, reliable techniques that meet all three criteria that are international good practices, local safety, and radiation protection criteria. This necessary precaution is part of the reason why decommissioning operations are still carried out mainly manually, hence requiring extensive personnel protection measures, engineering controls, and costly and inefficient detailed work planning and monitoring, to achieve the required high safety levels. Moreover, the “poorly reproducible nature” of the operations to be carried out from one site to another also explains a current approach that is still only partially industrial. This state of fact added to a large number of dismantling work sites in the next decades yields a major challenge for research and innovation in the field of nuclear dismantling. It is indeed necessary to rapidly bring to maturity technologies (digital technologies, automatised or semi-automatised robotics, LASER cutting) which will make the dismantling operations more efficient, safer and more cost-effective. This objective is common to the five European projects (INNO4GRAPH, LD-SAFE, PLEIADES, CLEANDEM and INSIDER) which are the topic of this article.

Thinking of technological developments, by analogy with other industrial sectors such as aeronautics, the first thought that comes to mind is the digital “revolution”. The PLEIADES project aims to accelerate this transition towards a more efficient and more widespread use of digital

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tools. Relying on existing and proven tools already used by some actors in the field, PLEIADES aims to make their use more fluid, even efficient and shared.

Furthermore, dismantling activities are based on an essential pillar: characterisation operations. These operations can be considered as a true "red thread" of a dismantling project. A site to be dismantled must indeed be characterised beforehand, to be able to plan and size the dismantling operations, in particular the management and disposal of waste. The complementary characterisations, which are performed during the whole dismantling operations, ensure that the current state conforms with the prediction made before the start of the works. Final characterisations are performed after the final clean-up operations to ensure compliance with the decommissioning objectives. This important activity has its own areas for improvement and challenges that the INSIDER and CLEANDEM projects aim to address.

Finally, the most visible part of the dismantling operations consists of dismantling and removing the equipment that is part of the facility. The LD-SAFE project focuses on the promising LASER cutting, and more particularly on how to ensure the total operational safety of this technology during cutting operations in future dismantling sites. The INNO4GRAPH project aims to define and develop tools that will make it possible to effectively and safely remove the graphite constituting the structure of graphite-moderated reactors (UNGG, Magnox, AGR and RBMK).

The present paper presents a short overview of these projects and their results. If necessary, more information may be found on the website of the projects respectively:

- https://www.inno4graph.eu/
- https://ldsafe.eu/
- https://pleiades-platform.eu/
- https://insider-h2020.eu/
- http://cleandem-h2020.eu/

2 Brief overview of the projects

2.1 INNO4GRAPH

The decommissioning of shut-down graphite nuclear reactors worldwide is still in its early stages with many reactors in "safe store" condition. For these reactors, there are still considerable industrial and technical challenges that remain to be tackled, even after more than 30 years of the operational shutdown of the first unit. The complex geometry, design and large dimensions of such reactors make their decommissioning a worldwide industrial and technical challenge. Being 2 to 5 times bigger than a Pressurized Water Reactor (PWR), the decommissioning of an industrial Graphite Unit is also expected to generate 10 to 30 times more waste.

The H2020 INNO4GRAPH project is the first international collaboration in order to address common challenges connected to graphite retrieval operations. It started in September 2020 for three years. It gathers 13 entities from five different countries: EDF (Consortium leader), Graphitech, Cyclife Digital Solutions, Enresa, Sogin,

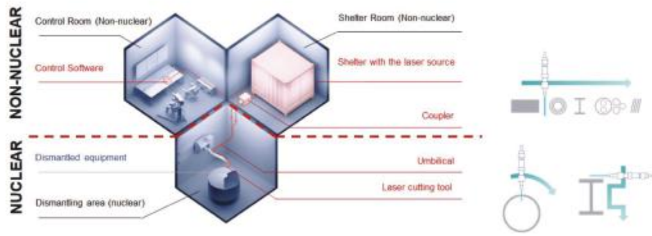

Fig. 1. LASER cutting typical configurations for decommissioning application.

LEI, CEA, Tecnatom, Ansaldo Nucleare, Cirten-Polimi, Westinghouse Spain, University of Manchester and ARTTIC.

The INNO4GRAPH project aims to support the operators to define the most optimal ways to decommission graphite reactors i.e., the tools that can help to safely remove radioactive material, and the most cost-efficient solutions for dismantling operations in reactors of such complexity and dimension. This goal will be reached through the development of physical and digital tools and methods to support the decommissioning of European graphite reactors.

To this end, the INNO4GRAPH project takes place in two phases:

- tools and methods will be used during tests and studies upstream of the dismantling operations to:
  - get an excellent knowledge of both the graphite properties thanks to the in-situ measurement of cracks and corrosion and the dismantling tools to be used;
  - evaluate the efficiency of the use of innovative tools in order to define the most adapted scenario for each reactor regarding the local context (technical constraints, regulations, ...) in terms of safety and cost-efficiency thanks to scenario grid analysis, mock-ups for physical tests and digital 3D models.
- Innovative cutting and handling tools will then be made available during the dismantling operations. It is for example the case of LASER cutting technologies, like in the LD-SAFE project.

2.2 LD-SAFE

Dismantling the reactor vessel and internals of a nuclear power reactor is probably the toughest task to be accomplished in the decommissioning programme, mainly due to the size of equipment to be cut and removed, but also the high dose and cost related to these operations. A number of "conventional" techniques are currently used by the nuclear industry, but innovation has not yet penetrated these operations due to risk-averse behaviour, reluctant to see new technologies that have not yet proved their advantages on the field. Among the innovative technologies which could be used to enhance such works, the laser cutting technology (see Fig. 1) is probably the most promising one due to its large maturity in the manufacturing industry and great advantages like the cutting performance but also the operability and reduction of secondary waste.

The global objective of the LD-SAFE project is to validate the laser cutting technology in an operational environment in-air and underwater (TRL7) and prove that the technology is mature to address the dismantling of the most challenging components of power nuclear reactors. 6 companies (ONET Technologies, CEA, IRSN, Tecnatom, EQUANS and Vysus Group) are deeply involved to make this demonstration through specific tasks started in August 2020 and to be completed by June 2024.

Safety being one of the major drivers for accepting innovative technologies, the LD-SAFE project will evaluate the safety of the use of laser cutting technology in 4 stages:

- risk analysis under nominal and accidental conditions, which preliminarily demonstrates the safety of its implementation;
- acquisition of laboratory results of hydrogen and aerosol generation, and the possible impact of the residual laser beam;
- generic safety assessment following IAEA methodology, with the additional objective of being easily adaptable to future end-user conditions and reducing their licensing effort;
- followed by an independent safety assessment, to be carried out by IRSN.

2.3 INSIDER

The project aims at improving the management of contaminated materials by proposing a methodology that allows us to define and select the best nuclear decommissioning and dismantling operations (D&D) and remediation scenarios, and which produce well-characterized waste for which storage and disposal routes are identified. In particular, the methodology developed in the INSIDER project helps to acquire characterisation data in a Medium and High radioactivity environment, which are the basis for D&D scenario studies compliant with regulations in European countries. This gives access to a reliable vision of the radiological state of a facility (and/or its components) at a relevant confident level, allowing the identification of the different D&D scenario options.

INSIDER proposes a common validation in the entire D&D process, based on three main use cases – nuclear R&D facility, nuclear power plant and post-accidental land remediation.

The project has developed three main strategic objectives:

- define the best sampling strategy for waste production optimization through new/improved statistics approaches for sampling plan establishment; feasibility of realistic cases, including safety and waste management impact; assessment of cost, duration, and impact on waste production.
- Assess the performance of available measurement techniques (methods & tools) to establish a scientific basis for decision-making through validation of quick/cost-effective analytical methods (in lab and in-situ); performance assessment; reference materials production.
- Establish common methodologies to deploy reference guidelines for selected use cases through the first mapping guide for potential support to standardisation commissions, a database of analytical methods and reference materials, training and software module offer.

Three use cases were specified, covering a large majority of D&D installation configurations:

- UC1: Cycle plant: effluent tank in Italy at the ISPRA site of the JRC (Joint Research Centre).
- UC2: Nuclear reactor: biological protection of the BR3 reactor vessel in Mol/Belgium.
- UC3: Post incident: contaminated soil on a CEA site in France.

2.4 CLEANDEM

The CLEANDEM project implements some of the learnings of the MICADO project (https://www.micado-project.eu/) by developing a mobile unmanned ground platform (UGV) equipped with upgraded highly mature detection technologies for radiological measurements. Indeed, the radiological conditions at the end of life of a nuclear facility vary, from very harsh at the beginning when the facility is close to its nominal working conditions, to nearly non-existent at the time when the facility is decommissioned. Today's need for human resources to conduct operations in the dismantling step is a clear limit with regard to the “As Low As Reasonably Achievable” (ALARA) principle which aims to avoid workers' exposure to radiation as far as it is reasonably feasible. Indeed, according to the level of radiation, the operating time can be limited or impossible and, in presence of contamination, the operators must be protected for their own safety.

Current radiological risk mapping implies exposing operators to the radiological conditions in the environment (i.e., to minimize dose exposure of dismantling operators, we still have to expose operators who will measure where the risks are).

Having a robot conduct this radiological assessment not only removes the risks to operators, but also removes the unavoidable errors due to organisational and human factors (limited intervention time [to reduce exposition time], repetitive tasks intrinsic to dose rate/contamination mapping, . . .).

CLEANDEM aims at reducing human exposure to radiation, as well as the duration and costs of D&D operations while achieving higher efficiency and traceability of the operations. One can notice here that the INNO4GRAPH project shares the same stake in developing remote tools, without compromising in terms of the efficiency of the operations, applied to the dismantling of graphite reactors.

This three-year project, which started in March 2021, will address the need for full-D&D-operations' spectrumable technologies through four main tasks:

- improvement of current radiological measurement technologies (dose rate, neutron/gamma detection and identification, and contamination monitoring).

- Their implementation on a UGV platform, enabling to carry out remote operations and minimise human intervention.
- Build a Digital Twin containing all the radiological information of interest, updated as and when new data is available from D&D operations.
- Field-tests of the CLEANDEM solutions during in-situ operations in real environment conditions based on the scenarios defined by end-users.

To achieve the best consistency with both end-users and stakeholders' expectations, a team is specifically dedicated to Market analysis.

To address these different challenges, leading actors from the nuclear industry and research have joined their expertise and efforts in a pan-European consortium, with 11 partners from France, Italy, Germany and Spain.

2.5 PLEIADES

The PLEIADES project (PLatform based on Emerging and Interoperable Applications for enhanced Decommissioning processES) aims at making the decommissioning of nuclear facilities more efficient, by demonstrating an innovative digital decommissioning approach inspired by the BIM (Building Information Modelling) concept.

BIM enables all the information related to a building to be managed through a central 3D model, enhancing information exchanges between different jobs and enabling scenario simulations for testing building or renovation work. CLEANDEM is the first example of BIM use in a digital twin approach. In this approach, the building model is coupled to its physical twin and updated in real-time as soon as the autonomous characterisation system is acquiring new data. By extension to almost all the operations of the dismantling of nuclear installations, PLEIADES will demonstrate how a BIM-like model (containing data required for decommissioning planning) can be used for scenario simulations improving safety, minimising radiation exposure, and optimising costs and schedules. It is also an aim of PLEIADES to provide evidence for its added value and cost-saving through realistic pilot applications in different facility types. In order to achieve these goals, PLEIADES will develop a platform and demonstrate a new methodology for costing, planning, radiation protection and waste management. The platform will include a set of innovative modules, developed by project partners, including 3D simulation-based solutions. Using this platform, PLEIADES will implement use cases based on data from three different nuclear sites: the Santa María de Garoña nuclear power plant in Burgos (Spain), the Halden research reactor in Norway and the BCOT nuclear maintenance facility in Bollène (France).

To structure the data, PLEIADES proposes a decommissioning-oriented ontology that extends the standard Open BIM ontology applied in the building industry. PLEIADES aims at demonstrating a BIM-like modular software ecosystem based on the connection of front-line support tools through an interface built on this decommissioning-specific ontology.

As mentioned in the introduction, the nuclear dismantling community needs mature technologies for efficiently performing a large number of foreseen dismantling operations. PLEIADES will integrate mature solutions from partners that were, individually, already tested in the nuclear or other sectors. The exploitation strategy of PLEIADES is based on capabilities and services offered through the integration and interoperability of the partner's solutions.

The expected results of the project are foreseen to:

- improve safety, specifically by providing improvements in radiological protection, communication between stakeholders and training of workers.
- Reduce costs by enabling better and more standardized costing, as well as higher optimisation of the waste management process.

3 Main results of the projects

3.1 INNO4GRAPH

The work carried out during the first 18 months of the project has made it possible to produce some initial results and to achieve part of the objectives of INNO4GRAPH.

During the first period, the technical and environmental dismantling requirements of the different European operators were gathered in a report reviewing existing global dismantling scenarios, main reasons for choices etc. This provided a good overview of the graphite decommissioning situation as well as an understanding of similarities and differences. It also allowed identifying discrepancies to be considered in developments during and after the INNO4GRAPH lifetime.

Improved knowledge of graphite properties was achieved by data sharing between graphite NPP operators, identifying what are the most relevant graphite properties needed to conduct a successful dismantling according to different issues and to the sequencing of the project.

The DEMplus® for Nuclear software is a digital tool which allows simulation scenarios in a 3D virtual environment, enriched by radiological, physical, waste streams and labour costs information. It is also used in PLEIADES, as one of the applications of the Platform for enhanced Decommissioning processes. In INNO4GRAPH, DEMplus® for Nuclear has been upgraded with a new module dedicated to Graphite reactors which will allow to capitalisation graphite core data, to use if needed, external calculation models and to perform sensitivity study on the decommissioning scenario.

3D models of each reactor (Latina, Chinon A2, G1, Ignalina, Vandellos 1 – see Fig. 2) have thus been integrated into the DEMplus® software. This will allow graphite retrieval simulation in the second period of the project.

Studies are also in progress on methodology to measure the mechanical properties of graphite as well as on the in-situ measurement of cracks and corrosion.

The development of tools and methods to define the most adapted scenario for each reactor is another main

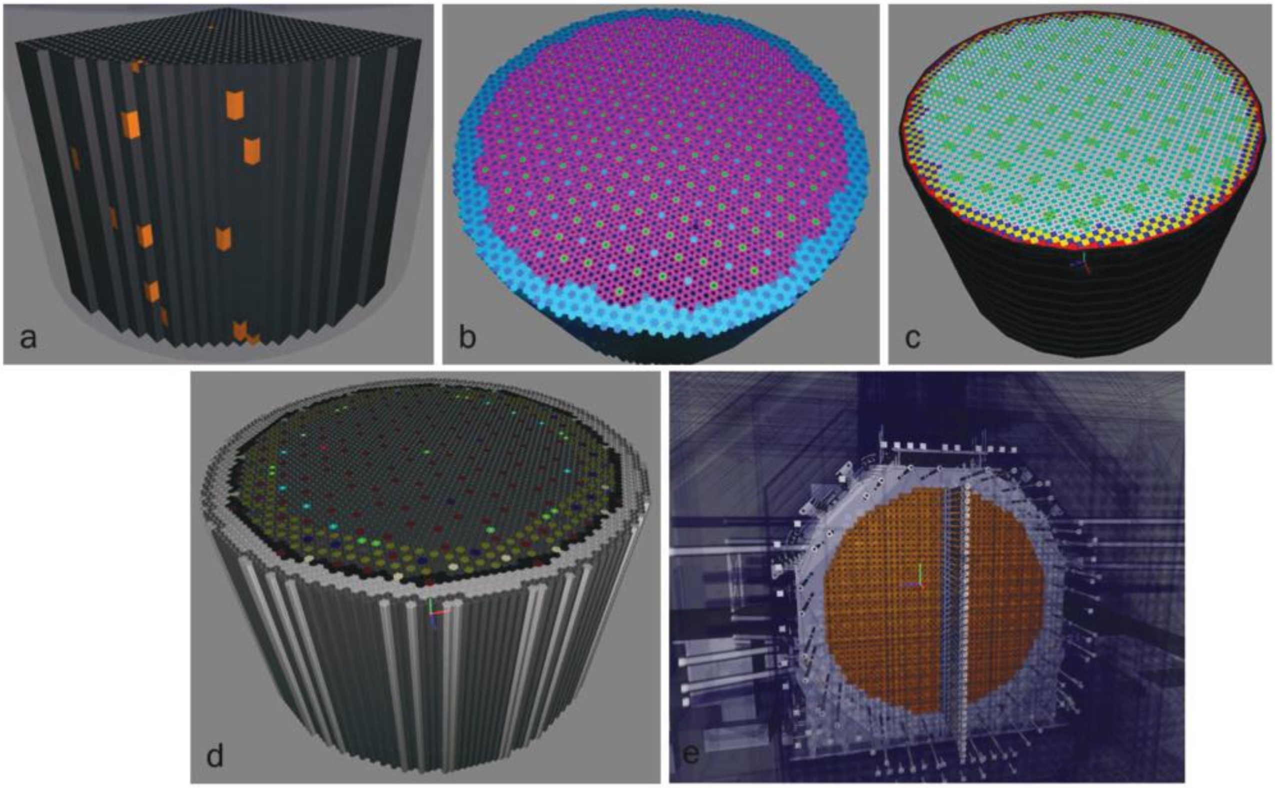

Fig. 2. Graphite core reactor 3D models integrated on DEMplus®. (a) Ignalina, (b) Vandellos I, (c) Latina, (d) Chinon A2, (e) G1.

objective of the project which is in progress. EDF's graphite industrial demonstrator (Fig. 3) will facilitate the uptake and further development of these tools. It will also be the place where operators from all around the world will be able to test them, train themselves and share experiences.

Among these tools and methods, one can mention:

- a multi-criteria grid analysis developed to allow graphite NPP operators to decide about their best dismantling scenario based on an objective evaluation of existing options taking into consideration risks and opportunities on different items.
- A representative and full-scale Chinon A2 NPP mock-up of the graphite stack designed and available for tests in the industrial demonstrator built by EDF in the township of Chinon in France.
- Definition of a testing methodology to assess the risk of bulk oxidation of the graphite during cutting operations [1].

3.2 LD-SAFE

Analysis of reactor dismantling with laser cutting

An analysis of the different reactor components in combination with the selection of conventional cutting techniques has been carried out including a comparison in regards to safety, secondary waste minimization, reliability and maintainability, and cutting performances. Specifications for the laser cutting system have been written to describe and explain the technology associated with the goals to be achieved in terms of cutting performance. A summary of safety-related challenges raised by laser has also been delivered.

Fig. 3. EDF's industrial demonstrator.

Finally, this task has been completed by identifying the most challenging piece to be cut into the reactor and describing the specifications for the mock-up in relation to the conventional technique band saw.

Laboratory trials and calculations

Experimental data are needed to support the safety demonstrations and define the technical countermeasures to be implemented when using laser cutting for reactor decommissioning.

Works have been implemented on the laser beam residual power, through the design of an experimental set-up to characterize laser beam residual power.

The secondary emissions (aerosols) topic is also key in the safety demonstration and the definition of the measurement needs and aerosol metrology has been done with the first results obtained on aerosol generation during laser cutting using nitrogen vs. air.

Finally, the experimental set-up for hydrogen gas generation during underwater laser cutting has been qualified with specific instrumentation for real-time hydrogen and oxygen gas monitoring.

The experimentations are ongoing with expected results in 2022 and 2023.

Protection of workers and environment

The Technology Qualification (TQ) of the Laser System in relation to the protection of the workers and of the environment in a nuclear decommissioning environment is ongoing with significant achievements so far with the final objective to develop a guideline for the industry for use of laser cutting technology.

The Goals for the Technology have been established against which the Technology Qualification will be assessed.

The full system decomposition (main components/subcomponents) has been implemented along with their TML (Technology Maturity Levels) and IML (Integration Maturity Levels) resulting in a Technology Qualification Plan shared with all partners: tasks to be completed to reduce the technology uncertainties by qualification activities including planning and management of TQ Plan.

Safety assessment

As a first step for the development of the safety assessment, a preliminary risk analysis was carried out in 2021, which includes the identification of risks, potential consequences, and the recommendations for associated safety measures and controls, all synthesized in a matrix of risks for normal conditions and in case of an accident.

This preliminary analysis will serve as the basis for the generic safety analysis, to be developed in later stages of the project, an analysis that will be available to the End Users of the European market, thus facilitating the possibility of including this technology in the safety assessments during the initial phases of decommissioning projects.

Involvement of end-users and dissemination

The project is committed to keeping strong connections with future end-users of the technology and enhancing the dissemination and promote education activities based on the exploitation and communication of the outputs of the project.

A group of 17 end-users and supporting companies have been established with a first workshop held in December 2020 to share the project objectives and gather inputs from the end-users. Questionnaires have been gathered and analysed, they will enable to compile of input data and precise the expectations of the end-users.

The project members have also been actively involved in nuclear conferences during 2021, in France, Spain and Germany concluded at the WNE with a large audience at the workshop held on December 1st 2021 in Paris.

3.3 PLEIADES

Requirements mapping for the design of the PLEIADES concept

The project started with an analysis of the needs and requirements. This gap analysis started with an online survey for gathering input from a large international audience. It provided details about user needs, expectations (of potential users towards emerging digital support concepts like the one developed in PLEIADES), requirements, key performance indicators, as well as blockers and enablers (impacting on possibilities for the adoption of the digital support systems proposed by PLEAIDES).

Identified needs mostly focus on:

- 3D/BIM-based inventory management with a focus on radiological risks.
- Scenario simulation for analysis/optimisation of work plans.
- Safety and risk management.
- Waste route planning.
- Monitoring of work implementation.

Expectations are related to benefits in terms of cost reduction, dose exposure reduction, schedule improvement (speed), time/effort for regulatory/review approval, waste reduction/optimization, training effectiveness and more flexible planning.

Generation of a core nuclear decommissioning specific ontology

As many of the software tools being integrated into PLEIADES already exist and bring along their own history of terms and concepts, it was concluded that a pure terminology-based approach is not suitable. Hence the idea of a common ontology was developed. An ontology is a collection of concepts and the underlying properties that connect these concepts. PLEIADES has defined an ontology specifically designed to represent nuclear-decommissioning projects. The PLEIADES platform and data management will rely on this ontology.

The PLEIADES ontology has also been aligned with results from international organizations, ensuring basic compatibility with international knowledge resources (such as communities of practice or databases).

Fig. 4. 3D models of the nuclear facilities provided by IFE (left), ENRESA (middle) and EDF (right).

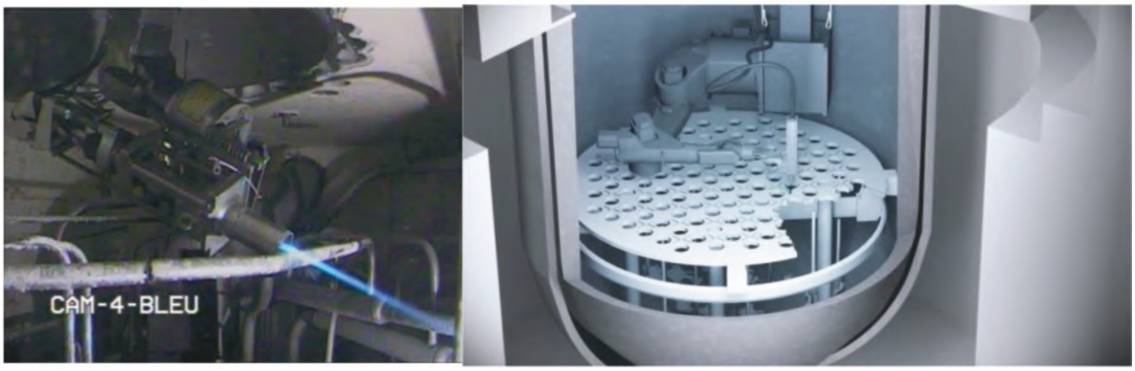

Fig. 5. Laser cutting technology applied to pipe in UP1 CEA facility and cutting and planned application of laser cutting technology in reactor environment (3D view).

Preparation of the prototype validation tests and demonstrations

The consortium has developed user stories to be used as a basis for validation tests to demonstrate the capabilities of the PLEIADES prototype system.

Six user stories were developed in such a way that their implementation in the PLEIADES prototype system will demonstrate capabilities corresponding to most expectations identified previously. They focus on the comparison of alternatives for radiological characterisation, dismantling and decontamination of building surfaces as well as management of risks, regulatory requirements and waste management.

The required data, 3D model features and procedures have been identified for each user story. The 3D models and other facility information are provided by the three partners of the PLEIADES consortiums (IFE-Norway, ENRESA-Spain and EDF-France) that are responsible for the sites selected for the PLEIADES demonstration (respectively, Halden Research Reactor, Santa María de Garoña power plant and Base Chaude Opérationnelle du Tricastin (BCOT)), see Figure 4.

PLEIADES platform architecture specification and development

With the objective of increasing interoperability, the PLEIADES platform architecture has been defined and guided by the following criteria: respond in a commonly accepted and flexible way to the technological heterogeneity of the software tools in the PLEAIDES ecosystem, guarantee that the solution meets data security requirements, while still being demonstrable within the timeframe of the project.

The PLEIADES architecture (see Fig. 5) aims at maximizing the collaboration between the different software modules. It is expected that this collaboration will not happen through direct communication between the different tools, but rather via data exchange to/from a common database with a specific focus on a system design that will take advantage of the common ontology.

The architecture is divided into the client-side and the server-side infrastructure.

The client side includes the interface developed in the domain of each partner's software included in the platform. Expected tools are indicated in Figure 6 (DEMplus® *for nuclear*, already mentioned in project INNO4GRAPH for example).

The server-side infrastructure stores the data and secures the data exchanges. It is divided into the front end (that covers the intelligent features) and the back end (that manages the BIM-like data and ontology-based structured data).

3.4 CLEANDEM

In the project's first year, the Technical Specifications and Concept of Operations have been set, as well as the in-situ operations against which robots are to be challenged.

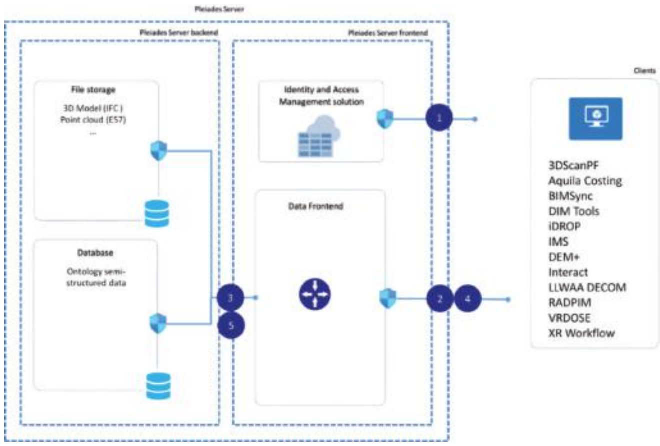

Fig. 6. PLEIADES platform high- level architecture.

Fig. 7. CLEANDEM robotic solution system.

These have allowed the teams to start their developments or eventually resumed them to upgrade them to meet the expected standards of the highly important matter which is the dismantling and decommissioning of nuclear sites.

The system shall be Universal Robot's UR 5e arm mounted on Robotnik Automation's RBVOGUI platform (Fig. 7).

The currently identified location to be the test and demonstration site for the developed technologies shall be located in Saluggia, Italy. No more details can currently be given on it at the moment according to CLEANDEM's project stage.

3.5 INSIDER

The general strategy supported by the INSIDER project for the initial characterisation of remediation sites consists of two complementary phases:

(1) the development of a coupled and iterative approach Sampling/Measurements (and uncertainties)/Data analysis – Mapping.
(2) The implementation of a structured metrological scheme by using Reference Materials of representative (as far as possible) matrices of the site as well as inter-team and inter-laboratory comparisons on real or simulated matrix reference materials.

This strategy is based on advanced statistical approaches, both for the design of the sampling plans and the analysis of the data. The application guide for these statistical approaches [2] and the resulting STRATEGIST (Sampling Toolbox for Radiological Assessment To Enable Geostatistical and statistical Implementation with a Smart Tactic) web tool (see Fig. 8) provides both an overview of the methodology and a step-by-step guide to its implementation in specific cases. The STRATEGIST tool is an open-access tool (`https://strategist.sckcen.be/`) that allows the promotion of all these developments carried out within the INSIDER project.

In situ measurement campaigns, according to pre-established sampling plans, remain essential and are at the heart of the approach. Two guides were drawn up and consolidated following the campaigns conducted as part of the project's benchmarking. The first guide concerns the requirements for implementing the measurement methods [3]. The second proposes an approach for the validation of the in-situ methods implemented [4]. A web-based tool named INSPECT (In Situ Probe SEleCtion Tool) was developed to assist in the selection and implementation of in situ measurements in the case of sites in a constrained environment [5].

Concerning the metrological approach of the project, two certified reference materials were produced with matrices specific to the characterisation problems of D&D worksites, namely high-density concrete and effluent-type solution. They were specially manufactured within the framework of the project by European National Metrology Institutes, NPL, CMI and LNHB (CEA). In particular, the "concrete" Certified Reference Material (CRM) is a unique material obtained from real inactive material taken from the BR3 site.

Statistical processing of inter-team and inter-laboratory comparisons based on these CRMs and Reference Materials (RM) of real samples taken from two different Use Cases sites (BR3 reactor and ISPRA effluent tank) provides valuable information on method performance and measurement uncertainties in real cases. This information is essential to improve confidence in the characterisation results. The approach for establishing the uncertainty budget for the initial characterisation of a site prior to its decommissioning and the application to the different Use Cases of the project are described in [6,7].

In terms of dissemination, the Insider project has set up a dedicated SoK (State of Knowledge), located on the European Commission's website. The tool for managing the SoK is the web-based Community "Managing decommissioning and radioactive waste management knowledge" at the JRC Science Hub.

The future exploitation of this work in France and Europe through common methodologies and guides requires a transfer of knowledge and results from the project to international standardisation bodies, ISO, ASTM, IAEA, AFNOR/BNEN, etc. Based on the initial mapping of existing documents, recommendations have

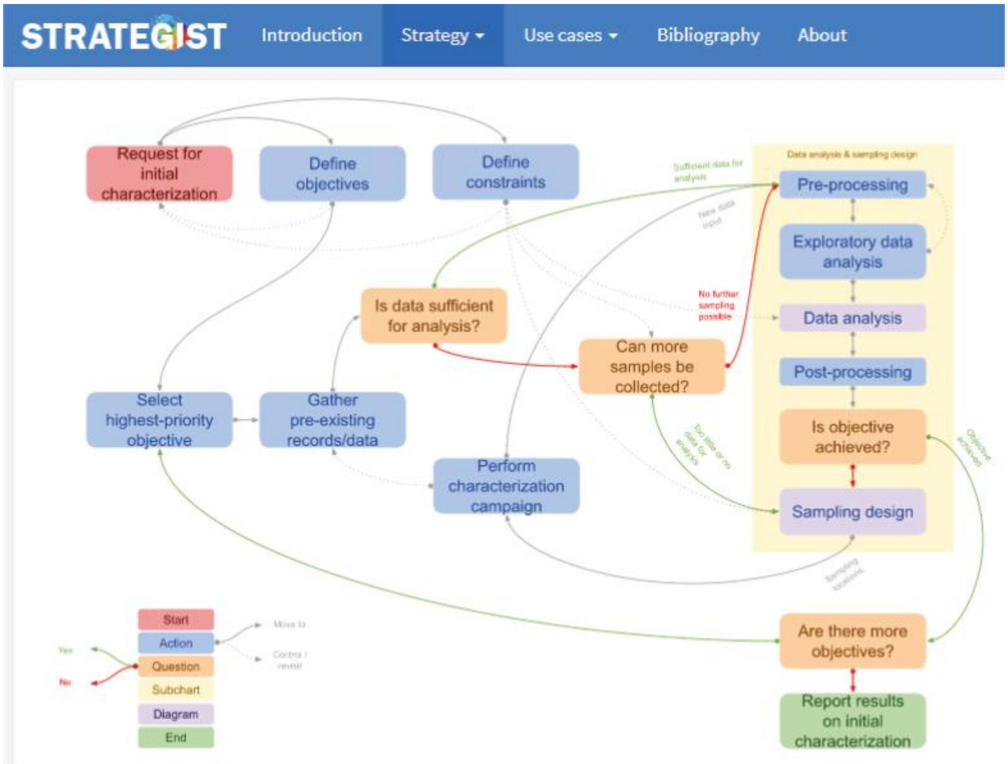

Fig. 8. Strategist Web tool.

been made [8] identifying the technical themes to be prioritized for future proposals for standards.

4 Conclusions and perspectives

The INSIDER project is now terminated and could be potentially continued in a European EURATOM framework to extend the methodology developed in the project to other D&D or waste site characterisation issues (also based on the roadmaps from the European projects EURAD and SHARE).

The LD-SAFE tasks will continue for the next two years more specifically the case study development and the construction/operation of the demonstrator. At the end of LD-SAFE, the suitability of the laser cutting technology to address the challenges of the dismantling power nuclear reactor and its capability to improve these projects in respect of safety, radioactive waste, time and cost will be confirmed based on the demonstrators and the other project outputs as the Technology Qualification and the Generic Safety Assessment. The next step should be the first deployment on a reactor decommissioning site as a world first.

Also continuing, the INNO4GRAPH project will now develop innovative cutting and handling tools which may be tested in the industrial demonstrator to make them available during the dismantling operations; while PLEIADES will develop and demonstrate a platform integrating many tools for dismantling operations.

CLEANDEM is now at halfway and, following the Technical Specifications, CONOPS and preselected tests and demonstration sites, the project team is developing technical solutions to address the characterization needs in D&D (notably reducing operator's exposure and reducing the overall time and costs of operations). CLEANDEM is thus clearly addressing an issue of D&D and will allow important improvements in terms of characterisation quality for the operators.

CLEANDEM developments will allow to radiologically characterize D&D environments which will then be implemented in a 3D model of their Digital Twin, all the while avoiding human exposure to radiations enabled by remotely operating the robot and its embedded sensors.

Moreover, the remotely-operated robot and technologies developed in the frame of CLEANDEM will allow low-cost dose rate and contamination mapping, directly for accessible grounds, walls or pipes, but also the airborne contamination. The developed technologies will also allow for distant measurement, either by identifying radiological hotspots through gamma spectrometry imaging or with distributed OSL optical fibres, combined with shape sensing, which will be capable to reconstruct a 3D dose-rate map of usually unreachable locations.

Even if many developments still are in their early stage, some visuals can be shown of the pixelated surface contamination monitor, the Nanopix coded-aperture gamma imager with spectrometric abilities developed by CEA (see Fig. 9)

The 5 projects supported by the European Commission over the period all have the common goal to

Fig. 9. Contamination Monitoring System and Nanopix gamma imager with spectrometric abilities developed by CEA to be implemented in the CLEANDEM robotic system.

implement technologies of the "4.0 Industry" in the nuclear dismantling sector. This objective aims to benefit from the lever of efficiency and reliability represented by these technologies, which must make it possible to:

- improve the reliability of the knowledge of the installations to be dismantled;
- minimise dose rates to workers, making the "as low as reasonably achievable" very low; To make it reasonably achievable, more intensive use of remotely carried out operations is necessary, and the rate of this operation must be increased. This will be made possible by mastering these 4.0 industry technologies and their implementation in the nuclear dismantling field;
- facilitate and make the exchanges/sharing of information between the stakeholders of a dismantling project more efficient.

Beyond the traditional technical locks which are on the way to the implementation and the adoption of this type of technology, two other challenges are common to all the projects presented here:

- tools and methodologies must be applicable to a maximum of projects in different countries and contexts. It is commonly agreed that it would be often more efficient, but not always possible, to adapt a proven technology or methodology from one country to another, rather than developing a new method or technology ex nihilo.
  It is also of great interest to develop as many as possible versatile tools, in order to reduce the time-consuming approach of equipment or switching of tools etc. However, the more complex the design, the less reliable and the less simple the maintenance. It is thus necessary to tackle this contradiction in the research and the implementation of new technologies in nuclear dismantling practices. This challenge is even bigger when considering the next major point that is to be considered at the same time.
- Indeed, drastic proof of both the safety and reliability of these new technologies are required for being acceptable in nuclear activities. A special effort has therefore been made in each of the projects to establish and take into account the developments, and the different regulatory, technological and societal contexts of each European country.

Due to these constraints, the works so far made in the five projects result in:

- a unique common data and knowledge base, as well as a significant sharing of experience on dismantling projects already carried out or to come.
- New tools design or methods natively taking into account the needs of a maximum of dismantling operators (rather than a design centred only on one operator or one facility or one dismantling project). Consequently, ten different European countries are involved in the five projects, plus Switzerland, Ukraine, United-Kingdom and Japan.
- New test facilities have also been put in place and will allow the joint work undertaken to be continued.

All of this paves the way to further collaborative projects and developments, in order to continue to implement safe, reliable and efficient new technologies in European dismantling projects. Based on this technical excellence, Europe is currently building a high-performance nuclear dismantling sector, generating activity and skilled employment in various sectors (engineering, robotics, digital, design of equipment and special machines etc.).

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 intellectual property and industrial protection reasons.

Author contribution statement

The author's respective contributions to the full paper are listed: N. Malleron acted as the coordinator of the full paper. M. Guerin and P. Lefevre contributed to the paper by providing specific information on the INNO4GRAPH project (Sects. 2.1 and 3.1). D. Roulet contributed to the paper by providing specific information on the LDSAFE project (Sects. 2.2 and 3.2). C. Rivier, contributed to the paper by providing specific information on the INSIDER project (Sects. 2.3 and 3.3). M. Michel, contributed to the paper by providing specific information on the CLEANDEM project (Sects. 2.4 and 3.4). M.-B. Jacques contributed to the paper by providing specific information on the PLEIADES project (Sects. 2.5 and 3.5). Common sections of the full paper (Sects. 1 and 4) have been written collaboratively with the contribution of all the authors.

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Review Article

Open Access

Supporting access to key pan-European research infrastructures and international cooperation

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Abstract. Large research infrastructures, especially nuclear ones, are extremely expensive to build and operate. Therefore, to develop expertise and competences in nuclear research is more efficient to have a limited number of complementary specialized large nuclear research infrastructures, shared by European researchers from different countries.

This paper describes three different actions to improve the European collaboration in the experimental nuclear research, namely open access to the nuclear research infrastructure of the JRC, the optimization of the use of research reactors in Europe and operation planning of the Jules Horowitz reactor currently under construction.

Supporting access to key pan-European research infrastructures strengthens research and innovation, avoiding duplication and optimising resources. It contributes to the European Research Area (ERA) and the European Strategy Forum on Research Infrastructures (ESFRI), as well as to maintaining competence in the EU, which is one of the objectives of the Euratom research and training programme.

1 Introduction

Large research infrastructures, especially nuclear ones, are extremely expensive to build and operate. Therefore, for developing expertise and competencies in nuclear research, it is more efficient to have a limited number of complementary specialized large nuclear research infrastructures shared by European researchers from different countries.

Different projects aiming at supporting the effective use of European nuclear research are running within Euratom. In this paper, three of them are described. Since 2002, the JRC has been providing access to its installations through different projects, and in 2019, a new project started, making it possible to provide financial support to the users of the JRC's nuclear research infrastructures.

In the case of the European Research Reactor (RR) fleet, the access strategies for the future are made in the TOURR project. The goal is to evaluate the current and future need for neutron sources in Europe along different science and technology axes.

Finally, the plans and access rights of the Jules Horowitz Materials Testing Reactor (JHR) are also described by the JHOP2040 project. As Euratom owns 6% of access rights to the reactor capacity, it is of utmost importance that these access rights are used effectively. The EU-JHOP2040 project is developing the first roadmaps for the use of Euratom access rights covering the first 15 years of the JHR operation.

2 Open access to the nuclear research infrastructure of the JRC

Since 2002, one of the objectives of the Euratom research and training programmes has been to maintain and further develop the scientific competencies in the nuclear area and the availability and the optimisation of the use of research infrastructures in Europe.

To fulfil this objective, while contributing to the European Research Area (ERA), the JRC has been providing access to its nuclear research infrastructures in the frame of collaborative EU research projects and agreements and dedicated JRC programmes.

The JRC's open access programmes enable scientists from EU Member States and associated countries' organisations, universities and strategic partners to carry out experiments at the world-class JRC's research laboratories. At the same time, the programmes contribute to the

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development of competencies and skills of young scientists and professionals and the development of nuclear technologies.

The infrastructures [1] where access has been provided are:

(a) ActUsLab (Actinide User Laboratory) is a facility for research on actinide science, preparation of nuclear samples and their characterisation to understand their chemical and physical properties in different environments.
(b) EUFRAT (European facility for nuclear reaction and decay data measurements) comprises accelerator laboratories for investigating neutron-induced nuclear reactions and radionuclide metrology laboratories for accurate measurements of radioactivity.

The open access programme's implementation follows the principles of the European Charter for Access to Research Infrastructures [2]. There are two modes of access: relevance and market-driven. In the relevance-driven mode, a committee composed of external experts representing the stakeholder community carries out the evaluation; the selection criteria are the relevance of scientific, educational, and socio-economic aspects of the proposals received, their relation to the JRC's programme and its strategic importance for Europe; this mode is mainly oriented to Academia and Research Institutions. The market-driven mode is mainly oriented to industry; the JRC selects the projects to be granted, and the costs are charged by the user.

2.1 ActUsLab (Actinide User Laboratory)

Actinides are key for nuclear fission technologies for nuclear energy and non-energy applications. They have very peculiar and complex chemical and physical properties. Besides their fundamental scientific interest, understanding their properties is also vital for the safety of their use in any technological application.

One of the few facilities worldwide to perform research on the basic properties of actinide materials is ActUsLab. Opening the facility to external users enhances the cost-effectiveness and, through collaboration and networking, increases the value and quality of the research and can lead to new research areas. Training the next generation of actinide scientists and technologists also contributes to maintaining and developing competencies in the EU.

The facility includes the following installations.

- **PAMEC (Properties of Actinide Materials under Extreme Conditions)**: an ensemble of state-of-the-art installations designed for basic research on the preparation, behaviour and properties of actinide materials under extreme conditions of temperature, pressure, external magnetic field, and chemical environment. The facility includes devices for measurements of crystallographic, magnetic, electrical transport, and thermodynamic properties, Mössbauer spectroscopy and surface science spectroscopy.
- **FMR (Fuels and Materials Research)**: dedicated to the synthesis and characterisation of actinide-bearing materials, up to temperatures of several thousands of degrees. It includes sample fabrication methods, encapsulation techniques and characterisation methods, such as x-ray diffraction, vibrational spectroscopy, electron microscopy, calorimetry, mass spectrometry, dilatometry, indentation, and laser heating, for the measurement of thermophysical properties.
- **HC-KA (Hot Cell Laboratory – Karlsruhe)**: laboratory consists of 24 shielded hot cells to analyse the behaviour of nuclear-spent fuel and radioactive wastes aiming to contribute to safe and cost-effective solutions for their treatment. Highly radioactive materials, including full-length light water reactor pins, can be handled at the installation. Access to HC-KA has been offered since 2020.

Since 2002, ActUsLab has delivered 1949 access units (operating days) to about 200 users, including about 45 Ph.D. students, on 144 projects (out of 237 submitted).

In the period 2014–2020, 46 projects were accepted (out of 62 proposals), including the participation of young researchers, 25 Ph.D. and 2 master's students performed experiments at ActUsLab. In the same period, 37 peer-reviewed papers resulting from the experiments performed were published.

ActUsLab collaborates as well with the key actors in the nuclear field worldwide, and it is involved in the organisation of the reference international scientific conference "Journées des Actinides (JdA)", and in the biannual actinide science school dedicated to students and young professionals.

2.2 EUFRAT (European facility for nuclear reaction and decay data measurements)

EUFRAT is a unique infrastructure that provides state-of-the-art reference nuclear data, materials and measurements for harmonisation and standardisation. The reference data and materials obtained are essential for the safe operation of nuclear reactors, safe management of nuclear waste, nuclear decommissioning, and the radiological protection of the persons and the environment. They are a reference used for other applications such as medical radionuclide production, fundamental physics, nuclear astrophysics, materials research, and cultural heritage.

The infrastructure comprises the following facilities:

- **GELINA (Neutron time-of-flight facility)**: it combines four specially designed and distinct units: a high-power pulsed linear electron accelerator, a post-accelerating beam compression magnet system, a mercury-cooled uranium target, and flight paths with measurement equipment;
- **MONNET (Tandem accelerator-based fast neutron source)**: it produces continuous and pulsed proton-, deuteron- and helium ion beams, serving as a source of well-characterised quasi-mono-energetic neutrons;
- **RADMET (Radionuclide metrology laboratory)**: it is used for accurate nuclear measurements and decay properties of radionuclides;

- **HADES (Low-level radioactivity laboratory)**: hosted in the deep-underground facility of the Belgian Nuclear Research Centre (SCK/CEN). Because of the low cosmic ray flux, in this laboratory, it is possible to detect very low amounts of radioactivity.

In the period 2014–2020, 75 Institutions, as research institutes and universities of EU Member States and associated countries to the programme, had access to EUFRAT facilities to carry out 112 projects. The projects included the participation of 28 Ph.D. and 11 master's students.

For the success of the project, the users' engagement is essential from the design phase. The projects are designed together by the JRC and the user Institution, continuing with the execution of experiments, analysis of the data, and preparation of publications. This interaction is beneficial for both Institutions, meeting the needs and requirements of the users and expanding the JRC research areas.

2.3 ACCESS (Open access to JRC nuclear research infrastructure)

To increase the impact, obtaining synergies between the JRC and indirect action of the Euratom research programme, the Commission services launched, 2019, a project aiming to enhance the scope of the existing schemes by further facilitating the mobility of researchers within EU. The project started at the beginning of February 2020, with 4 years duration.

The JRC continues offering free (of charge) access to its research facilities, promoting training and mobility activities and helping to maintain nuclear competencies in the EU. The new scheme, designed for this project, provides financial support to eligible users to cover their travel and subsistence costs.

Additionally, to the infrastructures already allowing open access, the Access project includes the laboratories in Petten (NL):

- AMALIA: Ageing of Materials under the effect of environmentally assisted stress corrosion cracking.
- LILLA: Liquid lead Laboratory.
- SMPA: Structural Materials Performance Assessment Laboratories.
- MCL: Micro-Characterization Laboratory.
- HFR-NB: High Flux Reactor Neutron Beams for residual stress measurements.

Financial support is offered to users coming from non-profit Institutions such as universities, research centres, and similar. The support can partly cover the travel and subsistence costs of users related to their access to the JRC nuclear infrastructure. Two types of user support are offered:

- short stay users, focused on the execution of approved experiments. The users are typically experts in the field, and the duration is about 10 operating days.
- Longer-stay users, primarily Ph.D. or master students, are linked to the approved experiments and with a focus on their education and training objectives. The duration of the stay can be extended to several months, receiving, in this case, a monthly allowance.

The first call for proposals was launched in July 2020, and 43 proposals were received. Three independent panels evaluated them, resulting in 18 accepted proposals for EUFRAT and 9 for the Petten laboratories. ActUsLab accepted 10 proposals holding six on a reserve list due to its own capacity to carry on the projects. Only one project was rejected, which shows the high quality of the proposals.

The impact of the COVID crisis on the project is very big. The access of the staff to the laboratories was very restricted and not allowed at all to visitors. Given the complexity of the projects, the ActUsLab projects (Karlsruhe site) had to be postponed, the first proposal could start only in September 2021, and four have started in January 2022, with all the others being prepared. The EUFRAT installation could adapt some proposals to be carried out remotely; three were performed, and two have started. The situation is quite the same in the Petten laboratories, the first project started at the end of 2021, and it is planned to start the others in 2022. After some adjustments, a second call was launched in 2021–2022.

3 Towards optimised use of research reactors in Europe-TOURR

The TOURR project is a response to the challenge of coordinating the optimisation of the exploitation of available research reactors in Europe [3], a project that started in October 2020.

The project's primary objective is to develop a strategy for using RRs in Europe and prepare the ground for its implementation. To achieve this goal, 6 specific steps have been identified.

I. Assessment of the current status of European RR fleet – Accomplished

As a starting point, there is a need to compile the inventory of existing RR. From the database created and maintained by the IAEA [4]. The information gathered under the TOURR project goes beyond what is already collected in [4]. Information, like the scope of implemented applications, scientific strength of each particular facility, user structure, instrumentation, future developing plans, actual and future needs, etc., has been collected via a questionnaire [5] and will be used as the base for deriving the strategy.

II. Estimation of future needs of RR and neutron sources

The main applications of the European RR fleet are classified into 5 categories:

(a) education and training.
(b) Basic and fundamental research and its instruments.
(c) Medical applications, including isotope R&D as well as beam applications.

(d) Material testing, including fuel, structural material and related instrumentation.
(e) Core physics testing for reactors in "zero power" installations.

III. Plan for the upgrade of the RRs fleet

Starting from the picture of the current status, which will be obtained with the questionnaire, it will be possible to suggest an updated plan to be developed for the use of the European RR fleet. The idea is to take into consideration also the fact that some major facilities are currently under construction. It is a fact that there is a need for RR increased availability because of the demand for isotope production (and the need to assure the supply), just to name one reason.

IV. Plan to maintain the fleet

Since the ultimate goal is to suggest an optimisation strategy, the analysis of potential problematic aspects will have to be performed. Information on which factors influence the sustainability of the RR will have to be gathered, spanning from component ageing to the cost of upgrades, including potential problems related to personnel turnover.

V. Developing tools for optimal use of RR fleet

The idea in this phase is to learn from other projects and initiatives that are already showing a great example of optimised use of resources and can be used as a model for the RRs fleet. Examples can be found in the coordination schedule of radioisotope production, the use by the international community of Material Testing Reactors (MTR) or also in the neutron scattering facilities coordination.

VI. Rising awareness of decision-makers and the public on the role of RR

A share of the public still sees them as nuclear power plants, often perceived negatively, while RRs are, in fact, modern research facilities providing answers to the challenges of modern society: in the field of health, energy, technology and cultural heritage, just to name a few. The suggested strategy for optimal use of RRs shall present all areas of application with emphasis on major achievements, and demonstrate how often research with neutrons led to practical applications used by everyone in everyday life.

3.1 TOURR Structure

The TOURR consortium is composed of 9 participants located in different EU countries. Six of them are RRs operators. The project is structured into four work packages as follows.

WP1 – Inventory of RR fleet

The main objectives of WP1 are:

- to collect data describing this database providing information about applications, future plans, and capacities of the RRs;
- to perform gap analysis in three domains: Research & Development, Medical applications and Education and Training.

WP2 – Assessment of needs and opportunities to support supply of medical radioisotopes

The world demand for medical radioisotopes is indeed growing: they are needed both for therapy and medical therapy applications. Furthermore, newly developed medical imaging techniques and new therapies require the use of new radio-pharmaceuticals.

WP3 – Tools for optimised of use of European research reactors

The specific objectives of WP3 are to:

- elaborate a strategy for optimised use of RRs in Europe;
- deliver the tools to support the implementation of the same strategy;
- support the planning of refurbishment of existing research reactors or construction of new ones (an assessment of to what extent existing and new RRs will fulfil the future needs);
- furthermore, crucial time gaps in the transfer between existing and future RRs will be identified.

WP 4 – Dissemination and outreach

3.2 Current status and vision

The project is currently in the second year of its implementation. It started in October 2020 and is scheduled to last until September 2023.

A survey was already conducted among European research reactors [6] and received an 84% of response rate. Data received are from Austria, Belgium, Czech Republic, France, Germany, Hungary, Italy, The Netherlands, Poland, Romania and Slovenia.

To decide who will participate to the survey, the starting point was represented by the information found in the IAEA RR database [5]. This information is public. For the task scope, facilities have been selected using the following filters: western Europe + eastern Europe + operational (Fig. 1).

A public report containing bulk considerations (to ensure confidentiality of the data transmitted to us by the RR) has been compiled and is available at this link [3]. If we consider the educational purpose of those RRs, according to the findings, most users of the RR fleet is represented by people working in the neutron activation analysis, closely followed by material scientists. Most are used by Master level experts while the private sector is dominated by R&D professionals and radiopharmaceutical experts. When it comes to technological applications, the majority of RRs involve neutron scattering and neutron activation analysis at a high level.

Left at the end, due to high importance, the majority of RRs cover the medical application field. More specifically, the production of medical radioisotopes in large quantities needed for nuclear medicine and, as a secondary focus, the production of radioisotopes for research purposes.

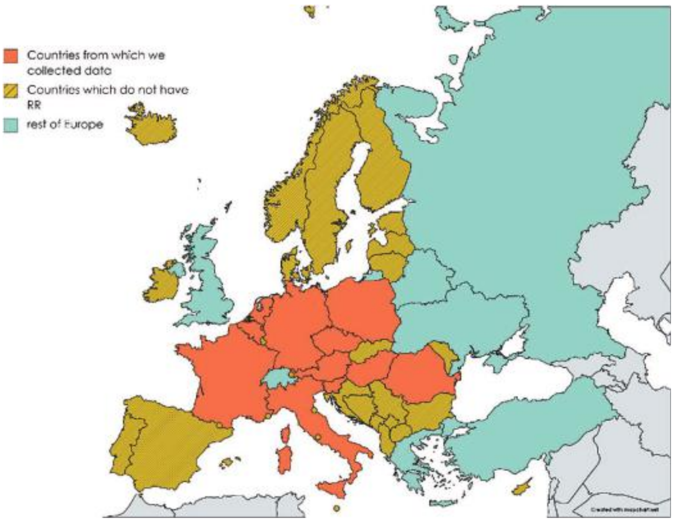

Fig. 1. Countries from which the data has been collected for the TOURR project.

About half of the RRs can satisfy all the demands they receive, and many RR already have private collaboration agreements in place to ensure continuity of supply.

Furthermore, three gap analyses on Research and Development, Medical applications and Education and Training have already been performed. Given the confidentiality required by our data contributors, we can safely observe from the analysis that there is a need to attract more people to the nuclear field since, in several cases, the lack of workforce was indicated as one of the problematic aspects.

Furthermore, once new personnel is attracted and retained to the nuclear sector (which demands some financial stability for the facilities, among other things), it should be found way to provide pedagogical tools to these people.

Finally, the RR community manifested a lack of exchange of information in some cases (understandable given the sensitivity of some data and the commercial implications). Hence the work done within TOURR acquires even more importance, in particular, if one thinks of the platform which will be realised and put online to facilitate information among RRs and between the RR community and the general public.

4 Jules Horowitz Operation Plan (JHOP2040)

Material Testing Reactors have been, for many decades, key research tools for fuel and material behaviour studies under neutron flux supporting nuclear industries, research institutes and regulators. Whatever the progress in simulation, MTRs will remain a necessity for the qualification of new fuels and materials under irradiation, notably in support of safety demonstration. Currently, in response to this need, the Jules Horowitz Reactor (JHR) is under construction. The JHOP2040 project presents a Coordination and Support Action aiming to (1) bring together with the JHR consortium of key actors, all relevant European nuclear research associations and member states that are not represented in the JHR consortium and (2) to produce strategic research roadmaps for the operation of the JHR. These roadmaps will cover the first 4-year programme and the following 11 years of operation. The outcome of JHOP2040 will be a financial and programme model for Euratom, taking into account also the governance and cost breakdown of the programmes. The JHOP2040 will strengthen and widen the JHR research network by bringing together relevant stakeholders and interest groups to identify and review their current and future needs for fuel, material and technology issues within and outside of the current JHR consortium. Extensive utilisation of the JHR via Euratom access rights and full use of the planned JHR capacity by promoting and enhancing the collaboration between potential users is the ultimate goal.

The scope of the research and training needs considered by the JHOP2040 includes activities in support of:

- current generation NPP, including component optimisation, lifetime extension, enhanced surveillance, enhanced safety of operation and inspection and waste minimisation;
- material, fuel and design development for the next generation of fission nuclear plant,including Small Modular Reactors (SMRs), Advanced Modular Reactors (AMRs), Liquid Metal-Cooled Fast Reactors (LMFRs), Gas-Cooled Fast Reactors (GFRs), Molten Salt Reactors (MSRs), and High-Temperature and Very High-Temperature Reactors (HTRs and VHTRs);
- materials irradiation and development for fusion reactors.

In this paper, we focus on planning the first four years of operation even if some references to the following 15 years will also be given.

4.1 JHR experimental capacity during operation

The start of operation for the JHR has not been announced yet, but most likely, it will happen during the next decade. The start of experimental programmes will be done in two steps. The first fleet of experimental setups will be limited to tests that are generally recognised to be the most needed. As the start of operation is known to be demanding in many ways, it is considered unnecessary to include all possible devices at the same time. It is to be expected in any case that the first experimental programmes will be started in a stepwise manner.

4.1.1 JHR experimental capacity in the start-of operation phase

The experimental capacity of the JHR will be realised in two fleets. The first fleet covers the equipment that is considered needed in the start-of-operation phase. That equipment will be Material devices MICA and OCCITANE and fuel devices MADISON and ADELINE, as well as NDE benches and neutron imaging.

The MADISON test device is designed to carry out irradiations of LWR fuel samples, during which no clad

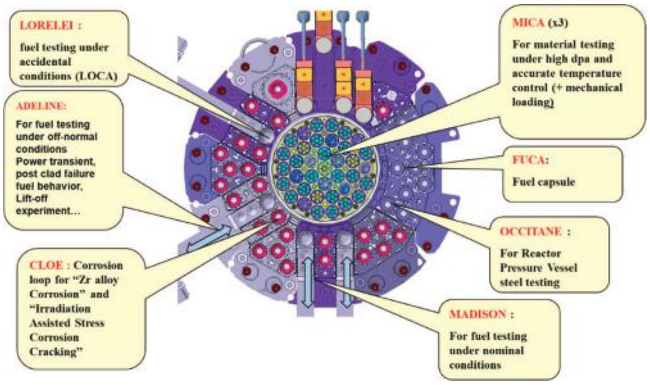

Fig. 2. JHR core experimental positions.

failures are expected. Consequently, the experimental conditions correspond to the normal operation of power reactors (steady states or slow transients that can take place in nuclear power plants). This experimental device is made of an in-pile part (holding the fuel samples) fixed on a displacement system. This system allows online regulation of fuel linear power on the samples.

ADELINE test device is able to hold a single experimental fuel rod from all LWR technologies to reproduce various experimental irradiation scenarios in which a clad failure is either a risk or an experimental objective. Similarly to the MADISON test device, this experiment is made of an in-pile part located on a displacement system in the JHR reflector and an out-of-pile water loop.

MICA test device is designed to irradiate structural materials in the core of the JHR within a fuel element. The typical temperature range is between 280 and 450 °C for the samples. Seven different locations are available for MICA devices: two in the first ring, two in the second ring and three in the third ring of the JHR core.

In the field of pressure vessel steels of NPPs, irradiations are carried out to justify the safety of this second containment barrier and improve its lifetime and, consequently the lifetime of the reactor itself. For this purpose, CEA is designing a hosting system named OCCITANE, which allows irradiations in an inert gas at least from 230 to 300 °C.

Gamma Scanning and X-ray tomography systems for NDE investigations before, between and after irradiation fuel cycles will be available in the reactor pool, in the storage pool and in the hot cells (U/HGXR).

A Neutron imaging system (NIS) will be installed in the reactor pool primarily intended to back the power ramp tests but also to secure the JHR imaging capacity and take advantage of the very different interaction of neutrons with the matter.

4.1.2 JHR experimental capacity after the start-of-operation phase

The second fleet of devices will expand the experimental capacity for e.g.:

- characterising new cladding materials, new fuel materials, new fuel assembly designs, new fuel management strategies (high burn-up, high duty) and the corresponding FP releases in LOCA situations (LORELEI device);
- a simplified fuel irradiation capsule (FUICA) in addition to the irradiation test devices;
- a mechanical loading device for irradiation experiments (MeLoDIE) to study biaxial creep online during irradiation;
- a corrosion loop to study the phenomena of irradiation-assisted stress corrosion cracking (IASCC) in the structural materials (CLOE);
- a test loop RISHI for irradiation studies in sodium at high temperatures dedicated to GEN IV structural material samples testing at different temperatures.

These devices will be available in the JHR after the start-of-operation phase.

4.2 Start-of-operation strategy for the JHR

The planning of the experimental programmes is mainly done by three JHR Working Groups for fuel (FWG), materials (MWG) and technologies (TWG). These WGs have communicated and collected the interests of not only the JHR consortium members but also those of non-JHR members in different questionnaires and made the ranking lists based on those answers.

Based on the needs listed, the main focus at the beginning of operation will be:

- for material studies: the experiments of greatest interest to the European nuclear community are mainly R&D actions related to LWRs, both those in current operation (i.e., Generation III reactors) and those in the process of building and start-up (Generation III+ reactors). The main objectives of these actions are characterisation of material behavior in the normal reactor or incidental operating situations and performance improvement. In the short-to-medium term, the community is looking to perform R&D actions which will provide information, making it possible to justify the integrity of the various structures, including in incidental situations (e.g., loss of the primary coolant for the vessel); to optimise their maintenance; and to validate their operation, including support for the evolution of the design margins and justifications for extensions to operational lifetimes.
- For fuel studies: focus will be on testing of the irradiation devices and checking the capability of each device to produce experimental results under actual irradiation conditions that are consistent with the expected uncertainties and ensure that the results obtained match correctly with the existing experimental domain for qualification, constructed with inputs from other research reactors and used for the qualification of many scientific calculation tools. This point is crucial for future experiments. In long-term planning, the investigations of fuel rod behaviour in both normal operation (including transients) and during design basis accidents (loss of coolant accidents and prompt reactivity induced accidents) will be in focus. Current fuel designs, evolutionarily advanced technology fuel designs and fuels for SMRs are all considered.

- For technologies: focus will be on qualifying tests for the experimental devices. In practice, many of these activities need to be performed before the onset of JHR operation in anticipation of using the JHR irradiation devices during the commercial period. For technological issues, it has been recognised a long list of new or improved existing technologies will require attention. Therefore, the technology development will not eventually depend on the phase of operation as much as it is for the fuel and material studies, but technologies will be developed on a constant basis or as needed.

4.3 Ways of operation of JHR experimental capacities

JHR, as a future international User Facility, is funded and steered by an international consortium gathering industry (utilities, fuel vendors, ...) and public bodies (R&D centres, TSOs, regulators, ...). The generic model of the JHR consortium is the following:

- CEA remains the owner and the nuclear operator of the nuclear facility with all liabilities.
- JHR Consortium Members are the owners of Guaranteed Access Rights to the experimental capacities in proportion to their financial commitment to the construction and with proportional voting right in the Consortium Governing Board.
- A Member can use totally or partly his access rights for implementing proprietary programs with the full property of results and/or for participating in the Joint International Programs open to non-members.
- JHR consortium membership is open to new members until the completion of the reactor.

CEA is encouraged by the consortium to enlarge JHR membership and, as of early 2022, the present member's list of the JHR consortium is the following:

CEA (France), EDF (France), FRAMATOME (France), TECHNICATOME (France), AREVA.SA (France), EUROPEAN COMMISSION, SCK-CEN (Belgium), CVR-UJV (Czech Republic), VTT(Finland), CIEMAT(Spain), STUDSVIK (Sweden), DAE(India), IAEC (Israel), NNL (UK), CGN(China).

Let us illustrate how the European Commission could tell us its Access Rights for the benefit of European Member States.

The EC (Euratom-JRC) – considering its contribution to the construction – gets:

- 6% of guaranteed Access Rights to JHR experimental capability for the whole life of operation of the reactor;
- 6% of voting rights in the JHR Consortium.

Regarding the utilisation of the Access Rights, they can be cumulated to some extent from one year to the following in order to implement greater research programs in one specific year (either proprietary program and/or Joint program (including shared with other Members).

The Operation Phase of the reactor will be partitioned into 4-year operation periods and shall be managed in consideration of the Reference Operation Plan (ROP) drawn up by the project leader for each four-year period and validated by the Governing Board.

To illustrate the Access Rights in the comprehensive unit as the quantity of experiments, let's converse Access Rights (AR) to Access Units (AU) regarding the experimental capacity of the JHR and the various factors associated with each experiment type. These Access units have to be seen as some "units of account" for the use of neutron flux and experimental capacity.

Let us consider, as an example – see Figure 2, the following experiments distribution in JHR core and reflector representative of the present developments: each experiment represents a number of Access Units depending on different parameters as indicated later on.

The weighted analysis of each experiment versus various factors, such as neutron flux, volume, complexity, and impact factors, is presented in the table below. This weight is taken as a reference Access Unit of the experiment for one cycle. This assessment of the use of Access Rights to perform experiments in JHR depends on various factors.

To translate these Access Rights to Access Units for each experiment, we need to take into account:

- the large variety and the specificities of these experiments,
- the number of experiments performed per year.

To illustrate such approach, the following example of possible weighting per type of experiment is considered in Table 1.

4.3.1 Example of experimental possibilities for European Commission with 6% Access rights

With the JHR configuration and operation described above, 6% of Access Rights represents about 78 Access Units per year (6% of 1318).

So, the EC, with its 6% Access Rights, can have access each year to:

- 7 to 8 Ramps type experiments using ADELINE device,
- or 6 Fuel loop irradiation type experiments using MADISON device,
- or 3 Material capsule-type experiments (Tab. 2).

5 Conclusions

Supporting access to key pan-European research infrastructures strengthens research and innovation, avoiding duplication and optimising resources. It contributes to the European Research Area (ERA) and the European Strategy Forum on Research Infrastructures (ESFRI), as well as to maintaining competence in the EU, which is one of the objectives of the Euratom research and training programme.

The current scheme of open ACCESS to JRC's infrastructure helps to bridge the gap between high and less wealthy institutions in the EU. The selection procedure, based on the scientific merit of the proposals and including feasibility assessment, as well as the strong collaboration of JRC staff members with users, are key factors for the success of the programme and its outputs. The number of participating organisations in previous schemes and the

Table 1. Preliminary weight factors of different experiment types in the JHR.

Kind of experimentation	Fixed part			Variable part			Impact factor (Fuel consumption, performances, ...)	"Weight" total
	Neutron flux factor	Equipment complexity factor	Utilities (water, electricity, ...)	Volume factor	Operation complexity factor	Services (NDE, FP lab, hot cells, ...)		
MADISON	1	3	2	1	3	2	–	12
ADELINE	1	3	1	1	2	2	–	10
MICA	1	2	1	1	2	0	1	8
Specific MICA	3	2	1	1	2	1	2	12
LORELEI	2	3	2	1	3	3	–	14
OCCITANE	1	1	0	3	1	0	2	8
CALIPSO	3	2	2	2	3	3	1	16
CLOE	1	3	2	1	2	2	1	12
Fast reactor support	3	3	2	2	3	3	–	16
Boiling device	1	2	1	1	1	2	–	8

Table 2. Example of the JHR loading plan.

Example of loading plan A.U. = Access Units			
Type of experiment	Associated Access Unit per experiment and per cycle	Number of JHR locations for the type of experiment considered	Cumulated number of Access Units per year (on the basis of 7 cycles per year)
Fuel ramps studies (ADELINE)	10	3	210
Fuel loop steady-state studies (MADISON)	12	2	168
Fuel loop for LOCA studies (LORELEI)	14	0, 3 (we consider only 3 LOCA tests per year)	30
Fuel capsule studies (FUCA)	10	4	280
Material capsule studies in core (MICA)	8	3	168
Advanced MICA in core	12	2	168
RPV studies in reflector (OCCITANE)	8	2	112
Corrosion studies (CLOE)	12	1	84
FR material studies	14	1	98
TOTAL	100		1318

JRC agreements with other strategic partners ensure the project outreach in the specialised scientific community.

The strategic planning for optimising the use of the research reactors is ongoing at the same time when one of the most important future research facilities, namely the JHR, is under construction. The TOURR project has six specific steps that are used to ensure that the available reactor capacity is used with the maximum advantage for not only nuclear research but also medical and education and training. On the other hand, the JHR will aim at a new generation of research capacity with a wide experimental device fleet under construction. The JHR will be one of the most important research facilities not only in Europe but also in the world- widely and currently, the operation planning in parallel with the construction is taking the various needs into consideration. Euratom's share of the future capacity will benefit the whole Euratom society eventually.

The experiences gathered in the implementation of open access projects in previous and current Euratom research and training programmes are a very good basis to be used for the design of future schemes for all kinds of nuclear facilities.

Acknowledgements

"Open access to the nuclear research infrastructure of the JRC" is based on JRC reports as the periodic reports released for the research groups on the EUFRAT and ActUsLab projects and the 1st periodic report of the ACCESS project. It is also based on the Impact case study "Open access to JRC research infrastructure 2014–2020". The JHOP2040 work has received funding from the Euratom work programme 2014–2020 under grant agreement No. 899360. The TOURR project has received funding from the Euratom research and training programme 2019–2020 under grant agreement No. 945269.

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.

Author contribution statement

Victor Esteban-Gran is the author of the text handling the project "ACCESS". Gabriel Pavel is the author of the text handling the project TOURR. Petri Kinnunen is the main author and Gilles Bignan the co-author of the text handling the project "JHOP2040" and the JHR access rights.

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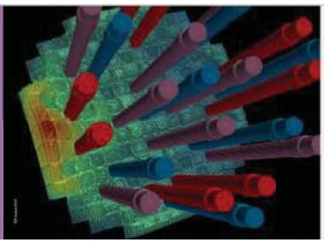


FISA 2022

30 May - 3 June 2022
Lyon, France

NEA Seeking Excellence in Nuclear Education, Training, Knowledge Management and Supporting Research Infrastructure

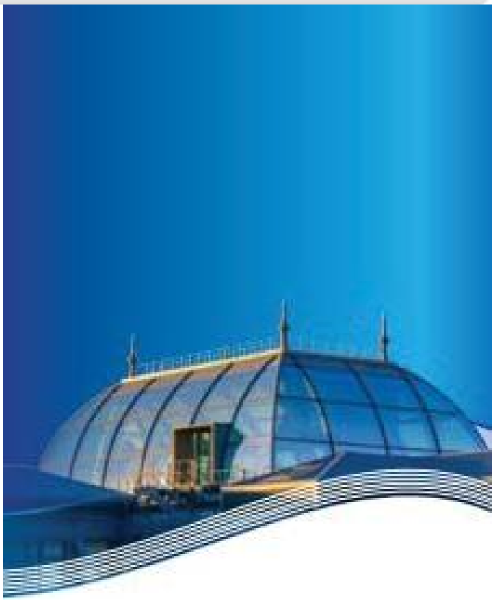
Tatiana Ivanova
Head of the Division of Nuclear Science and Education

10th European Commission Conference on EURATOM Research and Training in Safety of Reactor Systems
30 May - 3 June 2022 | Lyon, France

OECD BETTER POLICIES FOR BETTER LIVES — Nuclear Energy Agency — NEA NUCLEAR ENERGY AGENCY

Outline

- Knowledge Management, Education and Training
  - International Mentoring Workshops
  - Global Forum on Nuclear Education, Science, Technology and Policy
  - Nuclear Education, Skills and Technology (NEST) Framework
- Framework for Irradiation Experiments (FIDES)



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Nuclear Energy Agency

NEA NUCLEAR ENERGY AGENCY

The NEA: 34 Countries Seeking Excellence in Nuclear Safety, Technology, and Policy

- **34 member countries and strategic partners**
- **The NEA is a framework for technical and policy cooperation in nuclear safety, stakeholder engagement, science, current and new and technology, economics, nuclear law, nuclear codes and data, waste management, decommissioning, legacy management, and radiation protection**
- **8 standing committees and over 80 working parties and expert groups**
- **International joint projects**

NEA countries operate about 85% of the world's installed nuclear capacity

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NEA NUCLEAR ENERGY AGENCY

NEA Countries' Shared Vision

Building up talented individuals is a long term investment, for every country, requiring strategic vision and involvement

Need for **international co-operation** in the area of **Knowledge Management (KM), Education and Training**

- to guarantee the worldwide sustainability and availability of necessary skills in the nuclear area

- to preserve, transfer, share and create knowledge for the next generation and address both Explicit and Tacit knowledge

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Nuclear Energy Agency

NEA International Mentoring Workshops

 5

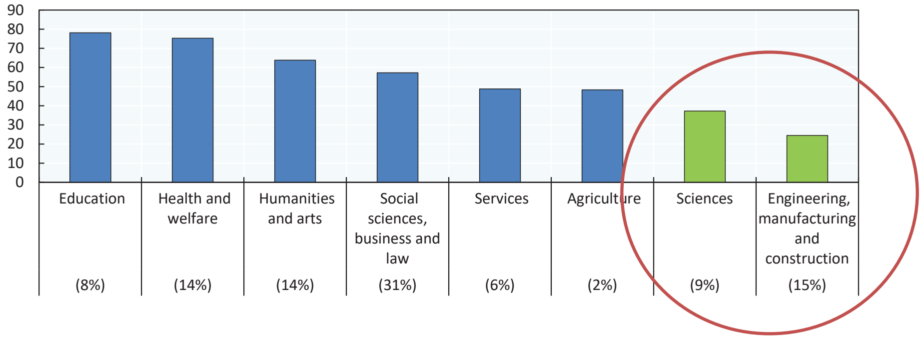
Nuclear Energy Agency

Purpose of the NEA International Mentoring Workshops

- Women remain **underrepresented in leadership positions** in science, technology, engineering and mathematics (STEM) fields.
- We believe that an event providing **mentoring** experiences for young female students with successful role models can help address these issues.

Women are underrepresented among new entrants in STEM fields in higher education

Proportion (%) of new entrants into tertiary education that are female, by field of education, OECD average, 2014



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NEA International Mentoring Workshops Objectives

- **Encourage young students** to pursue Science, Technology, Engineering, Mathematics (STEM) studies and careers by providing them the opportunity to meet and converse with highly accomplished professionals in the STEM field from the host country and from around the world.
- The Mentors show the students what they can achieve, using their own experiences as examples. They provide presentations based on their personal histories, explain what motivates them as scientists and engineers, and answer questions about technical studies, careers, and life.

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Nuclear Energy Agency

NEA International Mentoring Workshops – A Brief History

- **13 mentoring workshops and events held since 2017 (in-person, hybrid and virtual)** in Japan, Kenya, Russia, Spain and Romania with distinguished female STEM professionals and adolescent girls
- A number of mentoring workshops are being planned for 2022 and 2023, including in new NEA member/strategic partner countries

- ✓ Chiba, Japan (July 2017)
- ✓ Tokyo, Japan (August 2018)
- ✓ Ávila, Spain (September 2018)
- ✓ Fukushima, Japan (August 2019)
- ✓ Vigo, Spain (September 2019)
- ✓ Moscow, Russia (October 2019)
- ✓ Joshikai, Japan (December 2020 *virtual*)
- ✓ Mombasa, Kenya (July 2021, *hybrid*)
- ✓ Granada, Spain (October 2021)
- ✓ Joshikai, Japan (October 2021, *virtual*)
- ✓ St. Petersburg, Russia (October 2021, *hybrid*)
- ✓ Romania (November 2021, *virtual*)
- ✓ NEA-WiN session, Tokyo, Japan (May 2022, hybrid)

NEA mentoring workshops – YouTube
https://www.youtube.com/watch?v=V-4MKmV1tS4

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NEA Global Forum on Nuclear Education, Science, Technology and Policy

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NEA Global Forum Objectives

Entered into force on 28 January 2021

- **Engages with academic institutions** which are responsible for developing the next generation of nuclear science and technology experts
- Brings long-term, creative thinking to **address international policy challenges** that nuclear energy faces today as input to NEA processes
- Provides academic institutions around the world with a **framework for interaction, co-operation, and collective action**
- **Holds occasional symposia to highlight the Forum's work** and serve as a venue for academic experts, as well as other stakeholders, to identify emerging issues and creative solutions related to the strategic areas identified

1st Exploratory Meeting, Paris, 24-25 July 2019

2nd Exploratory Meeting, Paris, 23-24 January 2020

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NEA Global Forum: Areas of Work

Chair of the Council of Advisors: R. Lester (MIT, USA)

Council of Advisors
(35 members from 20 academic institutions)

Governs the Global Forum and defines its programme of work

www.oecd-nea.org/globalforum

Working Group 1 Gender balance in nuclear technology and academic workforces	Working Group 2 Future of Nuclear Engineering Education	Working Group 3 Relationship between nuclear energy and society	Working Group 4 Innovations in the nuclear sector
• Promotion of nuclear engineering and technology programs to women and non-binary individuals • Inclusion and leadership of women and non-binary in these fields • Encouraging men as vocal allies	• Tools and Digital Technologies for Nuclear Education teaching and outreach • Multidisciplinary approaches in Nuclear Education • Open Science: Educational Benchmark Activities	• Research benefits of nuclear, establishing affective associations • Research values of nuclear community • Research future nuclear scenarios and share with wider sectors of society and policy in accessible format	• Large reactors; modular, small and micro reactors; • Production of alternative energy vectors • Integration of nuclear with renewables, storage and flexible grid systems

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3rd Global Nuclear Science and Engineering Commencement
Theme: Nuclear Technology in Service to Society

Join remotely! **29 June 2022, 14:30- 16:00 CEST**

- Keynote Speech: Bill Gates, Chairman of the Board, TerraPower
- The event will feature a panel discussion with students and young professionals

Student competition

- Students are invited to send a 3-minute submission in any form on the theme *Nuclear and Society: What does this relationship mean to you?*
- Deadline: 22 May 2022
- Prize: Attend the major international nuclear conference with all expenses paid
- An international jury will select a winning entry to be shown at the commencement

https://oe.cd/4r2

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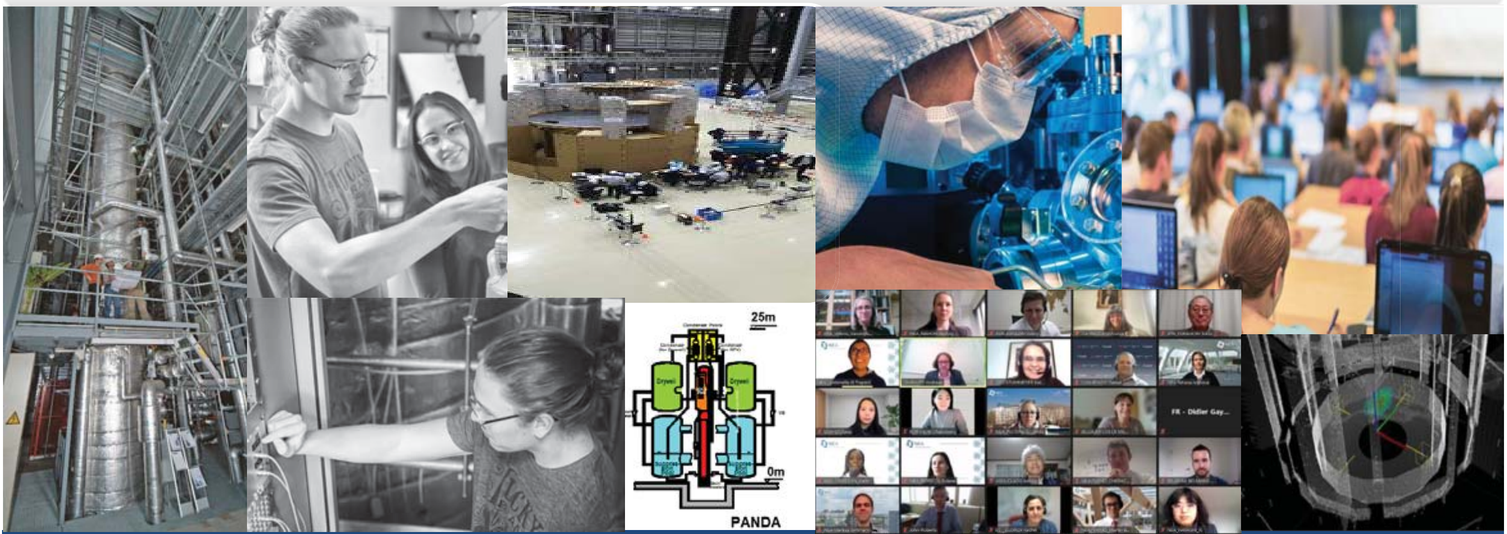


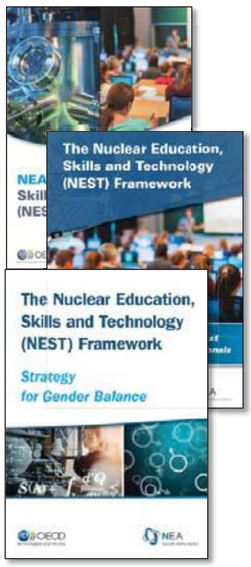
NEA Nuclear Education, Skills and Technology (NEST) Framework

Nuclear Energy Agency

Nuclear Education, Skills and Technology (NEST) Framework

Launched in February 2019

A multinational framework designed to develop skills and nurture the next generation of nuclear subject matter experts through transfer of practical experience and knowledge



Added-values and benefits

- Fast track to leadership
- Multidisciplinary skills and competencies through hands-on training
- Access to state-of-the-art facilities
- Opportunity to develop a network through multinational co-operation
- Participation in challenging and innovative activities

www.oecd-nea.org/NEST

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NEST: Status of Work

Chair of the NEST Management Board: A. Pautz (PSI, Switzerland)

- 10 Countries
- 8 Projects: 6 ongoing, 2 under preparation
- 50+ Participating organisations
- 200+ Fellowships
- 2 Hackathons, 3 Workshops
- 5 Management Board meetings

- The MB approved the adhesion of Romania (11th NEST Country) to the NEST Framework.
- Signature of the Framework Agreement is underway- *welcome to Romania!*
- All NEST Projects have finalised their Project Agreements
- NEST Projects have been extended to compensate for COVID halt of activities
- NEST Fellowships have restarted in 2021-2022
- Discussion is ongoing on involvement of industry in NEST Projects
- Discussion is ongoing on enlargement of NEST Framework beyond the NEA membership

NEST Framework has been included in the European Commission ENEN2plus project- additional mobility funding for Fellows (under conditions)
GA to be signed by 7 June 2022

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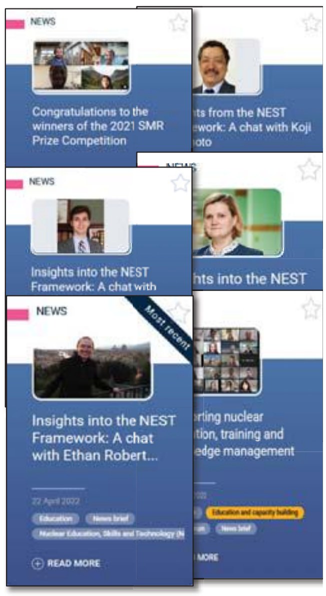
Ongoing NEST Projects

- **Hydrogen containment experiments for reactor safety (HYMERES)**
- **Small modular reactors (SMRs)**
- **Advanced remote technology and robotics for decommissioning (ARTERD)**
- **Radioactive waste management of i-graphite**
- **Medical applications, nuclear technologies, radioprotection and safety (MANTRAS)**
- **Building competence, expert knowledge, applied techniques, safe decommissioning, train fellows (BEAST)**



NEST Fellows: Master and PhD students, postdocs, and young professionals	200+ Fellows in 2019-2022 50+ participating organisations	NEST Mentors: experts in hosting organisations	Fellowship duration: 1-6 or 6-12 months

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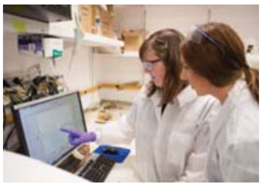
Benefits for NEST Members



For Nuclear Professionals

– Experience gained in relevant work jointly with experienced scientists, engineers and university professors
– A network of international contacts
– Opportunities for getting employment and/or better position

For Universities

– Education excellence connected to the state-of-the art in research organisations and industries bridging the gaps between the "know-why" and "know-how";
– Education strategy consistent with energy and R&D policies

For Member States

- Advanced students, post-doctoral appointees, young professionals equipped with critical skills and knowledge
- Co-operation with other partners in NEA multinational projects
- Direct links with national policymakers for better energy policies and R&D priorities

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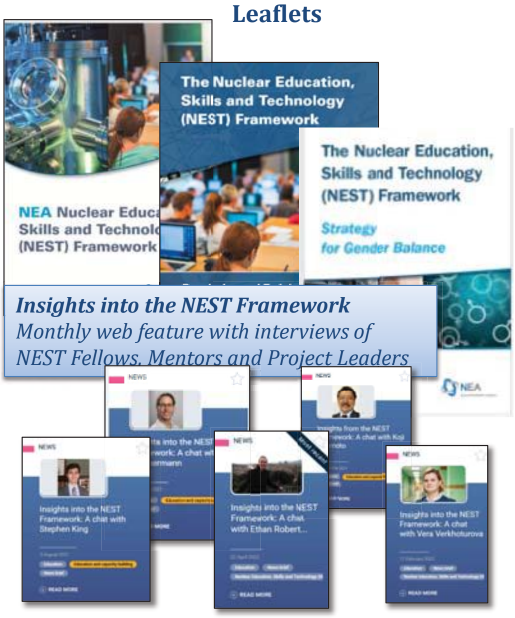
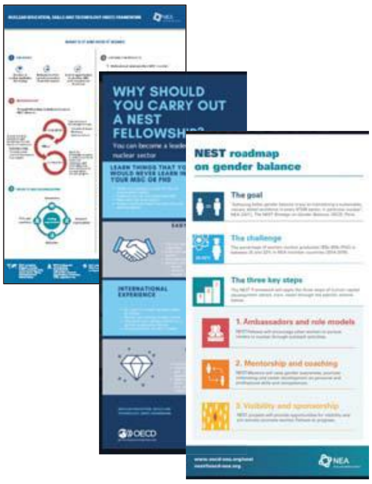
NEST Outreach and Publications

Leaflets



Infographics



Articles

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OECD
BETTER POLICIES FOR BETTER LIVES

Nuclear Energy Agency

NEA
NUCLEAR ENERGY AGENCY

NEA Framework for Irradiation Experiments (FIDES)

OECD
BETTER POLICIES FOR BETTER LIVES

Nuclear Energy Agency

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Why FIDES?

FIDES has been designed to address the post-Halden situation and

- Consolidate the needs of regulators, TSOs, industry and research institutions;
- Build a collective awareness of the needs and capabilities;
- Bring together a network of key research reactors in NEA member countries;
- Perform high-priority experiments on a cost-sharing basis to verify the safety and performance of fuels and materials;
- Support the sustainability of key research facilities;
- Safeguard the experimental knowledge for future generations;
- Address practical issues, including nuclear fuel transport and waste management;
- Enable bilateral arrangements between trusted partners within FIDES.

OECD BETTER POLICIES FOR BETTER LIVES — Nuclear Energy Agency — NEA NUCLEAR ENERGY AGENCY

FIDES Structure

- NEA joint undertaking, established pursuant to Article 5 of the NEA Statute
- A stable, sustainable, reliable post-Halden platform for fuel and materials testing using nuclear research reactors and related facilities in NEA countries
  - Generates experimental results and expertise for shared costs
  - Enhances modelling and simulation, instrumentation, training and education
- PoW 2021-2024: 4 JEEPs and Project on Data Preservation and Quality Assurance

- Parties: 27 organisations from 12 countries and the EC
- Budget: ~ 23 M€/3 years
- Launched in March 2021
- Experiments are ongoing in 6 countries

Joint Experimental Programmes (JEEPs)

P2M Tests in BR2 & LECA PIE Facility	LOCA MIR tests in MIR.M1	INCA Cladding creep tests in LVR15	HERA RIA tests in TREAT and NSRR	LOCA tests in CABRI	INSTEP RIA tests in NSRR	STRETCH Stress Relaxation and Creep Research	ENCORE Testing of In-Core Mechanical Properties	Tests for validation of 3D M&S TBD	Future experiments using existing RRs and RRs under construction

Project on Data Preservation and Quality Assurance

Training and Education

Modelling and Simulation

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FIDES Programme of Work, 2021 – 2024 (1/2)

- **JEEP P2M:** Programme for quantifying thermomechanical clad load mechanisms during LWR slow transient, or **P**ower to **M**elt and **M**anoeuvrability, BR2 reactor and hot cells, SCK.CEN, Belgium and LECA/STAR facility, CEA, France

  JEEP P2M Core Group: SCK.CEN (Belgium), CEA and EDF (France)

- **JEEP INCA:** **In**-pile **C**reep Studies of **A**TF Claddings, LVR-15 reactor and hot cells, ÚJV Řež, Czech Republic

  JEEP INCA Core Group: CVŘ, ÚJV Řež, and Alvel (Czech Republic), VTT (Finland), and CEA (France)

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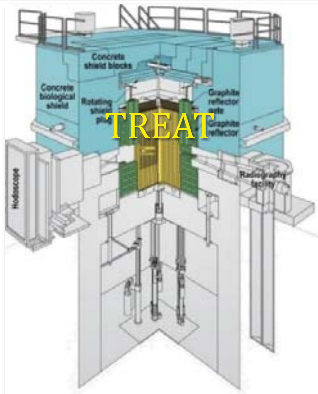
FIDES Programme of Work, 2021 – 2024 (2/2)

- **JEEP LOCA MIR:** **LOCA** experiments with Gd-doped fuel, **MIR.M**1 reactor and hot cells, RIAR, Russia
  JEEP LOCA MIR Core Group: RIAR and TVEL (Russia)

TVEL RIAR

- **JEEP HERA:** **H**igh burnup **E**xperiments in **R**eactivity Initiated **A**ccident, TREAT reactor and hot cells, INL, USA and NSRR, Japan
  JEEP HERA Core Group: DOE, NRC, Westinghouse (USA), JAEA (Japan), IRSN (France)



U.S.NRC U.S. DEPARTMENT OF ENERGY JAEA IRSN INL Westinghouse

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FIDES: Recent Accomplishments

- **Framework**
  - FIDES meetings: 26-29 April 2022
  - Groups are being created to address practical aspects of irradiation experiments
  - Members are confidently planning for future phases
- **Experiments**
  - LOCA-MIR experiments completed
  - INCA experiments loaded into LVR-15 reactor April 27, irradiation began May 2
  - 10-year strategic plan under development to guide future of FIDES
- **Modeling and simulation (M&S)**
  - A “feedback loop” between modelling and experiments is being created with M&S exercises
- **Training and education**
  - Internships at FIDES facilities
  - Universities involved in modeling and simulation
  - Platform for developing expertise in irradiation testing hardware and experimental design

FIDES Governing Board endorsed the co-operation with European Commission’s eurOpean platForm For accEssing nuclear R&d facilities (OFFERR) project

OECD BETTER POLICIES FOR BETTER LIVES — Nuclear Energy Agency — NEA NUCLEAR ENERGY AGENCY

Looking Ahead

- NEA multi-national activities foster nuclear technologies and innovation by
  - Contributing to maintain expertise and competences, enhance human resources development and capacity building networks, and equip the next generation with technical and non-technical skill
  - Enhancing experimental work and supporting experimental infrastructure
- The NEA looks forward to enhancing the co-operation with the European Commission Euratom Research and Training Programme (EURATOM) through the participation in:
  - Building European Competence through Continuous Advanced and Structured Education and Training (ENEN2plus) project, which will co-operate with NEST
  - The European Platform for Accessing Nuclear R&D Facilities (OFFERR), which will co-operate with FIDES

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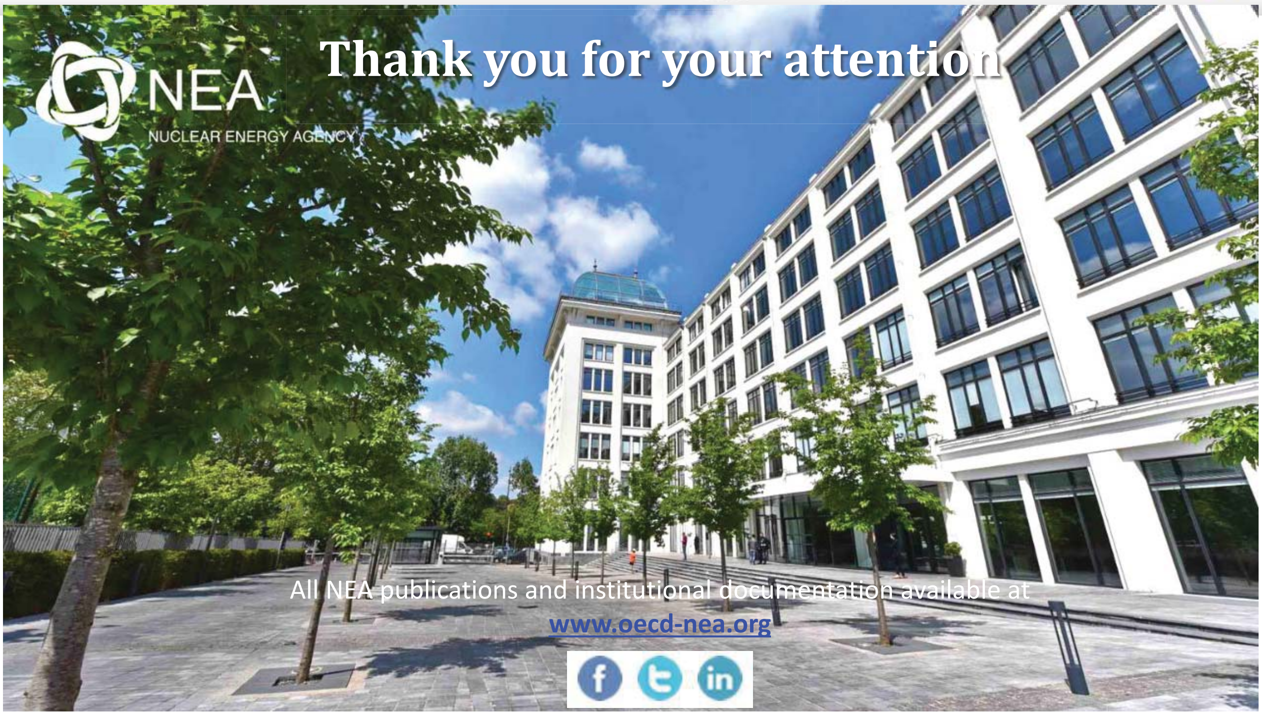

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FISA 2022
EURADWASTE'22

JOINT CONCLUSION FISA 2022 / EURADWASTE '22

Co-chair: Philippe STOHR (FR, CEA)

Co-chair: Bernard MAGENHANN (EC, DG JRC)

Rapporteur: Henri PAILLERE (FR, Expert)

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,

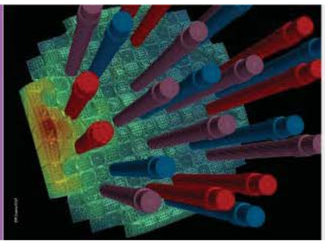
– la sécurité européenne et mondiale

– 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.



FISA 2022

30 May - 3 June 2022
Lyon, France

Joint conclusion FISA 2022 / EURADWASTE ’22:

FISA 2022 - Key messages and future perspectives

H. PAILLERE with input from
Ferry ROELOFS, Teodora RETEGAN VOLLMER and Said ABOUSAHL

Joint Introduction Session (1)

- **Challenging times/opportunities**: war in Ukraine, high energy prices – and climate change
  - A time to revisit the role of Nuclear Energy in our energy systems and its contribution to net zero
  - Eg. RepowerEU explicitly mentions nuclear energy for its contribution to strengthening security of energy supply, and as a potential source of low C hydrogen
  - More and more EU countries looking at nuclear ; EU investing in SMRs
- **Euratom treaty 65 years old**
  - Europe can be proud of its achievements, how it build up competence in the nuclear energy sector, from fission to fusion
  - EU regulatory framework for safety and radwaste management
  - European Commission wants to exploit synergies, across sectors – and financial instruments
  - Marie Skłodowska-Curie actions (25y old) opened to nuclear research
- This conference is an **opportunity to learn and share knowledge through the outcomes of Euratom research programmes**
  - Hear recommendations from the research community
  - Better inform policy-makers about the future potential of NE but also challenges to be addressed, for example the ageing workforce
- **A tribute to Bernard Bigot**, recognized scientist and promoter of nuclear research

Joint Introduction Session (2)

- **Rosalinde van der Vlies on behalf of Mariya Gabriel, Commissioner**
  - Research to build public confidence and acceptance, to make the nuclear sector more resilient and to attract young researchers
- **Claire Giry, Directrice Générale de la recherche et de l'innovation, France**
  - Nuclear science and technologies, an answer to the climatic crisis, the energy crisis and the health (cancer) crisis
- **Laurent Michel, Directeur General Energie et Climat, France**
  - Need for decarbonized energy (beyond decarbonized electricity): heat, H2
  - R&D challenges: Long Term Operation, High level waste and decommissioning, new technologies and construction
- **Rafael Mariano Grossi, DG IAEA**
  - Importance of knowledge sharing
  - Make (nuclear research) more visible to the public is how we demystify nuclear and allow people to make decisions based on science, rather than fear or ideology

Joint Introduction Session (3)

- **William D. Magwood, IV, DG OECD/NEA**
  - Today's crises are a wake-up call for the sleeping giant (nuclear energy), until recently considered an old technology with ageing staff
  - Have to go back to the 1960s to see so much excitement about nuclear energy
- **Francois Jacq, Administrateur Général, CEA**
  - New way of assessing the role of nuclear energy: integrated vision, complementarity between technologies, smart grids, flexibility of nuclear "offer": size, products
  - This leads to new research/innovation needs, importance of working together, especially at European level (example sharing infrastructures)
- **Baiba Miltoviča, European Economic and Social Committee**
  - Energy is more and more expensive → energy poverty
- **Marta Ziakova, Chair of the European Nuclear Safety Regulators Group**
  - Transparency and continuous enhanced nuclear safety are the two pillars of Nuclear Safety in Europe

Joint Introduction Session (4)

- **Yves Debazeille, DG FORATOM,**
  - without securing sufficient funding for research in the nuclear sector, the European Union will fall behind its competitors: serious consequences on EU targets related to climate, energy prices, and security of energy supply
  - It is time for Europe to rethink its position as a serious player in the nuclear sector.
- **Jadwiga Najder, Chair of the Young Nuclear Generation of ENS**
  - (Listen) to the perspectives of the youth
  - 36% of global nuclear workforce is 55y+

Session 1: Safety of Nuclear Installations (1)

- New nuclear reactors require **continuity in policy, a favorable regulatory context** and **financing mechanisms** reconciling revenue visibility and stable costs for customers.
- An **EU SMR partnership** is under preparation to support achieving **carbon neutrality** in Europe by 2050 and **sustainability** over the long term.
- With respect to safe and continued operation of current and future nuclear power plants:
  - Development, maintenance and preservation of **databases**, **advanced instrumentation**, advanced **destructive and non-destructive techniques**.
  - Development of **multi-scale multi-physics modelling and simulation tools**.
  - Simulation methods should be directly applicable to **industrial contexts**, **easy in use**, **robust**, **transparent**, available with **validated** software.
  - Exploiting and developing the use of transparent and robust **artificial intelligence** techniques.
  - Implementation of **uncertainty quantification** and **sensitivity analysis** as a standard.

Session 1: Safety of Nuclear Installations (2)

- It is important to improve the understanding of **phenomena influencing materials and components performance**.
- New code and fuel developments are encouraged in the field of **independent supply** for the existing and future VVER reactors in Europe.
- Experiments, instrumentation, and simulations should go hand-in-hand, **strengthening** each other and pushing each other **to the limits**.
- Novel **low enriched uranium fuels** for **research reactors** need to be tested and demonstrated for various high performance European research reactors.
- Guidelines to **design and implement new accident management procedures**, **validated simulation tools** (including **verification experiments**) and **safety devices** (including innovative passive safety systems) are expected and under development.
- There is a strong call to **set-up and maintain databases** collecting historic and new data for **validation and verification**.

Session 2: Advanced nuclear systems and fuel cycles (1)

- In this Session, some of the EURATOM Programme priorities were addressed, which are of paramount importance as these **projects and activities are contributing directly to the criteria for taxonomy compliance of nuclear projects** in line with the recommendations of the JRC report.

- Making nuclear energy more sustainable will require innovative thinking and technology breakthroughs allowing the **closing of the nuclear fuel cycle** as well as **advances in material science** and the **processing and disposal of nuclear waste**, including HLW.

Session 2: Advanced nuclear systems and fuel cycles (2)

- Realizing the **potential of nuclear energy to contribute fully to the decarbonization** of our energy system will require **extending the portfolio of nuclear technologies**, in large-scale installations as well as future SMRs, **beyond electricity production** towards other applications, such as heat and hydrogen production.

- This needs to happen **timely** and at the same time with full respect of utmost **priority on nuclear safety, transparency and public acceptance**.

Session 3: E&T, RI, LD radiation protection, decommissioning and int. coop. (1)

- This session focussed on **horizontal pillars**: Training, Education, Knowledge Management, Open access of European Nuclear Research Facilities
- **Synergies**:
  - Fusion and Fission (an opportunity to promote scientific exchange across communities within the Euratom Programme (Fusion/Fission)
  - Nuclear Medical Applications
  - Radiation Protection
  - Decommissioning

- Also a number of **posters** addressed these topics

Session 3: E&T, RI, LD radiation protection, decommissioning and int. coop. (2)

Education & Training / KM: attracting, developing and retaining young talents

- All the projects in sessions 1 and 2 have specific ET and KM components.
- **General Nuclear E&T** is done through projects such as ENEN+, or on thematic areas:
  - ENEN+ project: grant of more than 535 mobilities to BSc, MSc, PhDs and other young professionals to perform an E&T activity outside of their home country.
  - A-CINCH project: Augmented Cooperation in Education and Training in Nuclear and Radiochemistry, covers Nuclear wiki database of teaching materials Open Educational Resources to be shared, or Massive Open Online Courses.
  - ENEEP (European nuclear experimental education platform) demonstrates the European dimension of E&T activities, and a high attractiveness of the courses offers.
- **Knowledge Management**: a platform is being developed to improve the accessibility to the results of various EURATOM funded projects. The pilot project focuses on recent “materials projects”.

Session 3: E&T, RI, LD radiation protection, decommissioning and int. coop. (3)

Medical applications of ionizing radiation and radiation protection for European patients, population and environment

- Scientific evidence is to be comprehensively translated into procedure and practice guidelines as well as into policy recommendations, beyond the classical exploitation of scientific publications
- Several projects target applications of radiation in medicine:
  - Cancer treatment
  - Cardiology
  - Diagnostic exposures

Towards effective radiation protection based on improved scientific evidence and social considerations – focus on Radon and Naturally-Occurring Radioactive Materials

- RadoNorm aims at managing risks from radon and NORM exposure situations to assure effective radiation protection based on improved scientific evidence and social considerations.

Session 3: E&T, RI, LD radiation protection, decommissioning and int. coop. (4)

Radiation protection research and innovation

- MEENAS consortium of six European radiation protection research platforms behind PIANOFORTE partnership which aims to provide a European scientific and technological basis for a robust system of protection and consolidated science-based policy recommendations to decision makers.
  - In the long term, these efforts will translate into new and improved practical measures and better outcomes for the effective protection of people (public, workers, patients) and environment.

How to make the dismantling operations more efficient, safer and more cost-effective: SHARE - A roadmap for Research in Decommissioning

- Identifying the needs and opinions of stakeholders throughout the value chain. The project also considered existing and emerging innovative solutions, as well as international best practices in nuclear decommissioning.
- Need to rapidly bring to maturity technologies (digital technologies, automatised or semi-automatised robotics, LASER cutting). It is the common objective of the five European projects (INNO4GRAPH, LD-SAFE, PLEIADES, CLEANDEM and INSIDER).

Session 3: E&T, RI, LD radiation protection, decommissioning and int. coop. (5)

Supporting access to pan-European Research Infrastructures and International Cooperation

- OASIS: The current scheme of open ACCESS to JRC's infrastructure helps to bridge the gap between high and less wealthy institutions in the EU. The selection procedure is based on scientific merit of the proposals.
- The strategic planning for optimising the use of the research reactors (TOURR project) is on-going at the same time when one of the most important future research facility, namely the JHR, is under construction. On the other hand, the JHR will aim at new generation of research capacity with the wide experimental device fleet under construction.

The experiences gathered in the implementation of open access projects in previous and current Euratom research & training programmes, are a very good basis to be used for the design of future schemes, for all kinds of nuclear facilities.

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

Keynote: Région Auvergne-Rhône-Alpes, promoting Innovation Ecosystems and Strategic Clusters

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

NUCLEAR VALLEY

The French Nuclear competitiveness cluster

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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

Nuclear Valley today

+370 MEMBERS

+ 320 Labelled projects

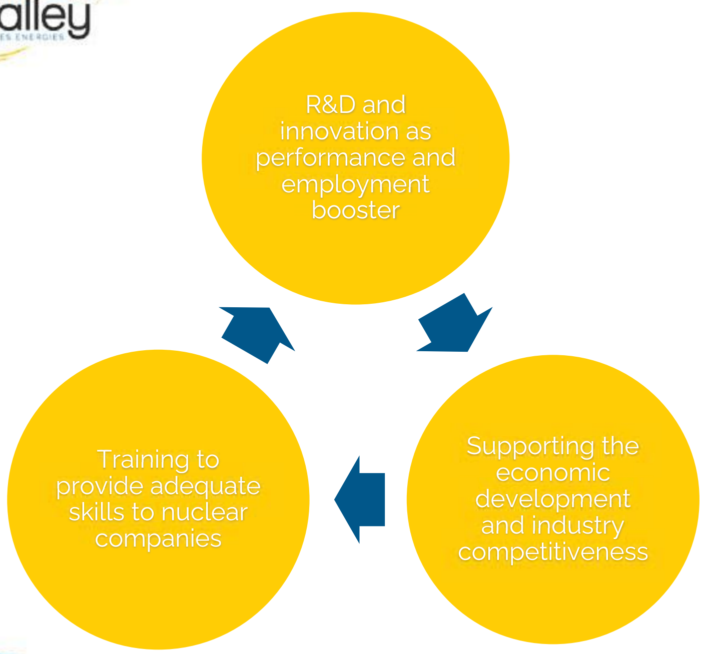
+200 Financed projects

+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

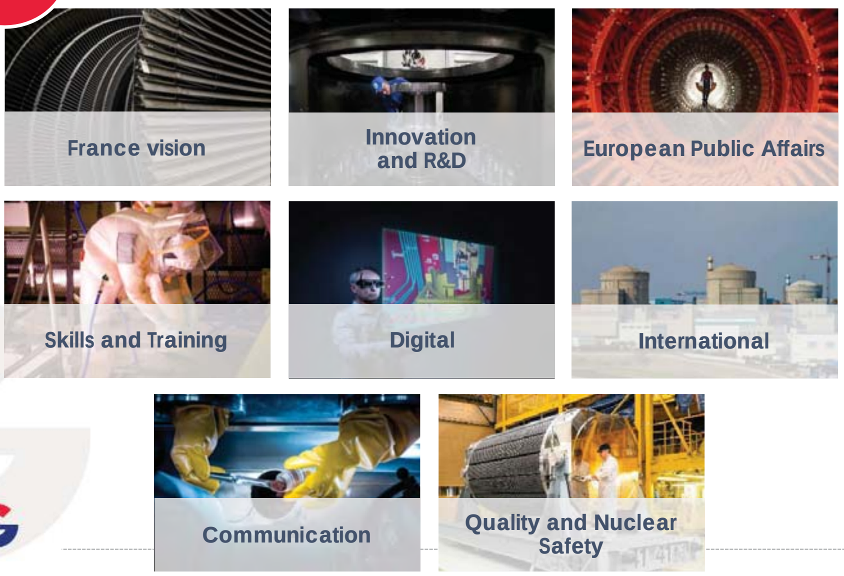
+ 1 200 Contributors

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)

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

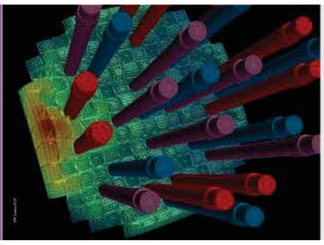
Nuclear Innovation Prize in safety of reactors systems

- 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

10th European Commission Conference on EURATOM Research and Training in Safety of Reactor Systems
30 May - 3 June 2022 | Lyon, France
7

EURADWASTE'22

30 May - 3 June 2022
Lyon, France

PhD Prize
R&D Prize
Euratom project

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

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

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.

FISA PhD PRIZES

FISA 2022
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EPJ Nuclear Sciences & Technologies

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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

Model-based system engineering, an industrialization path for decommissioning projects by ASSYSTEM

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Abstract. Dismantling projects (dismantling of the high activity tanks of the UP1 plant, treatment of residual sodium from the Rapsodie facility, recovery of bitumen drums from the STEL Marcoule casemates, ...) are complex because of budgets constraints, no return on investment, and characterized by an environment with great uncertainty (NEA OCDE, The decommissioning and dismantling of nuclear facilities, status, approaches, challenges 2020 [1]). This is particularly true for fuel cycle facilities, which are mainly all first-of-a-kind; but it is also valid for commercial NPP (notably on the budget constraints). The main challenges are to (i) conciliate the cost control & risks of uncertainties due to technical subjects, which is the hard skills of the system, and (ii) manage the interfaces between the product owner, engineering, technology provider, operators, & regulators, which is the soft skills of the system. These projects do not progress as much as everyone would like, with a reluctance to move into execution, stuck into several "rounds" of re-engineering studies leading to additional delays and costs. It is necessary to treat the subject as a complex system. The DEMOLOGIST suite is one answer that we implemented to treat these complex projects as systems by deploying a method based on system engineering management of data while developing adapted digital plug-in software to collect, organize and harmonize the data at every stage (archives, regulators requirements, field operations) to feed the method. This is notably the case on a project aiming at studying the best option to deal with sodium management in France.

1 Introduction

1.1 Context of decommissioning and legacy management projects

A common characteristic of legacy sites is that their "initial stage", meaning their radiological characterization, is broadly unknown because records have been lost, former site operators with knowledge of the sites are unavailable, and/or site owners have changed. On top of these poorly characterized chemical and physical hazards and other operational challenges may also appear over time. Among the most impacting ones, we can mention the increasing cost of regulatory constraints. Decommissioning a facility often comes with significant challenges, in direct relation to their ages:

- inadequate storage facilities:
  - both in volume and in capacity to deal with a new type of waste to be managed
  - aging, up to 50 years or even longer
- large and uncertain inventories
- miscellaneous material conditions
- working conditions range from difficult to extremely challenging
- extended time for hazard reduction:
  - complex tasks required to remove or recover wastes in a safe manner
  - variable confidence in the schedule.

Current legacy-related challenges include:

- legacy ponds and silos
- old waste drums.

Many decommissioning projects are delayed by several years due to a lack of adequate planning and management infrastructure, inevitably leading to increased costs. In such situations, funds usually set up for decommissioning are spent to maintain the facility in an "on hold" state depleting the financial resources required to terminate the project.

"Design and build" and/or also "design, build and operate" contracts are commonly used in this market. For projects facing important uncertainties, commercial risks can be limited by separating design from implementation.

The feedback around success factors is numerous in the literature. Key parameters to address the improvement of decommissioning contracts are:

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- a good understanding of the work as a contribution to risk management
- the development of the safety culture including through the deployment of daily "safety minute" for operators
- planning
- client contribution
- staff competence and training
- important project management lessons were:
  - encourage best use of client/contractor skills
  - establish performance monitors
  - regular management audits
  - full documentation of records.

In this context, the role of the supply chain, and in particular of engineering, is to define solutions that enable us to make progress in the management of risks and, where possible, to achieve economies of scale through industrialization.

1.2 Role and place of engineering

To control the risk of complex and lengthy decommissioning projects, it appears necessary to have the appropriate technical skills in all engineering fields such as mechanics, ventilation, and processes. However, although this is a necessary condition, it is not sufficient. For evidence, the conventional engineering development cycles are too linear to accommodate the uncertainties inherent to decommissioning and waste retrieval projects, leading to costly problems detection.

The mastery of complex projects over long periods requires the management of data and requirements over time, the ability to trace their evolution, and to make choices. It is in this context that ASSYSTEM has developed the digital suite DEMOLOGIST relying on:

- The implementation of the model-based system-engineering method
- The development of digital software to recover, analyze and make reliable data across the whole project.

2 Project management methodology based on systems engineering

Lessons learned have shown that instability in requirement definition and/or management is a major, if not the main root cause of scope creep on projects that are complex because each time a requirement is altered, it affects the technical baseline and likely the project baseline as well. The change of the requirements will often have cost, schedule, and risk exposure concerns that must be addressed. It is always beneficial to perform a cost, schedule, and technical impact analysis on any proposed change before committing to an engineering and/or contract change proposal. Any captured risks that are affected, or new or secondary risks that are created, must be noted in the risk registry. For example, if the technical complexity is increased, this will pose a direct risk to the cost and schedule baselines. In addition, the more the requirement changes come late in the project life cycle, the more it

Fig. 1. Decision-making process.

will negatively affect the cost and schedule risk. The first challenge is to strongly build the decision-making process (Fig. 1).

The fact is that sequential engineering methods based on documents are no longer sufficient, each change requires starting from the beginning and going through each step of the process.

3 What system engineering does?

System engineering is a method, a way to organize the project. It allows to:

- Keep the objective to keep linking the requirements with the design ⇒ define the set of desired outcomes and justify decisions
- Involve the strategic partnerships ⇒ collective intelligence – bringing stakeholders together around a tool: product owner, engineering workforces & operators
- Define the problem before hypothesizing a solution, which allows to identify several alternatives and choose the most appropriate solution ⇒ represent and divide the problem into several parts "A picture is worth a thousand words"
- Manage the interfaces between the parts ⇒ "The devil is on the interfaces"
- Help large teams to collaborate and manage changes ⇒ delay choices on technology as much as possible so as not to impose a technology that would block the system
- Manage complexity through models – test early, test often ⇒ interface modeling allows you to test whether the system has solutions and to identify blockages due to excess or conflicting requirements.

System engineering appears essential in identifying technical risks, managing and deriving requirements, aligning the technical baseline with the project baseline, deriving the system architecture framework, and translating technical issues into actionable business cases that the project manager can use to make critical business decisions.

The mastery of complex projects over long periods requires the management of data and requirements over time, the ability to trace their evolution, and to make choices.

It is in this context that ASSYSTEM has developed the digital suite DEMOLOGIST (Fig. 2) relying on:

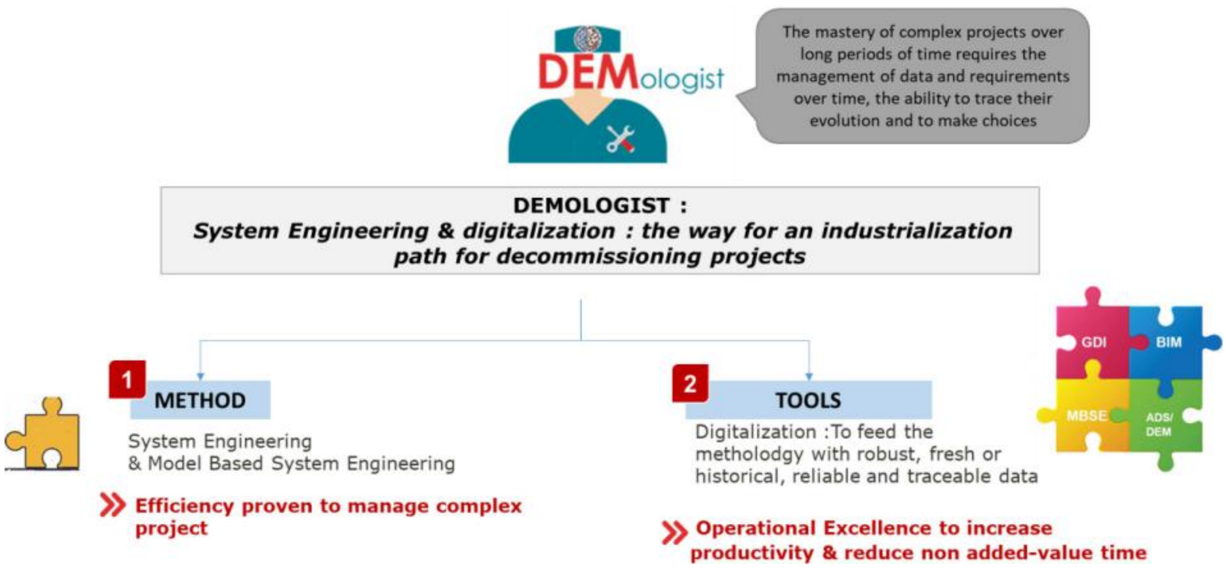

Fig. 2. DEMOLOGIST principle.

- The implementation of the Model-Based System Engineering (MBSE) methodology, which has proven its ability to deal with complex projects in space sector, notably by the NASA
- The development of digital tools is able to recover, analyze and make reliable data across the whole project. These tools, developed for and with users, will allow to feed the methodology with robust, fresh or historical, reliable, and traceable data while contributing to Operational Excellence to increase productivity & reduce non-added-value time

Figure 2 – Puzzle legend:

- GDI: Global Direct Inquire; an AI-based software fully engineered by ASSYSTEM acting like Google, but indexed with project-related engineering documentation
- BIM: Building Information Model
- MBSE/Model-Based System Engineering
- ADS-DEM: software fully engineered by ASSYSTEM aiming at defining the best decommissioning scenario.

4 MBSE methodology

Based on requirements, among other considerations, this methodology ensures that the identified requirements are documented and written in such a manner that they can be verified and validated.

From our experience, the design of a facility in the context of dismantling and legacy waste retrieval is based on three factors:

- Firstly, the synthesis of complex input data spread over documents, their compilation, and follow-up during project development phases, without any loss of information, redundancy, or ambiguity,
- Secondly, the definition of a structured, traced, and ordered requirements referential to facilitate safety and compliance demonstrations,
- Thirdly, the identification of all the functions of the facility, and in particular the interfaces and flows to optimize the layout of the facility housing the process.

To achieve all these objectives and enables all the players to be brought together around a decision tool ASSYSTEM is using model-based system engineering methods in order to:

- Rationalize the needs of the project owner,
- Identify data and requirements throughout the life of the project. In design phase, the management of the requirements is placed at the heart of the design and used to guide its development, assess its progress and progressively validate it.
- Adapt the architecture of the solution
- Manage its optimization through a quick and self-coherent follow-up of modifications.

Model-Based Systems Engineering is the formalized application of modeling to support system requirements, design, analysis, verification and validation, beginning in the conceptual design phase and continuing throughout development and later life cycle phases [3]. MBSE is known as a standard method in other industries (aeronautics, defense, etc.) and can be adapted to meet the specificities of the nuclear industry.

As a leading engineering company in nuclear, we always implement MBSE methodology starting from processes, needs, and practices in a very pragmatic way based on existing tools such as the open-source model Capella [2,4].

Modeling allows the relationships between the different elements of the projects to be described (actors, interfaces, sub-systems, processes, etc.) and all the requirements to be structured at different levels of abstraction (from the needs down to the solution) and over the entire project lifetime that can be particularly long in the context of dismantling. The approach can be deployed partially or over the entire project scope, depending on its progress and priorities.

The strength of modeling lies in the fact that it links data together, which implies being able to manage the resulting cascades of changes and analyze the consequences quickly.

5 Feed of the method by digital tools

In addition to that, one of the key features of DEMOLOGIST is relying on digital software specially developed to manage and work around data at different stages of the project (Fig. 3), not only for design but also at the operator levels.

Capture data from the archives: ASSYSTEM has developed a solution called Global Data Inquire (GDI), able to read, understand and structure disparate and scattered data in technical archives including handwritten.
This solution, based on optical character recognition and artificial intelligence processing, allows to build-up a set of ordered data, whereas a human analysis would focus on a limited number of documents.

Capture the requirements: the Rectify tool can capture the requirements from technical documents and is used to manage the requirements among the projects.

Capture data from the field: dismantling projects will last between 10 and 50 years and will generate a significant volume of data. The intermittent nature of decommissioning projects requires monitoring facility data to adjust the scenario as needed.

Data coming from the operations: ASSYSTEM developed a solution to monitor data coming from the operation. This module called "Field Studio" eases the dematerialization of on-site activities. The stakes are clear: save time, secure data, and reliability.

Data coming from BIM or scan to BIM

Data coming from scenario: ASSYSTEM compiles its technical background on dismantling and a new facility for waste retrieval in a digital application called ADSDEM which is a tool to evaluate and optimize cost. This tool allows qualifying and quantifying the impact of the choices, on waste, costs, safety, or deadlines and supports the demonstration of the design choices to the safety authorities.

All these data are structured and then coupled into a digital twin [5] which becomes the nerve center of the project data and facilitates the configuration management.

6 Use cases

6.1 Design study for a sorting and conditioning facility for low- and medium-radioactive waste

As already said, managing requirements is considered a key success factor for the project. The definition of the

Fig. 3. Digital tools feeding the engineering method.

Stakeholder Needs and Requirements is key, and it is the reason why the MBSE is very useful to drive the project.

A referential of all the requirements have been created (Fig. 4). Then these requirements are specified by means of attributes to distinguish functional, safety, or operational requirements. At the design stage, technical costs are defined to satisfy the required performance. These provisions are described in the engineering documents which provide the justification for their correct integration into the design.

These requirements referential is successively used to feed the design, assess its maturity and evaluate its progress through reviews or indicators provided by the requirements management tool.

The benefits of modeling are numerous:

- A structured view with links helps manage traceability
- A centralized, structured, synthetic glossary
- Visual support for configuration definition
- Different views complete in one model: several focuses but global consistency
- A model, which can be used as the reference for marketing data and can be completed to drive decisions (cost, risk, ...).

In addition to requirements management, system modeling, when implemented, supports the animation and efficiency of design. Indeed, correlated with functional breakdowns, it is possible to highlight the functional chains of a process required. Associated with a geographical breakdown and a layout of the facility, this type of modeling offers support to explain the organization of the facility and its operation. This type of support (Fig. 5) is used to share information within the project team as well as for the appropriation of the facility and its operation by the design actors (e.g. exchanges between technical and safety teams) or for the animation of reviews.

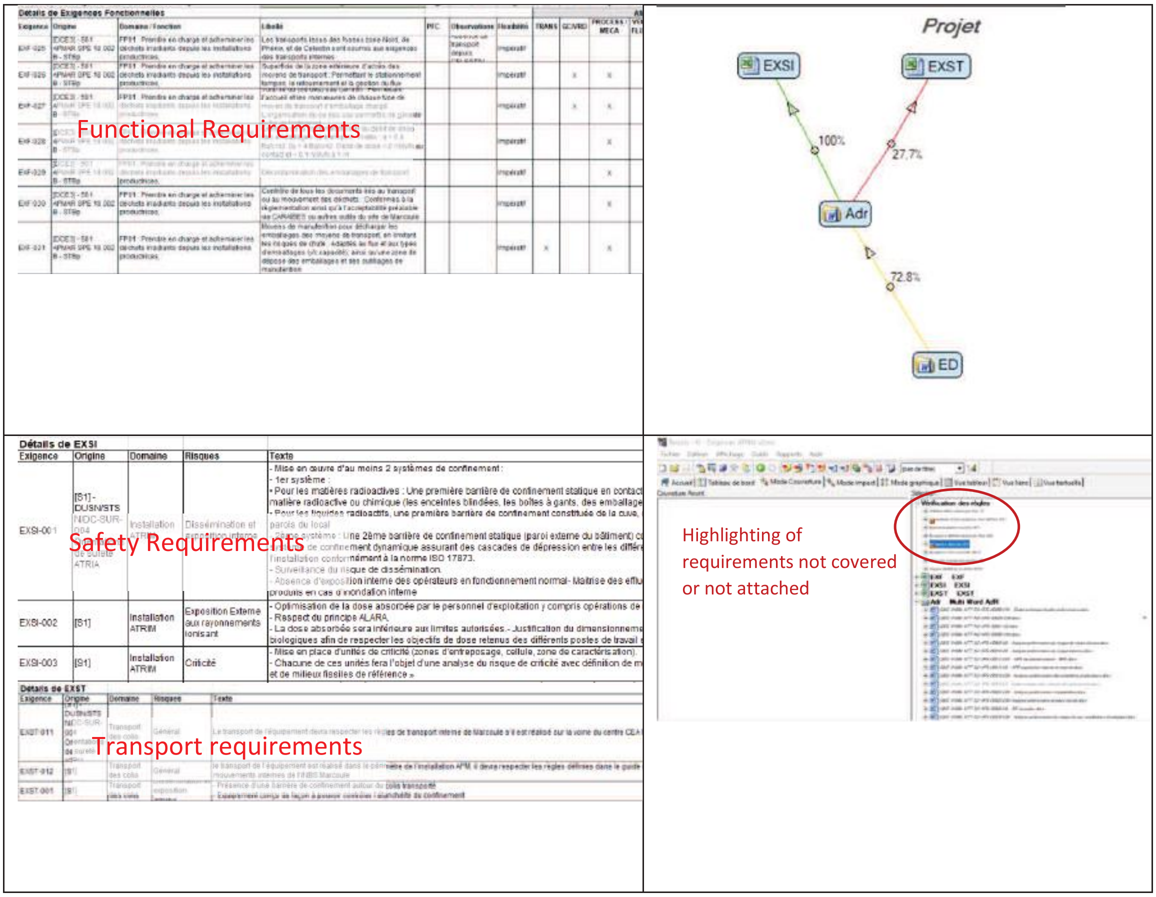

Fig. 4. Examples of baseline and requirements management indicators.

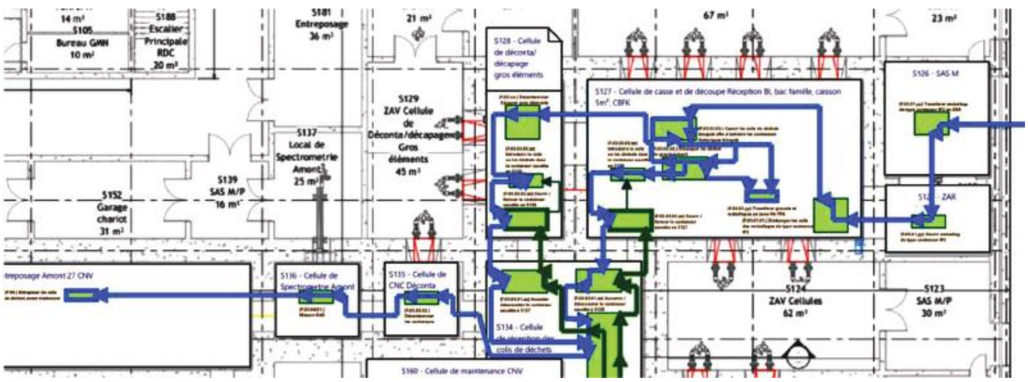

Fig. 5. Geographical and functional representation of the facility with, highlighted, the optimum path for the waste to be produced depending on some criteria such as nature, flow, radiological characteristics.

6.2 Digital twin for the operation & maintenance of facilities under decommissioning

This project consists of creating a digital twin to boost and simplify the monitoring of the operation and maintenance of a nuclear facility under decommissioning. This digital twin is composed of interconnected micro-services, with the objective to:

- Contribute to operational excellence in the preparation, supervision, and monitoring of operations at the facility,
- Improve the traceability/quality/reliability of data acquired at the work site, their exploitation, and their diffusion,
- Increase productivity.

The originality and success of the development of the digital twin lie in the understanding of the business processes of the operations on one hand and the knowledge and capacity to develop or adapt digital tools on the other. This digital twin was developed based on a combination

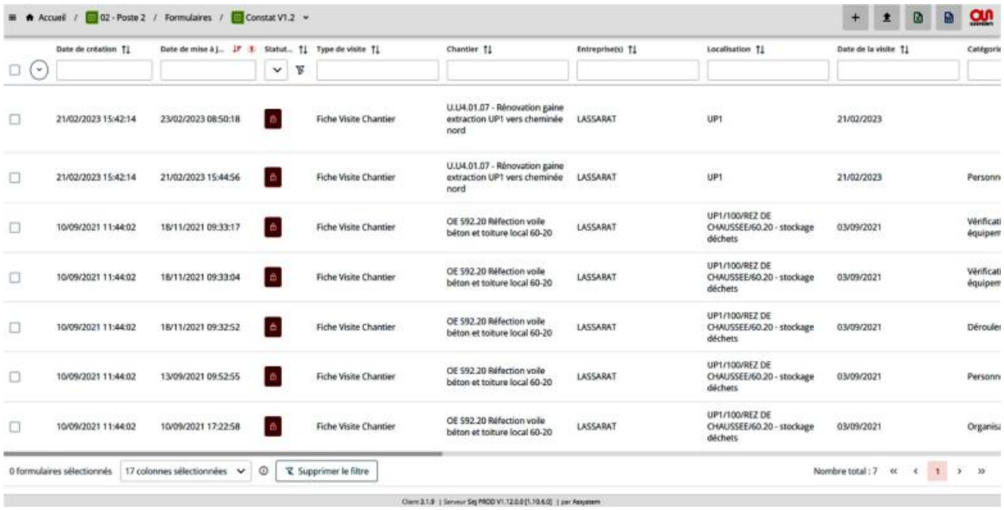

Fig. 6. Extract from the Field Studio tool – summary view of the visits carried out and in this case the findings made.

of software bricks, workflow modeling methodology, and business expertise (nuclear and digital).

In addition, the digital twin allows the operator to:

- Define the bricks of the facility being dismantled
- Bring together all the players (owner, industrial operators) around a shared collaborative space that allows access to the data acquired on-site.

After six months of using the digital twin, it has been shown that the automatic generation of reports reduces the duration of field visits, inspections, and inventories by a factor of 2 to 2.5. For inventories, this is an order of magnitude that depends on the completeness and complexity of the inventory. For inspection operations, the duration is effectively reduced by a factor of 2. For monitoring visits, the time spent on site is multiplied by 2. These orders of magnitude are valid for all types of work sites.

Other potential gains are emerging, including

The shared and collaborative space. The digital twin allows bringing together ASSYSTEM, the customer, and the operator around the same tool. Although difficult to evaluate in terms of quantitative gains, everyone knows that one of the major difficulties of projects lies in the management of interfaces and the capitalization of information.

The contribution to operational excellence

- Configuration control for the preparation of operations: configuration control is achieved when the operator anticipates and plans for future documentary changes (based on the planned physical changes to the facility). For a facility undergoing dismantling which, by nature, is constantly changing, this is a major challenge.
- Optimizing the monitoring of operations: progress and organization of operations, monitoring of operational findings (Fig. 6), etc.,
- Planning management: control of deadlines, anticipation of risks, and mitigation of causes (prevention) rather than limitation of consequences (correction).
- Productivity improvement including:
  - Control of waste produced: in a decommissioning facility, most of the operations lead to the production of nuclear waste. Controlling the waste produced includes
  - The inventory of waste produced: typology, volume,
  - Compliance of packages with specifications.

Gain in quality, traceability, and reliability

Reconstituting the facility's operating documentation: the documentation and associated processes were designed and structured according to the reference system at that time. The search for the best possible level of safety, regarding the techniques and knowledge at that time, requires restructuring and reverse engineering in the middle of the operation and dismantling phase.

Keep the operating documentation repository up to date and consistent with the physical state of the facility in the context of configuration control:

- Centralizing and securing the operational data acquired, as well as the flows of dissemination and use of this data, in the context of monitoring operations, reinforcing Safety & Security, managing the planning and controlling the waste produced (see below).
- Through in addition, it allows the improvement of the robustness of processes, by reducing the possibility of errors and by improving the quality, traceability, and processing time of information.
- Reinforcement of safety and security: acquisition and capitalization of weak signals (Fig. 7), monitoring, under the Quality Order of 10 August 1984, of compliance with the safety requirements set out in the standard.

7 Conclusion

The challenge concerning the dismantling & waste management project is to answer the complexity while derisk-

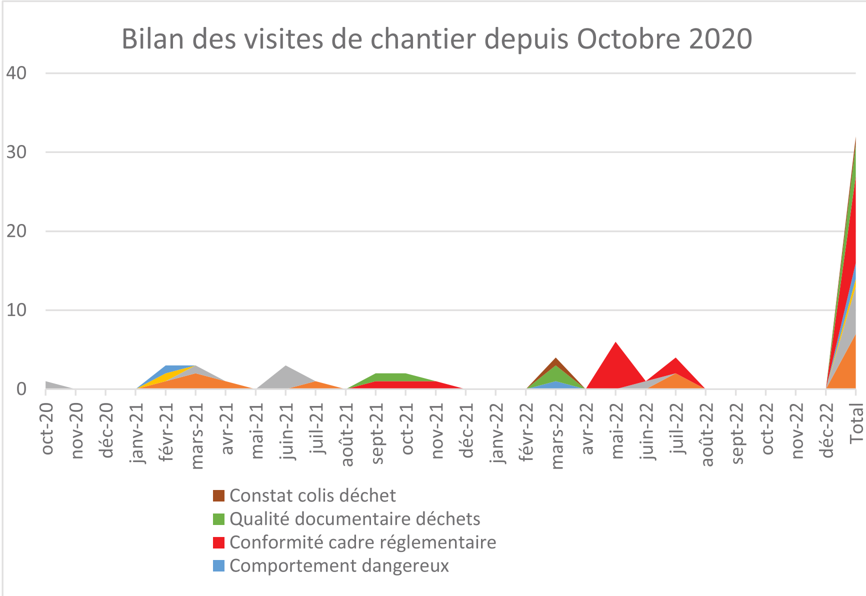

Fig. 7. Example of indicators from monitoring visits carried out with the Field Studio tool listing the weak signals acquired during dismantling operations at CEA Marcoule (average of 20 monitoring visits per month).

ing the operations. Firstly, there are challenges based on technical subjects such as the incomplete initial state, radiological, physical, regulatory requirements, availability and maturity of technologies, and skills that we could compare to hard skills.

However, there are also challenges due to the organization & management of the interfaces between all the stakeholders, the product owner, engineering, technology provider, operators, & regulators, and sometimes the final disposal operators what we could compare to soft skills.

Unfortunately, engineering is solicited on a case-by-case basis to produce studies. Engineering companies produce good studies, but we all know that the projects do not progress as much as everyone would like, with a reluctance to move the projects into execution. Engineering must play the role of integration through the development of tools that allow to do so and to maintain the vision and the overall coherence of the project; this is the goal of the DEMOLOGIST digital suite, which will be regularly enriched with new developments able to industrialize dismantling, and waste management projects 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.

Author contribution statement

Olivier and Christine established the general concept based on the acquired experience, Pauline, Mihaela, and Brice specified, tested, and implemented the concept in their activities.

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Side events
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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

PARUPM: A simulation code for passive auto-catalytic recombiners

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Abstract. In the event of a severe accident with core damage in a water-cooled nuclear reactor, combustible gases (H_2 and possibly CO) get released into the containment atmosphere. An uncontrolled combustion of a large cloud with a high concentration of combustible gases could lead to a threat to the containment integrity if concentrations within their flammability limits are reached. To mitigate this containment failure risk, many countries have proceeded to install passive auto-catalytic recombiners (PARs) inside containment buildings. These devices represent a passive strategy for controlling combustible gases, since they can convert H_2 and CO into H_2O and CO_2, respectively. In this work, the code PARUPM developed by the Department of Energy Engineering at the UPM is described. This work is part of the AMHYCO project (Euratom 2014–2018, GA No. 945057) aiming at improving experimental knowledge and simulation capabilities for the H_2/CO combustion risk management in severe accidents (SAs). Thus, enhancing the available knowledge related to PAR operational performance is one key point of the project. The PARUPM code includes a physicochemical model developed for the simulation of surface chemistry, and heat and species mass transfer between the catalytic sheets and gaseous mixtures of hydrogen, carbon monoxide, air, steam and carbon dioxide. This model involves a simplified Deutschmann reaction scheme for the surface combustion of methane, and the Elenbaas analysis for buoyancy-induced heat transfer between parallel plates. Mass transfer is considered using the heat and mass transfer analogy. By simulating the recombination reactions of H_2 and CO inside the catalytic section of the PAR, PARUPM allows studying the effect of CO on transients related to accidents that advance towards the ex-vessel phase. A thorough analysis of the code capabilities by comparing the numerical results with experimental data obtained from the REKO-3 facility has been executed. This analysis allows for establishing the ranges in which the code is validated and to further expands the capabilities of the simulation code which will lead to its coupling with thermal-hydraulic codes in future steps of the project.

1 Introduction

In severe accidents (SAs) large amounts of combustible gases may get released into the containment atmosphere. To mitigate the hazard of uncontrolled combustion, passive auto-catalytic recombiners (PARs) have been installed inside containment buildings. These devices are capable of converting the H_2 and CO present in the containment during the accident into H_2O and CO_2, respectively. The catalyst (e.g., platinum or palladium) promotes the reaction by lowering the activation energy so that the reactions take place at a lower temperature and concentration of species.

$$H_2 + 1/2\ O_2 \rightarrow H_2O + 242\,\mathrm{kJ/mol} \quad (1)$$
$$CO + 1/2\ O_2 \rightarrow CO_2 + 283\,\mathrm{kJ/mol}. \quad (2)$$

A PAR has the capability to convert hydrogen into water vapour without requiring an external source of energy. The hydrogen that reaches the device, which is shaped like a chimney, with the catalytic material located at its base, is adsorbed on the surface of the plates together with the rest of the species, such as the oxygen present. The catalytic reaction that takes place on the surface (heterogeneous reaction) generates heat that allows this convective flow to be self-maintained. On the other hand, the possibility that a homogeneous gas phase reaction can be initiated at high hydrogen concentrations must be considered as a risk of this type of device in high concentrations of hydrogen. To prevent this unwanted effect, innovative PAR designs have been proposed to control high catalyst temperatures in hydrogen-rich environments [1,2]. The most widespread PAR design involves an arrangement of vertical catalyst sheets located on the lower face of the rectangular box (Fig. 1).

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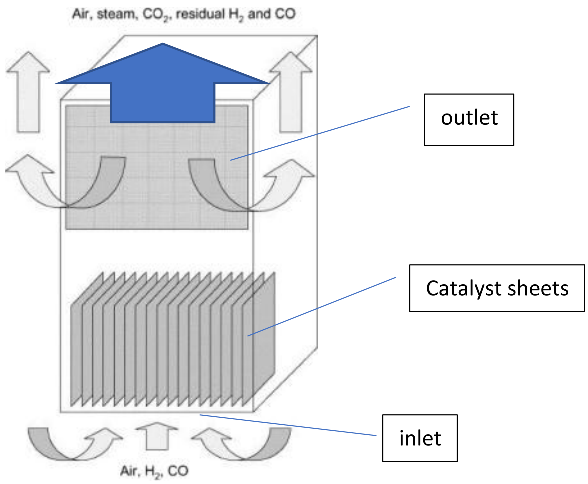

Fig. 1. Scheme of a generic passive auto-catalytic recombiner (PAR).

To study the behaviour of these devices, a physicochemical model of PAR has been developed, based on surface chemistry as well as heat and mass transfer involving platinum-based catalytic surfaces and gaseous mixtures of hydrogen, carbon monoxide, air, steam and carbon dioxide. Based on this model, the PARUPM code has been developed, a non-proprietary code [3].

The AMHYCO European project (Euratom 2014–2018, GA No. 945057) [4] aims to improve experimental knowledge and simulation capabilities for H_2/CO combustion risk management in severe accidents. The three main objectives of the project are to experimentally investigate the phenomena related to SA that are difficult to predict theoretically, to improve the predictability of numerical tools used for explosion hazard evaluation inside the reactor containment, and to enhance the SA management guidelines.

Based on the final results obtained in the preliminary phases of the project, the 12 AMHYCO partners will review and propose improvements to SA management measures in the containment, specifically those related to the mitigation of the combustion of heterogeneous gas mixtures, hence the relevance of the study of this model within the project.

2 PARUPM model

Numerical models describing PAR operation within comprehensive computational codes are typically based on empirical equations which correlate the relevant parameters, e.g., hydrogen concentration and total pressure, with the hydrogen recombination rate (AECL [1], FRA-ANP [5], NIS [6]). Regardless of their advantages in terms of computational efforts, their applicability is limited to boundary conditions similar to the underlying validation database. Considering the wide range of situations of a severe accident, there is a strong interest in developing a mechanistic model capable of exploring in greater detail the complex processes occurring inside the PAR (catalyst surface phenomena, natural chimney flow).

The catalytic reaction of gaseous species on the catalyst sheets involves the diffusion of species through the boundary layer, the adsorption/desorption on and from the active sites as well as chemical surface reactions. The heat released by these reactions increases the temperature (heating phase), thus influencing the surface processes, heating the gas mixture between the catalytic sheets, and reducing the gas density to induce a self-sustaining chimney flow. The presence of intoxicating species, unfavourable density gradients, as well as increasing pressure losses along the flow path through the PAR box, can limit or even prevent the operation of the PAR.

The developed model, PARUPM, is a numerical code to simulate the operational behaviour of a PAR device through a physicochemical approach. The PAR itself is considered a series of vertical parallel plates which form vertical flow channels [7]. PARUPM takes into account relevant phenomena involved in PAR operation: convective/diffusive heat and mass transfer between the gaseous mixture and the catalytic surface in a vertical flow driven by the chimney model, the adsorption/desorption of species on the plate surface, chemical surface reactions with subsequent heat release, and radiative heat exchange with the surrounding structures.

These phenomena occur simultaneously and must be resolved in a coupled manner. The coupling is carried out through expressions of the mass and energy balance at the interface between the catalytic plate and the gaseous current that runs constantly over it [7].

This model was specially tailored and developed for the surface chemistry on platinum-coated catalyst surfaces and gaseous mixtures of H_2, CO, air, steam, and CO_2 The model is based on a simplified scheme from Deutschmann surface methane combustion reaction [8] and Elenbaas analysis [9] for heat transfer between parallel plates induced by natural convection. Mass transfer is treated from the transfer analogy between mass and heat.

2.1 Surface chemistry

The model focuses on the surface reactions (heterogeneous), considering the reactions in the gas flow (homogeneous) negligible. Thus, recombination at the catalytic plates occurs via a chain reaction for Pt-catalysed combustion of adsorbed CO and H_2. These processes are described by the Deutschmann model for the combustion of CH_4 on platinum plates through a series of 20 reactions which, reduced to the species present in this application for PARs, simplifies to a total number of 10. The reactions of the chemical model are shown in Table 1.

The table defines the values of the following parameters of the chemical reactions: the sticking factor, S_{ia}, a dimensionless parameter; the pre-exponential factor, A_i, also dimensionless; and the activation energy of the reaction, E_i^{act} in J/mol. In addition, i(s) describes the species adsorbed on the catalytic plate and Pt(s) represents the presence of an active site in the solid matrix where the chemical radicals are housed. The subscripts a/d indicate that the reactions are adsorption/desorption of species, respectively.

Table 1. Deutschmann combustion model for methane catalysed with Pt [8].

Elemental reaction		S_{ia}	A_i	E_i^{act} (J/mol)
1a	$H_2 + 2Pt(s) \rightarrow 2H(s)$	0.046	–	–
1d	$2H(s) \rightarrow H_2 + 2Pt(s)$	–	3.7×10^{17}	R(8110–722θ_H)
2a	$O_2 + 2Pt(s) \rightarrow 2O(s)$	0.07 × (300/T)	–	–
2d	$2O(s) \rightarrow O_2 + 2Pt(s)$	–	3.7×10^{17}	R(25 631–7220θ_O)
3a	$H_2O + Pt(s) \rightarrow H_2O(s)$	0.75	–	–
3d	$H_2O(s) \rightarrow H_2O + Pt(s)$	–	10^{13}	40 300
IV	$OH + Pt(s) \rightarrow OH(s)$	1.00	–	–
4	$H(s) + O(s) \rightarrow OH(s) + Pt(s)$	–	3.7×10^{17}	11 500
5	$H(s) + OH(s) \rightarrow H_2O + Pt(s)$	–	3.7×10^{17}	17 400
6	$OH(s) + OH(s) \rightarrow H_2O + O(s)$	–	3.7×10^{17}	48 200
7a	$CO + Pt(s) \rightarrow CO(s)$	0.84	–	–
7d	$CO(s) \rightarrow CO + Pt(s)$	–	10^{13}	125 500
8d	$CO_2(s) \rightarrow CO_2 + Pt(s)$	–	10^{13}	20 500
9	$CO(s) + O(s) \rightarrow CO_2(s) + Pt(s)$	–	3.7×10^{17}	105 000
10	$CH_4 + 2Pt(s) \rightarrow CH_3(s) + H(s)$	–	4.63×10^{16}	–
11	$CH_3(s) + Pt(s) \rightarrow CH_2(s) + H(s)$	–	3.7×10^{17}	20 000
12	$CH_2(s) + Pt(s) \rightarrow CH(s) + H(s)$	–	3.7×10^{17}	20 000
13	$CH(s) + Pt(s) \rightarrow C(s) + H(s)$	–	3.7×10^{17}	20 000
14+	$C(s) + O(s) \rightarrow CO(s) + Pt(s)$	–	3.7×10^{17}	62 800
14–	$CO(s) + Pt(s) \rightarrow C(s) + O(s)$	–	10^{14}	184 000

For its application in the PAR model, not all the reactions of the Deutschmann model are necessary. Reactions 10–13 (marked in grey) correspond to the successive steps of methane dehydrogenation. Therefore, these reactions will not take place on the catalytic plates of a PAR as long as there is no CH_4 in the containment atmosphere. On the other hand, reaction IV (also indicated in grey) would correspond to the adsorption of the OH radical from the gas stream. Since homogeneous reactions have been neglected from the model, this reaction is eliminated. Finally, taking into account the forward and reverse reactions: 1a/1d, 2a/2d, 3a/3d, 7a/7d, and 14+/14−, the scheme of 20 reactions is reduced to 10 [2,6].

In this model, the desorption reactions are defined through a general Arrhenius law $k_{id} = A_i \exp\left(-E_{act}^i/RT\right)$, where R is the universal gas constant and T is the flux temperature. On the other hand, species adsorption reactions are modelled through sticking factors $k_{ia} = S_{ia}/\left[2\pi RTW_j\right]^{1/2}\Gamma$, where W_j is the molecular weight of the specie j and Γ is the surface density of sites in the catalyst. Meanwhile, the remaining catalytic reactions, which describe the reactions between surface-adsorbed species, are described as general Langmuir-Hinshelwood-type mechanisms.

2.2 Numerical model

With these parameters, it is possible to develop a numerical model composed of a system of 14 parameter equations that evolve over time. These equations represent [3]:

- the variation of the surface concentrations of the 7 species adsorbed on the catalytic plate as a function of the reaction rates and the adsorption/desorption rates: $\mathrm{d}\Theta_{i=\mathrm{H,O,vap,OH,CO,CO_2,C}}/\mathrm{d}t$.
- The variation of the fraction of vacant surface sites on the surface as a function of the adsorption/desorption rates and the reaction rates of other species: $\mathrm{d}\Theta_\nu/\mathrm{d}t$.
- Variation in concentrations (in molar fraction) of species in the gas near the wall due to diffusion and adsorption/desorption of species: $\mathrm{d}X_{i=\mathrm{H_2,O_2,vap,CO,CO_2}}/\mathrm{d}t$.
- The variation of the temperature of the catalytic plate, calculated through the energy balance due to the heat of the chemical reaction, convection, and radiation: $\mathrm{d}T_w/\mathrm{d}t$.

These equations contain 14 parameters that are considered constant at each time step and must be added as input in the numerical model: the surface concentrations of species: $\Theta_{i=\mathrm{H,O,vap,OH,CO,CO_2},C}$, the concentrations of species in the gas flow: $X_{i=\mathrm{H_2,O_2,vap,CO,CO_2}}$, and the average surface temperature T_w.

The system of equations is solved by treating it as a nonlinear system of differential equations of the type $\mathrm{d}X/\mathrm{d}t = F\left(X\right)$ where $\mathbf{X}$ is the vector of variables and F is the matrix function of the system of equations. Therefore, the solution scheme for this system is:

$$X_{n+1} = X_n + \left[I - \Delta T \left.\frac{\partial F}{\partial X}\right|_{X_n}\right]^{-1} \Delta t F\left(X_n\right). \quad (3)$$

The inversion of matrix $(I - \Delta tJ)$ is obtained by using DGETRF, DGETRI, DGEMV, and other auxiliary libraries from the LAPack collection [10]. An autonomous version of the model has been generated and implemented to the severe accident integral code MELCOR 1.8.5 to carry out various parameter analysis and validation exercises.

3 Model enhancement: diffusion model

Through the implementation of the linear system of differential equations that includes the simplified Deutschmann mechanism, PARUPM is capable of simulating the relevant phenomena associated with the recombination of H_2 and CO in PARs with plane-parallel plates. The transient model can approximate both the PAR heating phase and its quenching, as well as the transient changes in the boundary layer. Heterogenous catalytic reactions involve both surface and transport phenomena. Initially, the recombination rate inside PARUPM was determined by the surface reactions of the species over the catalytic plates, described by equation (4).

$$\mathrm{Rate}_i = \omega_i \Gamma \left(2Lh\right) M_i \tag{4}$$

where ω_i is the reaction rates of the recombined species i, Γ is surface site density of platinum, L and h are the height and width of the plate, and M_i is the molar mass of the species.

To enhance the code for simulating the behaviour of recombiners, a mass transfer model has been added to the code to consider diffusion through the boundary layer. In this case, it is assumed that the diffusion process is sufficiently slow so all the moles of the species that get to the catalytic sheet by diffusion are recombined. This approach is described in equation (5).

$$\mathrm{Rate}_{i,\mathrm{dif}} = \frac{\mathrm{Sh}_i D_{\mathrm{dif},i}}{D_h} \left(\frac{p_i}{RT}\right) \left(L * h\right) \tag{5}$$

where Sh_i is the Sherwood number of the species i, $D_{\mathrm{dif},i}$ is the diffusivity of the species through the boundary layer, D_h is the hydraulic perimeter, p_i is the partial pressure of the species, R is the ideal gas constant, T is the temperature of the gas in the inlet, and L and h are the length and width of the catalytic plate.

Recent works [11,12] have proven that recombination process is primarily driven by the recombination process is primarily driven by the diffusion phenomenon. Thus, although the code calculates the recombination rate by both diffusion and chemical reaction processes, the final value chosen for the recombination rates is the one obtained with the diffusion model. This decision is supported by the results shown in Figure 2. This graph shows the values for the recombination rates obtained with PARUPM against the experimental values for several experiments performed in the REKO-3 experimental facility. Both the diffusion-based (blue dots) and the reaction-based rates (grey dots) are represented. The deviation of the recombination rates reduces from an average ≈40% in the case of the reaction-bases rates to just a ≈5% deviation with the diffusion-based rates.

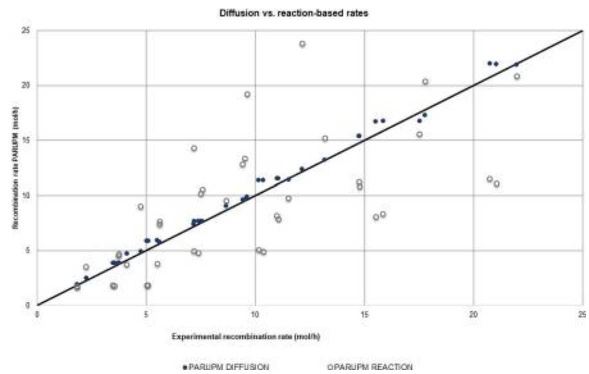

Fig. 2. PARUPM diffusion and reaction-based recombination rates against the experimental recombination rates in mol/h obtained with REKO-3.

4 Code validation

As it was showed in Figure 2, the PARUPM model has been compared to experimental data obtained by Forzschungzentrum Jülich (FZJ) in the REKO-3 facility, shown in Figure 3 [13]. The facility consists of a vertical channel with 4 catalytic sheets. This installation simulates a section of a passive autocatalytic recombiner, though normally the commercial PARs contained more than 20 sheets. Different to the commercial PARs, the main characteristic of this facility is that the flow is carried out under forced flow conditions. This allows us to characterize the flow rate of the different species that pass through the recombiner.

The objective of the REKO-3 experiments is the detailed investigation of the processes which occur in plate-type recombiners (reaction kinetics, catalyst temperatures, heat transfer, etc.), for which it is necessary to have strict control of the gas stream conditions. Thus, the experimental data obtained from this facility represents the behaviour of a recombiner once a steady-state or a pseudo-steady-state is reached.

The validation analysis of the code capabilities was performed with experiments run with generic catalyst plates made of 1.4571 steel coated with platinum and a thickness of 1.5 mm. The size of the plate is 143 mm in length per 143 mm in width. In the analysed experiments four plates were displayed with a separation of 8.5 mm between them. The experimental data obtained with this configuration correspond to the following conditions:

- dry air, $T = 25\,°\mathrm{C}$, gas velocity, $u = 0.25$, 0.5, and 0.8 m/s; and H_2 molar fractions, $X_{\mathrm{H}_2} = 1$, 2, 3, 4, and 5%.
- Same conditions, but with $T = 110\,°\mathrm{C}$.
- Same conditions, but with $T = 110\,°\mathrm{C}$ and 20% molar fraction of steam.

The recombination rates obtained with PARUPM for the prior conditions are expressed in Figure 4 as well as the experimental data obtained with REKO-3. Linear regression was represented on the graph from the experimental data. This shows that the PARUPM code is capable of simulating the expected behaviour of a PAR device in the conditions defined above.

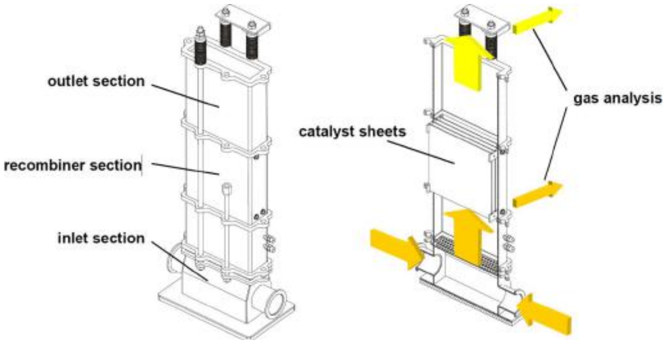

Fig. 3. Scheme of the REKO-3 experiment with the vertical channel and the catalytic sheets located inside it.

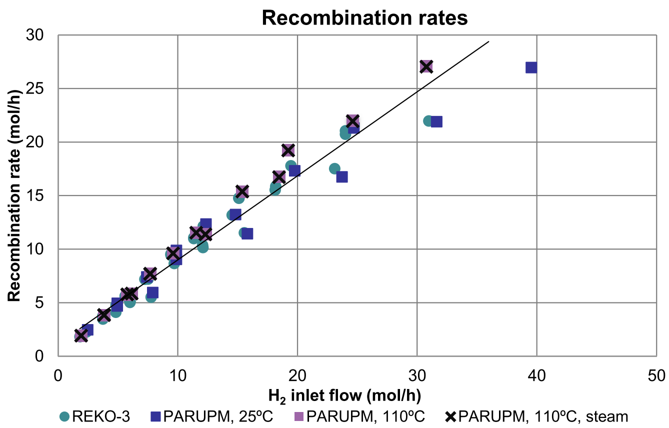

Fig. 4. PARUPM and REKO-3 recombination rates against inlet H_2 flow.

Although the REKO-3 installation corresponds to a configuration of forced and controlled flow in the injection lines and the model proposed in PARUPM is developed under the configuration of a flow channel driven by natural convection, the code is capable of simulating the behaviour and the recombination process.

5 Conclusions and future works

The paper presents the code PARUPM as well as its enhancement process and subsequent validation. The results obtained show that the physicochemical approach implemented in the PARUPM model is able to reproduce the behaviour of PARs in a wide range of boundary conditions, from low temperatures and concentrations to more extreme conditions at higher temperatures and hydrogen concentrations.

The introduction of the diffusion model significantly improves the results of the model, independently of the velocity of the inlet gas. With the reaction-based rates, the recombination rate was overpredicted at lower velocities by an average ≈40% and was underpredicted for higher velocities by an average ≈40% as well. Good Reaction-based rates are obtained for lower H_2 inlet concentrations (1%), and lower velocities (0.25 m/s), although these conditions are far from the typical operational conditions on PARs. Once normal operating conditions are tested (higher than 1% H_2 inlet concentrations and flows bigger than 0.25 m/s) the diffusion-based model. Moreover, the biggest deviation with the diffusion model appears for low H_2 inlet concentrations, and higher velocities, although this deviation is lesser than the average deviation from the reaction-based results. With the diffusion model, the average deviation is reduced to ≈5%. Thus, good predictions of the recombination rate are achieved with the new diffusion model.

Furthermore, the diffusion model is capable of simulating the behaviour of the recombination process in a wide range of conditions showing that the recombination rate is proportional to the volumetric flow of hydrogen through the channel in the analysed conditions. Further investigation is required for studying the numeral limitations and simulation capabilities of the diffusion model, although preliminary studies show that the code is capable of predicting the behaviour of a PARs device once O_2 starvation and CO poisoning conditions are obtained over the recombiner.

Due to the characteristics of the PARUPM code, described in the previous sections, it has been proposed, within the AMHYCO project, as a tool for studying the behaviour of PARs in containment. The PARUPM code can be implemented in detailed thermo-hydraulic codes, as is the case of GOTHIC, where the phenomenology experienced by containment in the event of an accident can be analysed in greater detail.

GOTHIC [14] is a general-purpose integrated thermo-hydraulic software package for the design, licensing, safety and operational analysis of nuclear power plant (NPP) containment and system components. Solve the conservation equations of mass, momentum, and energy for multi-component, multi-phase compressible flow in three states: vapour, continuous liquid, and droplets. GOTHIC uses empirical correlations to calculate heat transfer between fluids and 1D and 2D structures by convection, condensation, and evaporation. It also uses a 1D correlation for fluid friction with solid structures.

Additionally, GOTHIC contains a simple built-in PAR component model that makes this tool useful for analysing PAR responsiveness and capacity within containment. PARs are included in GOTHIC via the "H_2 recombiner" component, which is used to model natural and forced convection recombiners of catalytic or ignition type. The performance of the PAR depends on the parameters defined by the user, so the implementation of DLLs and other analysis mechanisms external to the code itself is necessary to obtain more realistic values of the H_2 recombination. The PARUPM code, once implemented in the GOTHIC software, will be able to study the recombination of H_2 in containment in a more realistic way, thus being able to study in depth the impact of recombiners when it comes to reducing the risk of combustion in containment.

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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 legal reasons.

Author contribution statement

Araceli Domínguez-Bugarín performed the calculations, processed the data, and wrote the manuscript. M.A. Jiménez developed the main code, performed software architecture, and reviewed the manuscript. E.-A. Reinecke supervised the work described in this document, provided with experimental data, and reviewed the manuscript. G. Jiménez supervised the work described in this document, ran the duties of project administrator, and reviewed the manuscript.

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Regular Article

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Start-up, operation and thermal-hydraulic analysis of a self-propelling supercritical CO_2 heat removal system coupled to a pressurized water reactor

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Abstract. The supercritical carbon dioxide (sCO_2[1]) heat removal system, which is based on a closed Brayton cycle with sCO_2 as a working fluid, is an innovative, self-propelling and modular heat removal system for existing and future nuclear power plants. By changing the number of CO_2 cycles, the heat removal capacity can be adapted. In this paper, up to four sCO_2 cycles are analyzed in interaction with a pressurized water reactor, using the thermal-hydraulic system code ATHLET and considering a long-term station blackout and loss of ultimate heat sink scenario with conservatively high and low decay heat curves. The presented start-up procedure for the heat removal system might require further optimization due to the non-linear thermal gradients. Independent from the start-up, a heat removal system with three or four CO_2 cycles keeps the primary loop temperatures sufficiently low. However, with only three cycles, the core is almost uncovered, and the danger of recriticality may occur due to cold leg deboration. Controlling the turbine inlet temperature via the turbomachinery speed and subsequent shutdown of single cycles successfully adapts the operation of the heat removal system to the declining decay heat. This enables reliable decay heat removal for more than 72 h.

1 Introduction

In case of a station blackout and loss of ultimate heat sink accident in a nuclear power plant, the plant accident management strongly depends on the recovery of electricity. If not available, core integrity will be violated, like in the Fukushima Daiichi accident. Such scenarios inspire the development of advanced decay heat removal systems. Since space is a limitation in existing power plants, the supercritical carbon dioxide (sCO_2) heat removal system "sCO_2-HeRo" was proposed because of its compactness and self-propelling features [1,2]. Such a system could be incorporated in newly-built nuclear power plants as well as retrofitted to existing nuclear power plants due to its compactness. The system is not only self-propelling but, its excess electricity can even be used to support other accident measures, e.g. recharging batteries. Moreover, no cooling water is required because the decay heat is transferred to the ambient air. To assess the benefits for nuclear safety, the sCO_2-HeRo system needs to be analyzed in interaction with different nuclear power plants.

Figure 1 shows the scheme of the sCO_2-HeRo system attached to the steam generator (SG) of a pressurized water reactor (PWR). For better visualization, only one primary loop, which is connected to the pressurizer (PRZ), the corresponding steam generator (SG), and one attached CO_2 cycle of the sCO_2-HeRo system are displayed. In the case of a station blackout and loss of ultimate heat sink accident, the main coolant pumps stop, and the containment is isolated. In the following, natural circulation develops on the primary side via the hot (HL) and cold legs (CL), and the heat is transferred to the steam generators (SG) on the secondary side. Natural circulation also builds up on the secondary side via the compact heat exchangers (CHX) of the sCO_2-HeRo system. After the start of the accident, all CO_2 cycles are ramped up to their design heat removal capacity simultaneously. Later, when the decay power is lower than the total heat removal capacity, the operation of the cycles is adapted to the declining decay heat by control and successive shutdown of single cycles, as shown later in Figure 8. In the CHX, the steam condenses and heats the sCO_2. The pressurized and heated sCO_2 is expanded

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[1] sCO_2 is defined as carbon dioxide at supercritical conditions with $p > 73.8$ bar and $T > 31\,^\circ C$

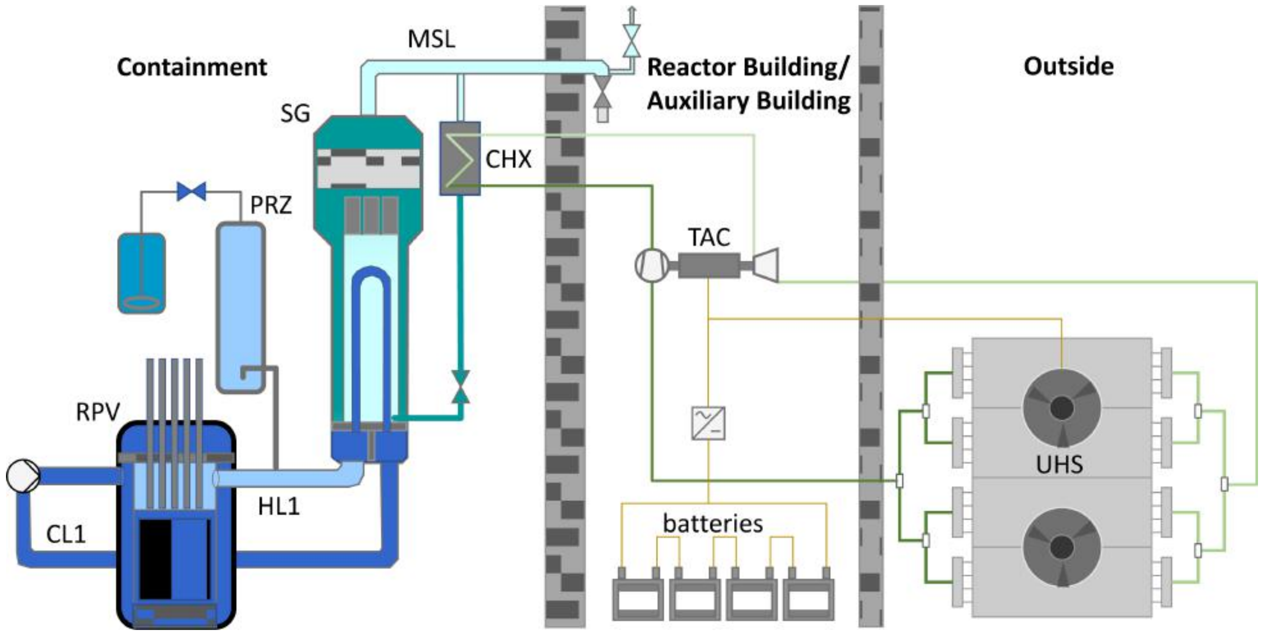

Fig. 1. The sCO_2 heat removal system attached to the steam generator (SG) of a pressurized water reactor (PWR).

in the turbine, which drives the compressor and generates power for the fans of the gas cooler (UHS). The compressor and the turbine are mounted on a common shaft together with the alternator and are referred to as turbo-alternator-compressor (TAC) or turbomachinery. After the turbine, the remaining heat of the CO_2 is removed from the gas cooler to the ambient air, which serves as the diverse ultimate heat sink. For simplicity, the heat exchanger to the diverse ultimate heat sink will be called "UHS" in the following. Finally, the sCO_2 is compressed and flows to the CHX. Similarly, the sCO_2-HeRo system can be directly attached to the reactor pressure vessel (RPV) of a boiling water reactor [1].

A comprehensive review of all kinds of sCO_2 power generation applications as well as cycle, component, and control aspects was given by White et al. [3]. Wu et al. [4] provided an extensive review of the sCO_2 Brayton cycle for nuclear applications, considering experimental and numerical work, the application as a power conversion system as well as a heat removal system. Among other things, they highlight the need for further safety analysis and dynamic simulations. The safety and thermal-hydraulics of water-cooled nuclear power plants are discussed in detail by D'Auria et al. [5]. For the simulation of the thermo-hydraulic behavior, different system codes are used, e.g. CATHARE, RELAP, TRACE, ATHLET, SCTRAN, and SAS4A/SASSYS-1 [5–8]. Because sCO_2 is considered a working fluid for 4th generation reactor concepts as well as for the proposed heat removal system, work is in progress to extend or couple these system codes for the simulation of sCO_2 power cycles [1,7–14].

The thermal-hydraulic system code ATHLET [6,15,16], which is used for this study, is applied to analyze the whole spectrum of leaks and transients in nuclear power plants of Generation II–IV as well as Small Modular Reactors. The highly modular code structure of ATHLET includes advanced thermal-hydraulics as well as physical and numerical models. The main modules are thermo-fluid dynamics, heat transfer and heat conduction, neutron kinetics, control, and balance-of-plant, and the numerical time integration method. For a detailed study of the code features, the ATHLET "Models and Methods" manual [15] can be used. Bestion [6] compares different thermal-hydraulic system codes regarding their models, capabilities, and limitations. A short introduction to ATHLET is provided in [1,17].

Venker [1] investigated the feasibility of the sCO_2-HeRo approach for a boiling water reactor in detail by implementing the first extensions to simulate the heat removal system in ATHLET. The successive shutdown of single cycles enabled the decay heat removal for more than 72 h. However, the component models, design, and control of this system should be improved, and different ambient temperatures and decay heat curves need to be considered in the future. Within the project sCO_2-HeRo, Hajek et al. [18] and Vojacek et al. [19] described the basic principles for integrating the sCO_2-HeRo system into the European PWR fleet including safety, reliability, and thermodynamic design considerations and first simulations with Modelica. As part of the project sCO_2-4-NPP, the validation status for modeling sCO_2 cycles was provided for the codes CATHARE, Modelica, and ATHLET, including a blind benchmark [13]. Successful simulations were performed, but it was also found that component models need further improvement and some numerical issues need to be solved in the future. Hofer et al. [12] presented improved models for ATHLET, including heat exchanger and turbomachinery models. The turbomachinery models are performance map based and use a real gas similarity approach [20] to account for changes in the inlet conditions. They also provided a design approach for the sCO_2-HeRo system and analyzed the sCO_2 cycle with varying decay heat

[21] and at different ambient temperatures [17,22]. The cycle was successfully operated in part-load by adapting the rotational speed of the turbomachinery, keeping the compressor inlet temperature constant and without the need for inventory control. In [17,22], the modeling and design were improved, including new sCO_2 turbomachinery performance maps with a higher surge margin, and the start-up from an operational readiness state (ORS) was considered. Using Modelica coupled with ATHLET, Frýbort et al. [23] presented a first analysis of the challenging push-start from shutdown conditions and an alternative control strategy for low ambient temperatures, a combination of inventory control and UHS bypassing. Future analysis is required to analyze the feasibility of the push start, e.g. start at low ambient temperatures or determination of an appropriate heating procedure. The sCO_2-HeRo system was integrated and simulated coupled to an EPR, VVER 1000, and Konvoi PWR with CATHARE, ATHLET/Modelica, and ATHLET, respectively [17,24]. In all power plants, the same modular sCO_2-HeRo system with a heat removal capacity of 10 MW per sCO_2 cycle was installed, and successfully coupled simulations with a different number of systems were performed.

In the field of sCO_2 cycles for power generation, various dynamic analyses were conducted. Despite the focus on power generation, many findings are also relevant for the considered heat removal system. Hexemer et al. [11,25] presented a detailed TRACE model of a recuperated sCO_2 cycle with two turbines. They highlighted the importance of performing a detailed transient analysis before the system design is finalized. Moreover, attention is drawn to the problem of compressor surge and turbine flow reversal. Nathan [26] investigated control strategies for an indirect sCO_2 recompression cycle. The major control strategies are high and low-temperature control, turbine bypass, and inventory control. These strategies enable successful cycle operation for different transients, like start-up and shutdown, part-load operation, loss-of-load, loss of heat sink, and over-power. Liese et al. [27] demonstrated load following with fast ramp rates of 7.5%/min of full load, warm start-up, and shut down for a sCO_2 recompression cycle by applying PI-controllers with gain scheduling while considering the equipment constraints. Furthermore, they highlighted the need for a one-dimensional cooler model to capture the oscillatory control interaction between the cooler outlet and inventory control. Moisseytsev and Sienicki [28] performed extensive steady-state and transient studies with the Plant Dynamics Code, including validation with data from Sandia National Laboratories and the sCO_2 Integrated System Test facility. Moreover, the Plant Dynamics Code was coupled to SAS4A/SASSYS-1, e.g. to analyze the thermal transients in the sodium-CO_2 reactor heat exchanger [29].

In this study, the coupled ATHLET simulations of the sCO_2-HeRo system with a generic Konvoi PWR are discussed in detail. First, the most important findings regarding the design, layout, and control of the CO_2 cycle are summarized. Secondly, the integration of the sCO_2-HeRo system into the PWR is presented. Thirdly, the start-up of the system from its operational readiness state is discussed. Fourthly, the required number of CO_2 cycles is determined, and the need for a control strategy to adapt to the declining decay heat is highlighted. Finally, the successfully controlled simulation is presented. Overall, the ATHLET simulations show that a sCO_2-HeRo system with four controlled CO_2 cycles can safely remove the decay heat for more than 72 h.

2 The sCO_2 heat removal system

The design, layout, and control of the CO_2 cycle were already presented in [17,22]. Therefore, only the most important points are summarized here. In case of an accident, the task of the sCO_2-HeRo system is to remove the declining decay heat reliably over several days at any ambient condition. To follow the decay heat curve, the system consists of several CO_2 cycles, which are shut down step by step. At the beginning of the accident, the maximum thermal capacity of all cycles together can be lower than the initial decay heat because an inventory loss in the reactor for a limited time span can be tolerated as long as the cooling of the core can be guaranteed [1,21]. Assuming that other safety systems, as well as electricity supply, are unavailable, the system has to be self-propelling. This means that the power of the turbine P_{turb} must be higher than the power consumption of the compressor P_{comp} and the fans P_{fan} of the UHS. To quantify the margin to zero, the excess power is defined as

$$\Delta P = P_{turb} - P_{comp} - P_{fan}. \tag{1}$$

The basic cycle layout is provided in Figure 1. Additional bypasses, like a turbine bypass, are only required for special operating conditions, e.g., for the start-up. At the design point, which is located at the highest ambient temperature of 45°C, the heat removal capacity of one cycle is set to 10 MW. The design point performance of the turbomachinery is specified conservatively with isentropic efficiencies of 0.7 and a pressure ratio of 1.7. With a turbine inlet temperature of about 287°C and a compressor inlet temperature of 55°C, the design point optimization yields a compressor inlet pressure of 126.3 bar and an excess power of 283 kW. Altogether, the cycle does not focus on efficient power generation but self-propelling heat removal over the whole range of considered boundary conditions. On the CO_2 side, the compressor and turbine inlet temperature are controlled via the fan speed of the UHS and the turbomachinery shaft speed, respectively.

The performance maps of the sCO_2 turbomachine employed in this study were generated by mean-line analysis codes for the compressor [30] and turbine [31]. These maps are provided as the input of a recently developed turbomachinery model in ATHLET, which considers real gas effects [12,20]. The CHX and UHS are modeled with the standard approach of modeling just one representative channel or pipe in ATHLET [13,32]. The upscaled CHX consists of 9000 channels with a size of $2 \times 1\,\text{mm}^2$ per fluid with a length of 1.1 m, and the UHS consists of 732 pipes on the CO_2 side with an inner diameter of 10 mm and a length of 22 m. The UHS is by far the largest component and thermal inertia of the cycle, with a total structural mass of 18.1 t, containing 56.8% of the total CO_2 mass in design conditions.

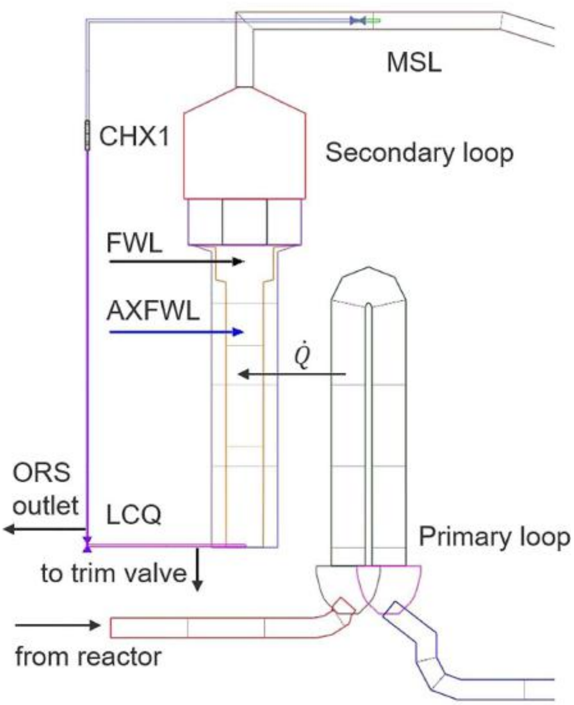

Fig. 2. ATHLET nodalisation scheme of one steam generator including the compact heat exchanger of the sCO_2 heat removal system.

3 Integration of the sCO_2 heat removal system into the PWR

In this paper, the sCO_2-HeRo system is attached to a generic four-loop Konvoi PWR [33]. The CHX of the first CO_2 cycle is attached to the main steam line (MSL) of the first steam generator, as shown in Figure 2. Valves in the inlet and outlet pipe of the CHX enable disconnection and control of the new line. During the normal operation of the NPP, the valve in the outlet pipe is closed. However, a small amount of steam flows to the CHX to keep the CO_2 cycles in an ORS. The condensate is led to the steam generator blowdown system (LCQ) downstream of the trim valve. This is modeled in a simplified manner in the simulation by the “ORS outlet” sink. Due to the higher pressure losses in the main steam line and the higher water level in the steam generator during normal operation, the condensate cannot be injected into the part of the LCQ before the trim valve. Approximately 1% of the feedwater mass flow rate is discharged via this pipe to demineralize the coolant. In the case of the station blackout, the trim valve and the “ORS outlet” line is closed in the same way as the feedwater line and the main steam line to isolate the steam generator. At the same time, the valve in the outlet pipe of the CHX is opened, and a natural condensation-driven circulation develops over the CHX.

In a parameter study, the inner diameter of the piping before the CHX is set to 0.1 m and after the CHX to 0.05 m, and the lower end of the CHX to the height of 18 m. For comparison, the water level in the steam generator 60 s after the start of the accident is approximately at a height of 10 m. Under accident conditions, this results in a CHX water outlet temperature of 165°C at the design point of the CO_2 cycle. During the simulation, the target value of 150°C for $T_{H_2O,out}$ can be reached by controlling the valve opening in the outlet pipe of the CHX. This is required to avoid the thermal stress limitation in the CHX. During the progress of the accident, the valve opening must be adjusted continuously due to the changing water level in the steam generator and the changing CO_2 side conditions. The first tests revealed that the outlet valve should be controlled instead of the inlet valve because the reverse flow and flow oscillation may occur if the pressure drop in the inlet pipe is too high.

4 Start-up of the heat removal system

In the following, the start-up of the sCO_2-HeRo system from an operational readiness state (ORS) is described. The goal of the ORS is to enable a fast start-up in case of an accident at any ambient temperature. Therefore, the ORS should fulfill the following criteria:

- preheated components to reduce thermal stress during start-up.
- Low thermal and electrical power consumption to minimize the impact on the NPP plant efficiency.
- Self-propelling operation (preferred but not required) to allow the start-up without battery support in case of an SBO.

In Table 1, the operation conditions of one selected ORS are presented. To keep the thermal power consumption in the CHX low, the turbomachinery is operated at only 20% of the speed compared to the cycle design point. In addition, the H_2O mass flow rate has to be throttled to limit the heat transfer. This results in a temperature difference of almost 0 K between the CHX inlet temperature on the CO_2 side and the CHX outlet temperature on the H_2O side. The CO_2 side outlet temperature of the CHX is already at 150°C, and the compressor inlet temperature is controlled to its design value of 55°C. Despite the part-load operation with a low speed and very low-pressure ratio, the isentropic efficiencies of the turbomachinery are close to their design point.

Altogether, it can be observed from the total power of the system that it might be possible to achieve a self-propelling operational readiness state at only 11% of the design thermal power input. The results in Table 1 are preliminary because the operating points are located far from the design point, where the accuracy of the models and the input needs to be analyzed and improved further. Moreover, the conservative assumption of the turbomachinery isentropic efficiencies, and the ORS condition may be adapted in the future. More details regarding the ORS can be found in [22].

In the following simulation, all CO_2 cycles are started identically, and the conservatively high decay heat curve [24] is considered together with the highest ambient temperature, which is 45°C. In Figure 3, the parameters of the start-up procedure are presented over time, with $t = 0$

Table 1. Operation conditions of the ORS.

	Unit	Value
Turbomachinery speed relative to the cycle design point	%	20
Compressor inlet p	MPa	12.2
Compressor outlet p	MPa	12.5
Compressor inlet T	°C	55
CHX inlet T (CO_2)	°C	56
CHX outlet T (CO_2)	°C	150
CHX inlet T (H_2O)	°C	282
CHX outlet T (H_2O)	°C	56
CHX thermal power relative to cycle design point (10 MW)	%	11.3
Mass flow rate (CO_2)	kg/s	5.6
Mass flow rate (H_2O)	kg/s	0.45
Compressor efficiency	%	69.0
Turbine efficiency	%	71.4
Compressor power	kW	4.8
Turbine power	kW	6.2
Fan power ($T_{\text{air}} = 45°\text{C}$)	kW	0.4
Total power	kW	1.0

marking the start of the accident. At the top left, the relative shaft speed of the turbomachinery in relation to the cycle design point speed and the relative valve opening area in the pipe after the CHX are shown. The H_2O mass flow rate is provided at the top right, and some CO_2 side and H_2O side temperatures are displayed at the bottom left and right, respectively. At $t < 0$, the parameters of the ORS can be observed, e.g. a turbomachinery shaft speed of 20%, an H_2O mass flow rate of 0.45 kg/s, and a CHX outlet temperature of 150°C on the CO_2 side. During the ORS, the condensate of the CHX is injected after the trim valve to the steam generator blowdown system (ORS outlet in Fig. 2). An active control strategy is applied, i.e. controllers and valves are powered by batteries (Fig. 1), which are constantly recharged with the excess electricity produced by the cycles.

First, 2.5 s after the start of the accident, the ORS outlet is closed to isolate the steam generator in the same way as it is done in the feedwater and main steam line. Therefore, at the same time, the valve in the pipe after the CHX is opened partially, as shown in Figure 3, and the condensate flows into the bottom of the downcomer via the LCQ (Fig. 2). It is important to open this valve only to a predetermined value because fully opening this valve would lead to rapidly increasing temperatures on the water as well as on the CO_2 side resulting in high thermal stresses for the components. To limit the stress in the CHX, the mentioned valve is kept at its predetermined value for the first 100 s. Then, this valve is opened slowly within the next 20 min to allow an increase in the H_2O mass flow rate. At the same time, the turbomachinery speed is increased linearly to its design value. Finally, in the last 100 s, before the valve reaches a second predefined opening value, the control of the CHX condensate outlet temperature is activated. After the procedure is finished, the valve opening is controlled to keep the condensate temperature constant at 150°C, and the CO_2 cycle has reached its design performance.

Averaged over the 20 min lasting start-up procedure, the gradient of the CHX condensate outlet temperature is only 4.7 K/min. For the CHX outlet temperature on the CO_2 side, the average gradient is 6.5 K/min, and for the UHS inlet temperature, 4.5 K/min, respectively. However, the temperatures are not increasing linearly, as shown in Figure 3. First, all temperatures except the condensate outlet temperature show a small peak at the beginning of the start-up procedure. This is due to the heat-up of the secondary side and the following cooldown, which is caused by the partial depressurization to 7.5 MPa. The maximum CO_2 side temperature peak is reached when the shaft speed increase is started. Increasing the shaft speed earlier damps this peak. However, depending on the considered battery capacity for the start-up procedure, care must be taken because the excess power of the system will drop below zero if the shaft speed is increased too early.

While the increase of the CO_2 side temperatures is stretched almost over the complete ramp-up period, the major increase of the CHX outlet temperature occurs during the last 300 s, where the average heat-up is 21 K/min. A detailed CHX design and thermal stress analysis are required to investigate the effects of the non-uniform heat-up. A reduction of thermal stresses can be achieved by simply extending the start-up time. Furthermore, the ORS or the start-up procedure may be optimized, e.g. by implementing an advanced control strategy to limit the thermal gradients.

5 Variation of the number of sCO_2 cycles without a control strategy to adapt to the declining decay heat

In this chapter, simulations of the sCO_2-HeRo system with different numbers of CO_2 cycles are compared to each other. A conservatively high decay heat curve [24] and the maximum ambient temperature of 45°C are applied to conservatively determine the required minimum heat removal capacity, corresponding to a minimum number of CO_2 cycles, to keep the PWR in a safe condition. Start-up of the cycles and control of the CHX outlet temperature on the H_2O side were conducted as described in the previous chapters.

On the CO_2 side, the compressor inlet temperature is controlled to its design value of 55°C by varying the speed of the UHS fans. At lower ambient temperatures, the compressor inlet temperature may still be controlled to 55°C, mainly resulting in lower fan power and a slightly higher heat removal capacity [17]. Therefore, the conclusions drawn regarding the required number of CO_2 cycles are valid over the whole range of ambient temperatures. Furthermore, the turbomachinery shaft speed is kept

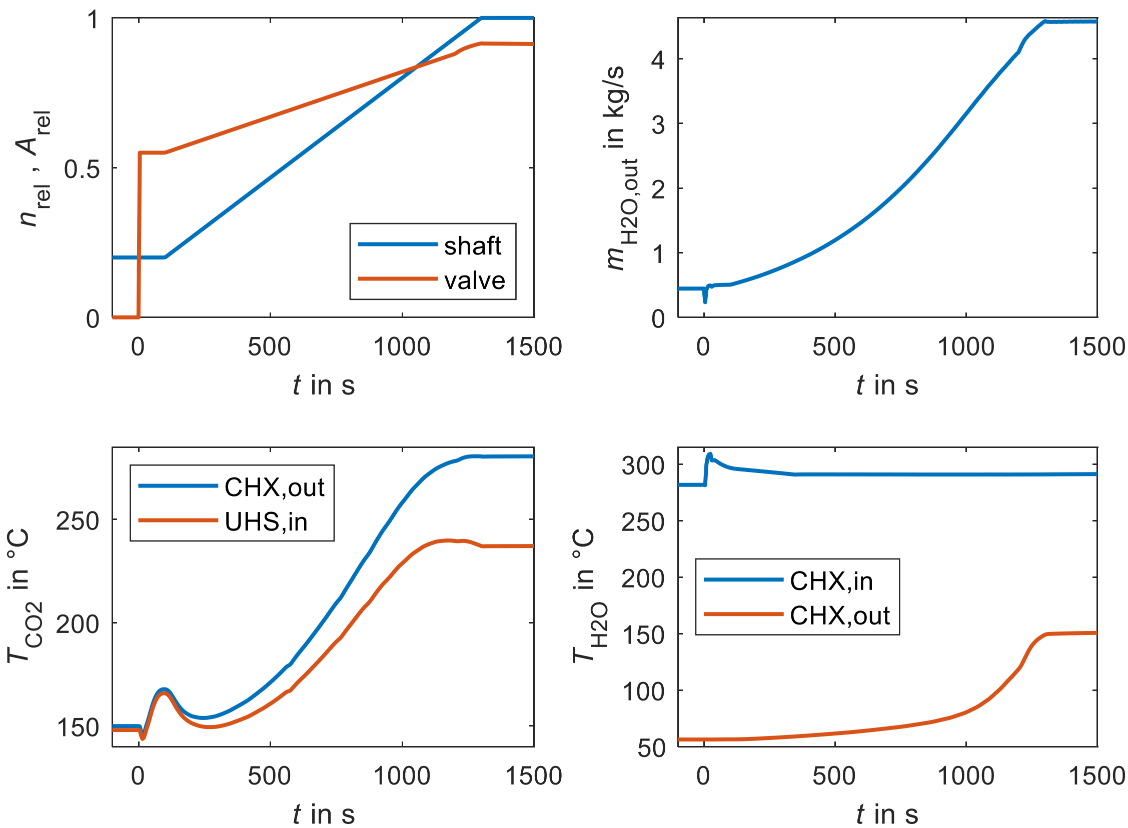

Fig. 3. Parameters during start-up: relative turbomachinery shaft speed in relation to the design point speed and relative valve opening in the pipe after the CHX (top left); condensate mass flow rate of the CHX (top right); CHX outlet and UHS inlet temperature on the CO_2 side (bottom left); CHX inlet and outlet temperature on the H_2O side (bottom right).

constant at its design value after start-up, and no shutdown of single CO_2 cycles is considered. This allows showing the long-term effects of a missing control strategy to adapt to the declining decay heat. These effects are discussed in the second part of this chapter.

The simulations were performed with zero (Ref. case [24]), two, three, and four CO_2 cycles available, labeled with "0", "2", "3", and "4" respectively, in Figure 4. This figure shows different parameters of the accident during the first 24 h, beginning at the top left with the balance between decay power (dashed green curve) and the heat removal capacity of the available CO_2 cycles combined. Only in cases 3 and 4 the equilibrium between the decay heat and the heat removal capacity is reached. In the other cases, the heat removal capacity is not sufficient, resulting in steeply increasing temperatures, as indicated by the temperature at the nozzle of hot leg 1 at the top right. In case 2, the temperature reaches 650°C after about 3.45 h. This is about 1.5 h later than in the reference case. In all figures, the simulations are only shown up to a hot leg temperature of 1000°C because no core degradation is simulated. In case 3, the hot leg temperature is kept at about 351°C, determined by the saturation temperature regarding the setpoint of pressurizer safety valves. From about 10.5 h on, after passing the break-even of heat removal and decay heat, the decreasing temperature on the secondary side causes a decrease of pressure and temperature on the primary side, too. Due to the higher heat removal of case 4, almost no temperature increase can be observed in this case, and the temperature decrease starts earlier. A lower heat removal capacity due to a delayed start-up or failure of one of the CO_2 cycles would also lead to a subsequent primary side temperature and pressure increase towards the setpoint of pressurizer safety valves.

With four CO_2 cycles (case 4), heat removal from the primary to the secondary side of the steam generators was effective in keeping the primary temperature low enough to avoid pressure increase and action of the pressurizer safety valves. This can be verified from the primary mass content at the lower right in Figure 4. In contrast, 32% of the primary loop inventory is lost in case 3 before the blow-off from the primary side stops. The initial rapid mass loss on the primary side is determined by subcooled water from the solid-filled pressurizer.

In the bottom left of Figure 4, the water level in steam generator 1 is shown. For all simulations, it decreases to practically zero at a certain time. However, this does not limit the heat transfer from the primary to the secondary side and further to the CO_2 cycles. Even in case 3, in the period when the steam generator is practically dried out, the resulting heat transfer coefficient on the secondary side between 65 W/m^2 K at the top and 105 W/m^2 K at the bottom of the riser proved sufficient together with the

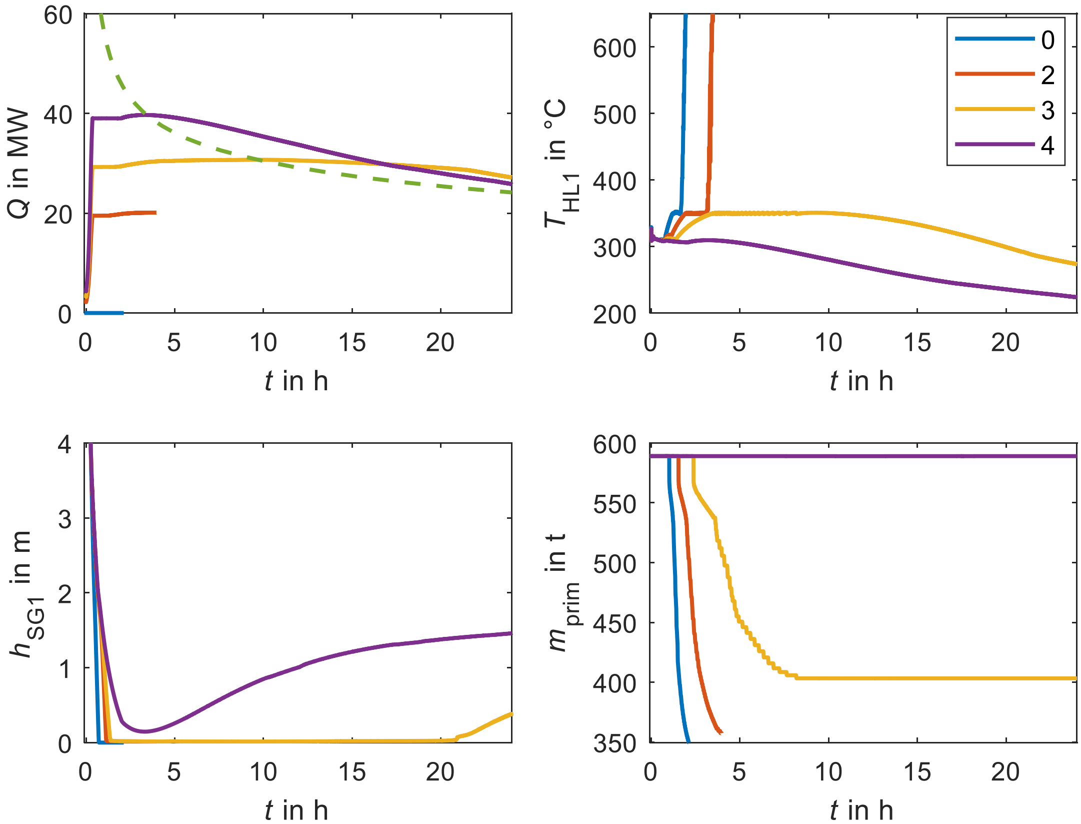

Fig. 4. Comparison of different numbers of CO_2 cycles without a control strategy to adapt to the declining decay heat: total thermal power removed by the CO_2 cycles compared to the decay power [dashed green line] (top left); temperature at the nozzle of hot leg 1 (top right); water level in steam generator 1 (bottom left); primary loop mass inventory (bottom right).

increased temperature on the primary side. When the temperature decreases, the water level increases again, as can be observed in cases 3 and 4 at the right end of the time axis. These cases do not end after 24 h, which is the right end of the diagrams, but they face several other problems. These are discussed in the following, starting with case 3.

The following discussion of case 3 is almost independent of the control strategy regarding the declining decay heat because the observed problems occur due to insufficient heat removal in the time before the equilibrium of the decay heat and the removed thermal power is reached. Figure 5 shows the water level in the reactor pressure vessel (PRV) and pressurizer (PRZ) on the left side for the simulation with three CO_2 cycles. Initially, the pressurizer level drops from the shrinking of the coolant in the primary circuit after scram. The following increase is related to the described heat-up. In the following, the filled pressurizer spills out the liquid until the evolving head bubble in the reactor pressure vessel reaches the upper end of the hot leg after 3.4 h, thus, sending vapor through the pressurizer. The plateau of the reactor level results from the separation of liquid and steam in the legs, providing a certain source of liquid mass flow towards evaporation in the reactor. This liquid source can be considered exhausted when the hot leg nozzles are uncovered after 6.7 h, about 5.1 h later than in a reference case [24]. Until the equilibrium between the decay power and the heat removal capacity has been reached after around 10 h, the reactor boils off further just to a few centimeters above the top of the core. Afterwards, the cooldown of the primary circuit results in backflow from the pressurizer to the hot leg and back into the reactor.

Before, the several hours lasting reflux condenser mode combined with a stagnation of the core internal circulation resulted in a nearly total dilution of the boron in the cold leg and the bottom of the reactor core, as to be seen on the right of Figure 5. Since neutron kinetics had not been simulated, the impact of boron and void for subcritical cannot be judged, but such a situation has to be avoided, either by using a sufficient number of CO_2 cycles beforehand or by using the excess electricity of the cycles to power boron injection.

After the thermal power equilibrium is reached around 10 h, the decreasing pressure and resulting flow oscillation in the reactor cause a fast decrease and following increase of the boron concentration. Finally, after 13 h, the concentrated boron from the upper part of the core is purged downwards due to the refilling of the reactor pressure vessel from the pressurizer via the hot leg. In addition, internal circulation in the core builds up again and decreases the gradient in the boron concentration. Nevertheless, the downcomer, which is not involved in this circulation, is still almost completely unborated, posing a serious risk for recriticality at sudden fill-up from the cold leg side.

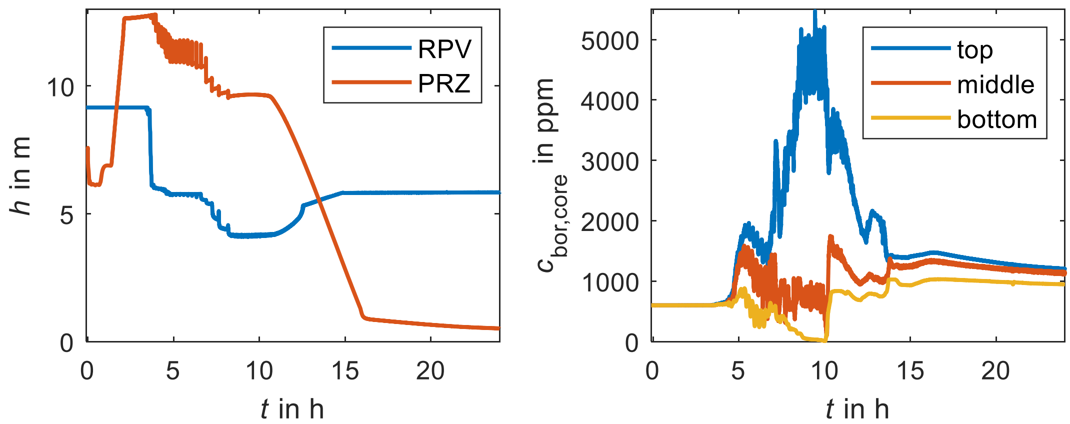

Fig. 5. Simulation with three CO_2 cycles without a control strategy to adapt to the declining decay heat: water level in the core and pressurizer (left); boron concentration in the top, middle and bottom of the core (right).

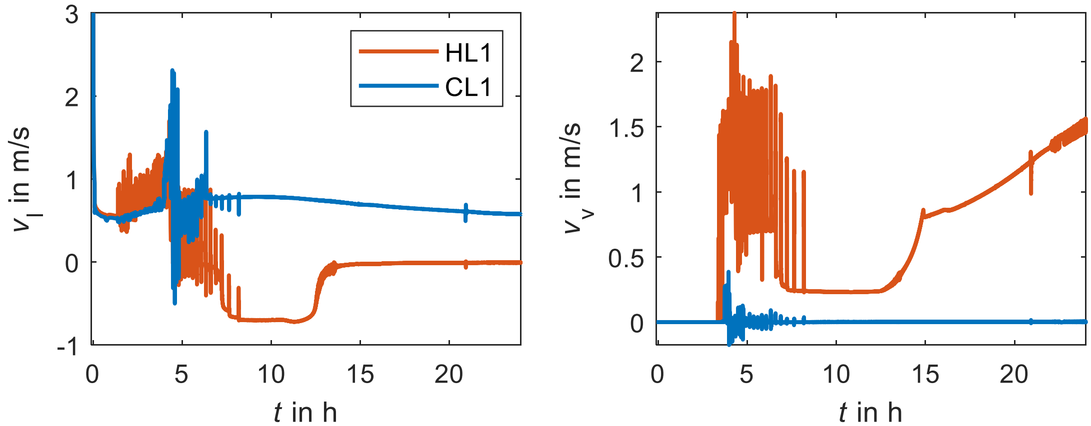

Fig. 6. Simulation with three CO_2 cycles without a control strategy to adapt to the declining decay heat: liquid velocity (left) and vapour velocity (right) at the hot and cold leg nozzles of leg 1.

Thus, in the long term, filling from the hot leg side only should be advised, e.g., from the hot leg side borated pressure accumulators, resembling the demonstrated purging down. With the total mass reduced by blowing out boron-reduced steam and mixture via the pressurizer, the final boron concentration stabilizes at around 1000 ppm.

The mentioned thermal-hydraulic effects in the hot and cold leg of the first primary loop, which is connected to the pressurizer, can be verified in Figure 6. In this figure, the flow velocities of the liquid and vapor phases are presented. After the stop of the main coolant pumps, the liquid flow stabilizes at about 0.55 m/s. At around 1.4 h, the heavily oscillating liquid phase flow marks the spill out of the water through the pressurizer safety valves. As mentioned above, the two-phase flow starts around 3.4 h. After 4.5 h, the reversal of the liquid flow marks the beginning of reflux condenser mode. Due to the lost liquid flow over the top of the U-tubes, the boron concentration in the bottom of the core starts to decrease as presented in Figure 5. In the following, positive liquid flow velocities in the hot leg are only caused by the actuation of the pressurizer safety valves. Finally, the blowout from the pressurizer gradually stops as the decay power approaches the heat removal capacity, as shown in Figure 4 for case 3.

After the onset of the two-phase flow, both legs are only partially filled with liquid. Therefore, changing phase velocities do not necessarily reflect a change in the phase mass flow rate but may be related to a change in the respective phase flow area. This is mainly the case for the change of the velocities in the hot leg around 13 h when the leg is refilled with liquid from the pressurizer. Before, the unborated liquid mass flow rate in the cold leg of approximately 6 kg/s gradually mixes the boron concentration in the bottom of the core down to zero, as shown in Figure 5.

Other long-term effects related to the decreasing temperatures in the PWR will be discussed together with case 4 because the cooldown in case 3 sets in, too, nevertheless, later. According to the left of Figure 7, the primary and secondary temperatures start to decrease for case 4 after a few hours. After 13.7 h, a temperature of 260°C is reached. At this temperature, the boron injection should be started to prepare the primary loop for the cold shutdown. Temperatures below 200°C are only allowed when the boron injection is finished, and a concentration of approximately 800 ppm is reached.

Furthermore, the decreasing temperatures on the NPP side lead to a decreasing turbine inlet temperature on the CO_2 side, as displayed at the left of Figure 7. That, in

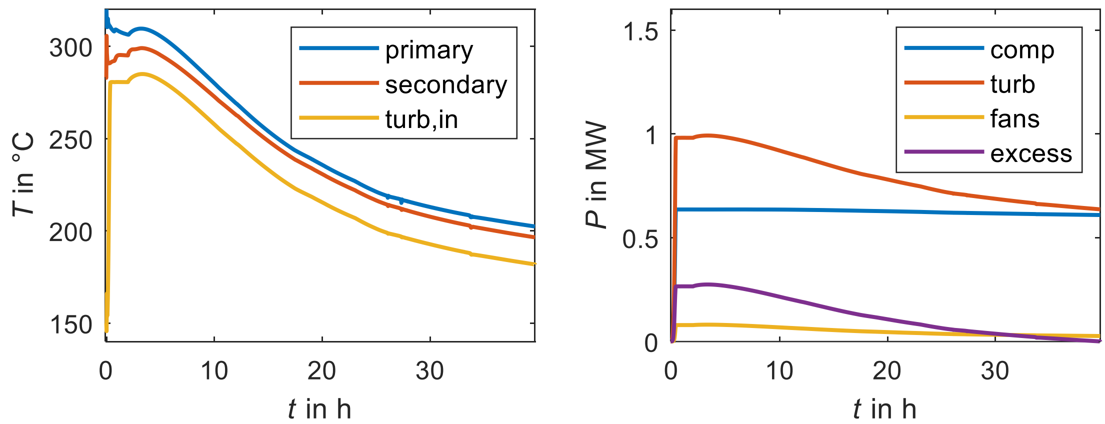

Fig. 7. Simulation with four CO_2 cycles without a control strategy to adapt to the declining decay heat: primary (hot leg), secondary (steam generator dome) and turbine inlet temperature of one CO_2 cycle (left); power of compressor, turbine, fans and excess power of one CO_2 cycle (right).

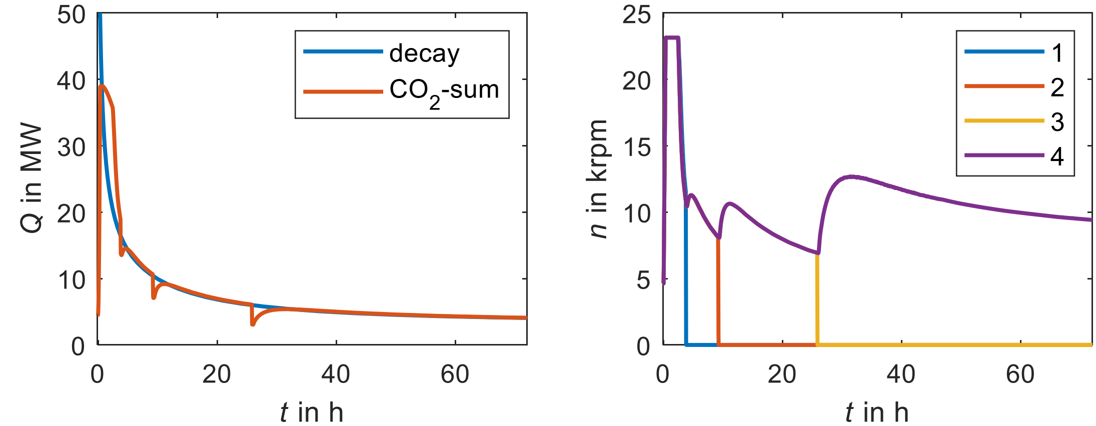

Fig. 8. Simulation with four CO_2 cycles with a control strategy to adapt to the declining decay heat: decay power and total power removed by the CO_2 cycles (left); shaft speed of turbomachinery for each cycle (right).

turn, results in a decreasing turbine power, as shown at the right of Figure 7. The required compressor power stays nearly constant due to the constant shaft speed and the almost constant pressure ratio and cycle mass flow rate. The required fan power is also decreasing due to the lower turbine exit temperatures, but this hardly affects the overall power balance. After 39.7 h, the excess power reaches zero, which means that the cycle is not self-propelling anymore. In conclusion, a self-propelling operation without a strategy to adapt to the declining decay heat is possible for quite some time, but, finally, active control is required to keep the sCO_2-HeRo system self-propelling.

6 A control strategy to adapt to the declining decay heat

In this chapter, four CO_2 cycles, one attached to each steam generator to keep symmetry, and a control strategy to adapt to the declining decay heat curve are investigated. According to the previous chapter, the four cycles without such a strategy failed because they removed too much heat from the NPP. Moreover, the cycles fail earlier if less decay heat is available. Therefore, in contrast to the previous chapter, a conservatively low decay heat curve [24] is applied in this chapter to analyze the long-term operation of the sCO_2-HeRo system. The control methods regarding CO_2 compressor inlet temperature and H_2O CHX outlet temperature from the previous chapter are also applied in this chapter. The additional strategy to cope with the declining decay heat is explained together with the presentation of the results.

In Figure 8, the decay power and the total thermal power removed by the CO_2 cycles are shown on the left, and the turbomachinery shaft speed of each cycle is on the right. As in the last chapter, the CO_2 cycles are started from the ORS and ramped up to their design speed, and then the speed is kept constant, resulting in a heat removal capacity of approximately 10 MW per cycle. Due to conservatively low decay heat, the break-even between the heat removal capacity and the decay power is reached already after 38 min. This initiates the decrease of the temperatures on the primary and secondary sides in the NPP and the turbine inlet temperatures of the CO_2 cycles. As mentioned in the previous chapter, this decrease should be limited because below a primary

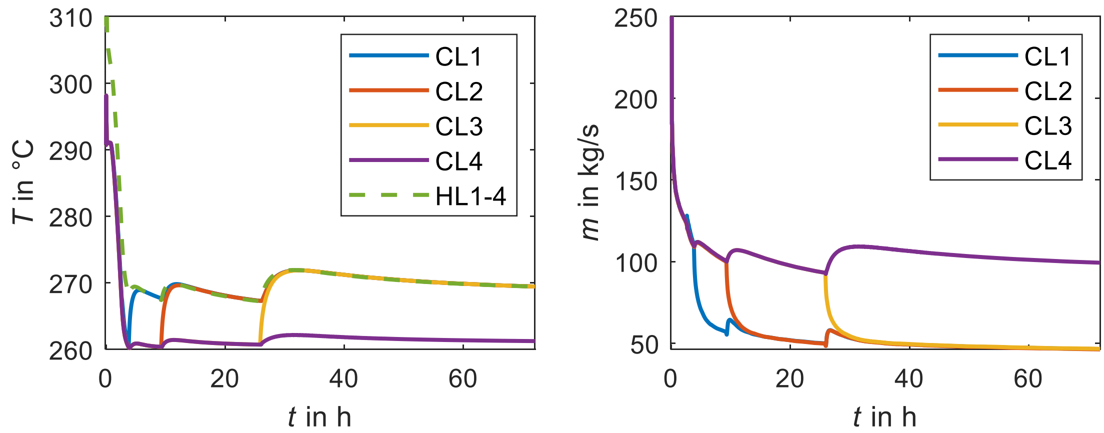

Fig. 9. Simulation with four CO_2 cycles with a control strategy to adapt to the declining decay heat: temperatures at the cold and hot leg nozzles (left) and corresponding mass flow rates in the cold legs (right).

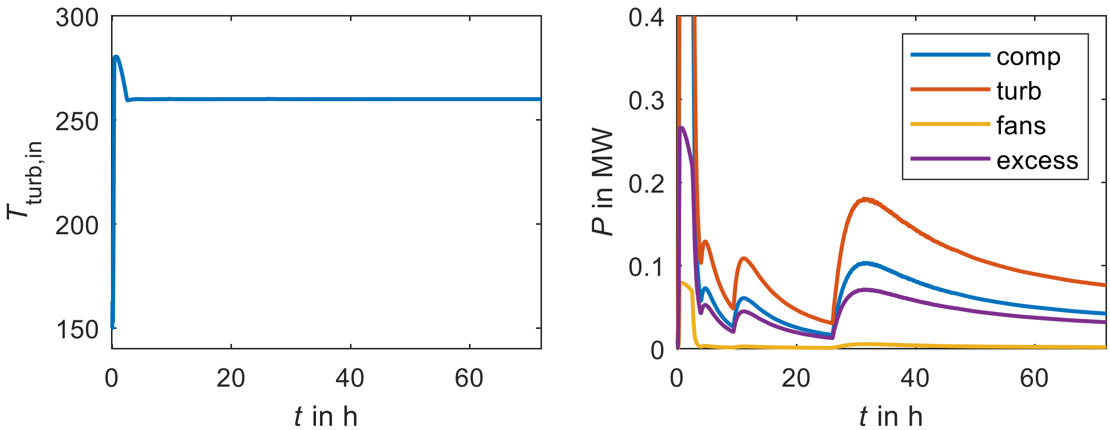

Fig. 10. Simulation with four CO_2 cycles with a control strategy to adapt to the declining decay heat: turbine inlet temperature (left); power of compressor, turbine, fans and excess power (right) of CO_2 cycle 4.

temperature of 260°C, the boron injection should start, and ultimately the decreasing temperatures also would render the CO_2 cycles inoperable. However, slightly decreasing the primary and secondary temperatures is also beneficial because this increases the thermal buffer if something unexpected happens, like a technical failure in one of the CO_2 cycles. Therefore, a target value of 260°C was specified for the CO_2 turbine inlet temperatures. After 2.4 h, the target value is reached, as shown later in Figure 10, and the shaft speed control is activated to keep the turbine inlet temperature at 260°C. In addition to the shaft speed control, the subsequent shutdown of single CO_2 cycles is required to avoid a decrease of ΔP to zero due to very low shaft speeds, as shown later in this chapter. In the simulation, relative switch-off speeds in relation to the cycle design point speed of 50%, 35%, and 30% were specified for the first, second, and third cycles, respectively. The switch-off speeds were selected to be relatively low to be able to buffer the unexpected failure of another operating cycle. This results in the successive shutdown of three cycles after 3.8 h, 9.3 h, and 25.9 h. At each switch-off point, the removed thermal power drops below the decay heat curve and then gradually adapts to the curve as the shaft speed increases again, as shown in Figure 8. In the end, only cycle 4 is still under operation. As long as the cycles are under operation, they run almost at the same shaft speed, and all other operating conditions are also very similar since all running cycles are controlled in the same way.

The temperatures and mass flow rates in the hot and cold legs, as shown in Figure 9, decrease until the thermal power balance has been established, which occurs approximately at the same time as the switch-off of the first cycle. As long as all CO_2 cycles are running, the cold leg temperatures and mass flow rates are equal in the different legs. When one of the cycles is switched off, the heat transferred to the corresponding steam generator decreases rapidly toward zero. This leads to a considerable reduction of the mass flow rate in this leg, and the cold leg temperature increases to the temperature of the hot leg. The reduced mass flow rate results from the loss of the natural circulation driving density difference over the elevation of the steam generator U-tubes since the heat removal is stopped in this leg. After 2 h, the temperature difference between the hot leg and the corresponding cold leg never exceeds 10 K. In a leg with an operating CO_2 cycle, the difference also does not drop below 6.5 K. The lowest difference occurs before the second last cycle is switched off because, at this point, the heat removal per cycle is at its lowest value. The heat produced in the reactor always builds up the required driving force in the form of a temperature and density difference, respectively, to overcome the pressure losses in the legs. Altogether, the cold leg temperature never drops below 260°C.

In the following, the operation of the CO_2 cycles is analyzed, illustrated by cycle 4, which is still running in the end. The shaft speed of the turbomachinery and the sum of the thermal power of all CHX were already displayed in Figure 8. The thermal power of one CHX is the current power divided by the number of operating cycles. In Figure 10, the turbine inlet temperature and the power production of the turbine compared to the requirement of the compressor and the fans and the excess power are shown. For better visualization, the y-axis is cut-off at 0.4 MW. The power at the maximum speed is almost the same as in Figure 7. After a short period of almost constant power, the shaft speed control is activated to keep the turbine inlet temperature constant at 260°C, as described before. The decrease in the shaft speed leads to a steep decrease in the mass flow rate, the compressor outlet pressure, and the power levels. Compared to Figure 7 also, the compressor power decreases, enabling a self-propelling operation. Even at its lowest point, the excess power still exceeds 12.8 kW. If a higher margin to zero is preferred, the control strategy could easily be adapted by specifying higher switch-off speeds for the second and third cycles. After 72 h, at the end of the simulation, the excess power of the last cycle running is 32 kW.

7 Conclusions

In this study, a long-term station blackout and loss of ultimate heat sink scenario in a PWR was analyzed with the thermal-hydraulic system code ATHLET. For the mitigation of the accident, the self-propelling sCO_2-HeRo system was considered. After summarizing the most important points regarding the design, layout, and control of the CO_2 cycle, the integration of the CHX to the secondary side of the PWR was presented. Stable control of the CHX outlet temperature on the H_2O side was achieved by adapting the valve opening in the condensate pipe after the CHX. During the relatively fast start-up from the operational readiness state, non-linear thermal gradients were observed in the CHX outlet temperature on the H_2O side, which require further investigation in terms of component stress.

A sCO_2-HeRo system with four CO_2 cycles with a heat removal capacity of 10 MW per cycle provided sufficient heat removal from a generic Konvoi PWR with thermal power of 3840 MW even under consideration of a conservatively high decay heat curve. With three cycles, the core could still be cooled but was almost uncovered. In addition, the impact of the deboration in the cold legs in the simulation with three cycles remains open and would require coupling to a neutronic model for further analysis. Therefore, the use of only three sCO_2 cycles is not recommended. Furthermore, the unavailability of one cycle due to a failure or maintenance should be taken into account by installing two additional cycles as a backup. Independent of the number of CO_2 cycles, a control strategy is required to adapt to the declining decay heat, otherwise the cycles remove too much heat in the long term. This leads to decreasing temperatures and finally also stops the self-propelling operation.

This paper demonstrates the adaption to the declining decay heat by controlling the turbine inlet temperature of the CO_2 cycles to a constant value of 260°C via the shaft speed of the turbomachinery. In addition, the subsequent shutdown of single CO_2 cycles is required. These strategies are enforced when the decay heat is lower than the total heat removal capacity of the cycles. In the beginning, the cycles are operated at their design speed to maximize the heat removal and to keep the inventory loss of the reactor to a minimum. When one cycle is switched off, the control ramps up the remaining cycles automatically to match the decay heat again. The switch-off also affects the flow distribution and temperatures in the PWR. During the whole simulation, a self-propelling operation can be maintained and, in the end, the last one of the four cycles is still under operation with a remaining excess power of 32 kW. Generally, it can be recommended that all CO_2 cycles should be operated to the lowest feasible excess power before one cycle is switched off because this provides the highest operational flexibility in case of an unexpected event, e.g. failure of one or even multiple cycles. Considering the proposed strategies and findings, this heat removal system can also be applied to other types of existing and future nuclear power plants in order to increase the level of safety.

In the future, the response of the system to various transients should be analyzed in more detail. These include the failure of the control systems, the valves or a complete cycle, fast shutdown and restart, and the blowdown of the steam generators via the safety valves when the batteries for the relief valves are not available. During these transients, the thermal stress on the components needs to be investigated, and advanced control strategies might be required to minimize the stress. Moreover, the system may be further optimized and used for operational tasks in the NPP.

Nomenclature

A opening area of valve (m^2)
c concentration (ppm)
h water level (m)
m mass flow rate (kg/s)
n rotational speed (krpm)
p pressure (MPa)
t time (h)
T temperature (°C)
ΔP excess power (MW)
P power (MW)
Q thermal power (MW)
v velocity (m/s)

Subscripts

bor boron

comp compressor
el electrical
in inlet
l liquid
out outlet
prim primary loop
rel relative
turb turbine
v vapor

Acronyms

CHX compact heat exchanger
CL cold leg
FWL feed water line
H_2O water
HeRo heat removal
HL hot leg
LCQ steam generator blowdown system
MSL main steam line
ORS operational readiness state
PRZ pressurizer
RPV reactor pressure vessel
PWR pressurized water reactor
sCO_2 supercritical carbon dioxide
SG steam generator
TAC turbomachinery (turbo-alternator-compressor)
UHS gas cooler/ heat exchanger to the diverse ultimate heat sink (ambient air)

Conflict of interests

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

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Data availability statement

The underlying data is confidential, as stated in the data management plan of the project sCO_2-4-NPP. The initial datasets may only be provided to a third party after a confidential agreement with the sCO_2-4-NPP consortium has been signed. The simulations were performed with a developer version of the simulation code ATHLET. A license can be requested from GRS (Gesellschaft für Anlagen- und Reaktorsicherheit). However, not all features regarding the modeling of CO_2 cycles are available in the current release version. Further features will be released together with future versions. The code extensions, models, assumptions, and boundary conditions are described in the cited references [12–14,22]. The simulation data presented in this paper is available on request.

Author contribution statement

Markus Hofer: conceptualization, methodology, software, validation, investigation, visualization, writing – original draft; Frieder Hecker: writing – review and editing, conceptualization; Michael Buck: writing – review and editing, project administration; Jörg Starflinger: supervision, funding acquisition, writing – review and editing.

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Regular Article

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Turbulence-induced vibrations prediction through use of an anisotropic pressure fluctuation model

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Abstract. In nuclear fuel rod bundles, turbulence-induced pressure fluctuations caused by an axial flow can create small but significant vibrations in the fuel rods, which in turn can cause structural effects such as material fatigue and fretting wear. Fluid-structure interaction simulations can be used to model these vibrations, but for affordable simulations based on the URANS approach, a model for the pressure fluctuations must be utilised. Driven by the goal to improve the current state-of-the-art pressure fluctuation model, AniPFM (Anisotropic Pressure Fluctuation Model) was developed. AniPFM can model velocity fluctuations based on anisotropic Reynolds stress tensors, with temporal correlation through the convection and decorrelation of turbulence. From these velocity fluctuations and the mean flow properties, the pressure fluctuations are calculated. The model was applied to several test cases and shows promising results in terms of reproducing qualitatively similar flow structures, as well as predicting the root-mean-squared pressure fluctuations. While further validation is being performed, the AniPFM has already demonstrated its potential for affordable simulations of turbulence-induced vibrations in industrial nuclear applications.

1 Introduction

A particularly important topic in the field of nuclear safety is the behaviour of fuel rods. Fuel rods are submerged in a coolant, such as water in current-day reactors or liquid metal in advanced fast reactors, which flows axially along the fuel rods. While the axial flow leads to efficient cooling of the fuel rods, it can also cause Turbulence-Induced Vibrations (TIV) of the fuel rods, which originate from pressure fluctuations in the flow. This phenomenon plays a critical role in terms of nuclear safety, as it can cause structural effects such as fatigue problems, fretting wear, and stress corrosion cracking [1,2]. The phenomenon has been studied since the start of nuclear reactor development in the 1950s, and it has been the root of several incidents [1,3]. In the previous century, an emphasis was put on experiments to increase the understanding and knowledge of TIV, as well as using semi-empirical laws to establish a relation between the amplitude of vibration and relevant flow parameters [4,5]. More recently, due to the larger availability of computational resources, the use of Fluid-Structure Interaction (FSI) simulation applied to fuel rods has received more interest. In one approach the turbulence is (partially) scale resolved (LES/DNS), but due to the excessive computational requirements, these simulations typically rely on a simplified approach for the fluid-structure interaction, at moderate Reynolds numbers [6–8]. Due to the large Reynolds numbers associated with the axial flow along fuel rods, LES/DNS is too expensive for industrial use of simulations of fuel rods or fuel assemblies. For reference, the LES calculations of De Ridder [9] took 2200 days in equivalent computational time to simulate 0.1 s of 1/10th of the length of a fuel rod. Extending this to a fuel assembly is not realistic. Furthermore, these simulations are typically one-way coupled. However, due to the large density ratios that are typically found in nuclear reactors, two-way FSI coupling is preferred, in order to capture the effect of the changing flow field on the fuel rods. A computationally much cheaper method is to use URANS for the fluid domain [10,11], which would allow simulations of fuel assemblies. However, URANS causes severe underprediction in the vibration amplitude. This is because URANS only calculates forces resulting from the mean flow, as it does not resolve the instantaneous turbulent pressure fluctuations. To remedy this, the Pressure Fluctuation Model (PFM) was proposed by Kottapalli et al. [12], which assumes that the turbulence statistics from URANS are sufficiently accurate to construct synthetic turbulent pressure fluctuations to be superimposed on the Reynolds-averaged pressure. This

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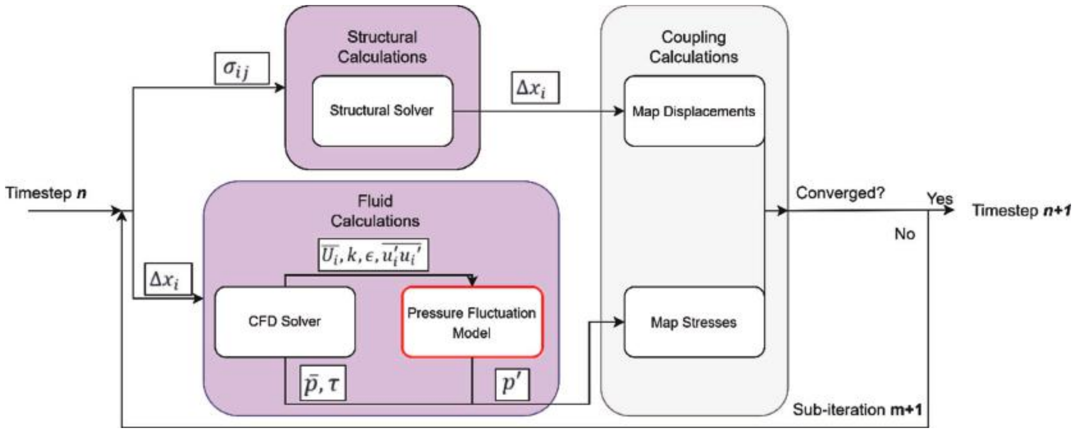

Fig. 1. A flow-chart of the global interactions between the several numerical solvers.

would artificially reintroduce the turbulence-induced forcing to the structure, at a lower computational cost than scale-resolving approaches. From comparison to experimental data, it was found that the PFM shows vibration amplitudes in the same order of magnitude, however, it did not give the required accuracy yet [12]. In the current paper, an improved pressure fluctuation model, called AniPFM, is proposed. The new model tackles several limiting assumptions of the PFM, such as the assumption of isotropic turbulence, as well as the method of time correlation. With this, the AniPFM the accuracy in the prediction of vibration amplitudes through FSI-simulations of TIV. Figure 1 summarizes how the AniPFM interacts with the other components in FSI simulations.

2 Methodology

The AniPFM is based on the formulation given of the PFM of Kottapalli et al. [12] and Senthooran et al. [13], though major modifications have been made to incorporate anisotropy and time correlation, using approaches from Billson et al. [14], and Shur et al. [15]. Details of the new AniPFM are given in this section.

2.1 Pressure fluctuations

Similarly, to the method of Kottapalli et al. [12], the divergence operator is applied to the Reynolds averaged and instantaneous Navier–Stokes equations, to obtain the following Poisson equation:

$$\frac{\partial^2 p'}{\partial x_i \partial x_i} = -\rho \left[2 \frac{\partial \overline{u_i}}{\partial x_j} \frac{\partial u_j'}{\partial x_i} + \frac{\partial^2}{\partial x_i \partial x_j} \left(u_i' u_j' - \overline{u_i' u_j'} \right) \right]. \quad (1)$$

Equation (1) shows that the pressure fluctuation p' solely depends on the mean velocity $\overline{u_i'}$, the Reynolds stresses $\overline{u_i' u_j'}$, and the velocity fluctuations u_i'. Only the velocity fluctuations are unknown. The governing equation for computing the pressure fluctuations is given by equation (1) where the velocity fluctuations are modelled.

Note that equation (1) assumes that the full spectrum of pressure fluctuations is computed, but in reality, only the fluctuations that can be resolved by the mesh are taken into account. Thus, the effect of unresolved turbulence on pressure fluctuations is not accounted for in this method.

2.2 Velocity fluctuations

Constructing the velocity fluctuations consists of three main parts, namely the construction of dimensionless velocity fluctuations, correlating the fluctuations in time, and finally scaling the fluctuations to match the input Reynolds stresses. The dimensionless fluctuations $\mathbf{w}_t(x)$ are created by a Fourier decomposition, as shown in equation (2). Here, q_n is the mode amplitude, σ_n is the direction vector, κ_n is the wavenumber vector, and ϕ_n is a random phase shift with a uniform distribution, the subscript n denotes that it is for the nth mode.

$$\mathbf{w}_t(\mathbf{x}) = \sqrt{6} \sum_n^N \sqrt{q_n} \left[\sigma_n \cos\left(\kappa_n \cdot \mathbf{x} + \phi_n \right) \right]. \quad (2)$$

2.2.1 Turbulent kinetic energy spectrum

The amplitude for each mode is determined by the non-dimensionalized Von-Karman spectrum, shown in equation (3) [15]. Here, k_e is the eddy wavenumber, which is the wavenumber which contains the highest energy density. The variable k_η refers to the Kolmogorov wavenumber, and f_{cut} is a cut-off frequency based on the maximum resolvable wavenumber. As shown in equation (4), the amplitude is based on the relative weight of the energy of mode n. Note that even though the AniPFM can represent anisotropic turbulence, the energy spectrum is based on isotropic turbulence, thus it is still expected that the results near walls are not as accurate as in fully isotropic conditions.

$$E(k) = \frac{(k/k_e)^4}{\left[1 + 2.4 (k/k_e)^2\right]^{(17/6)}} \exp\left(- \left(12 \frac{k}{k_\eta} \right)^2 \right) f_{\text{cut}} \quad (3)$$

$$q_n = \frac{E_k(k_n)\,\Delta k_n}{\sum_n^N E_k(k_n)\,\Delta k_n}. \tag{4}$$

The eddy wavenumber is based on the RANS length scale as shown in equation (5), where C_l is a calibration coefficient set to 3.0, based on isotropic turbulence.

$$l_e = C_l \cdot l_t. \tag{5}$$

The cut-off function is shown in equation (6) [15]. For the cut-off length, several definitions were investigated. However, it was found that the cut-off length as defined by Shur et al. [15] (shown in Eq. (7)) gives the most accurate results.

$$f_{\text{cut}} = \exp\left(-\left[\frac{4\max(k - 0.9k_{\text{cut}}, 0)}{k_{\text{cut}}}\right]^3\right) \tag{6}$$

$$l_{\text{cut}} = 2\min\left[\max(h_y, h_z, 0.3h_{\max}) + 0.1d_w, h_{\max}\right]. \tag{7}$$

2.2.2 Wavenumber and direction vector

As shown in equation (2), the velocity fluctuations are determined by a sum of wavenumbers. As the sum is finite, it requires the specification of a start and final wavenumber, as well as the distribution of discrete wavenumbers in the resolved wavenumber space. The starting wavenumber is based on a conservative dimensional analysis, shown in equation (8). In the case of a zero-mean velocity, the RANS length scale is used to determine the starting wavenumber. Additionally, the starting wavenumber must also be lower than the wavenumber with the maximum energy density. Finally, the geometrical considerations must also be taken into account. This is done by introducing a user length scale, which denotes the maximum length that can be captured given the geometry of the problem. These requirements are fulfilled by the expression for the starting wavenumber, as shown in equation (9).

$$k_{\text{start}} = \frac{\varepsilon}{\max\left(||u||^3\right)} \tag{8}$$

$$k_{\text{start}} = \max\left[\min\left(k_{\text{start}}, \frac{1}{2}k_e\right), \frac{2\pi}{l_{\text{user}}}\right]. \tag{9}$$

The highest wavenumber is based on the cut-off wavenumber (see Eq. (10)), as the energy spectrum quickly goes to zero after this point. In between the lowest and highest wavenumber, the wavenumbers are logarithmically distributed.

$$k_{\text{end}} = \frac{3}{2}k_{\text{cut}}. \tag{10}$$

The wavenumber vectors are defined similarly to [12,14], as shown in Figure 2. The mathematical description is displayed in equation (11). Here, θ_n and ψ_n are uniformly distributed random variables, described by equation (12).

$$\kappa_n = \kappa_n\left[\sin\theta_n\cos\psi_n, \sin\theta_n\sin\psi_n, \cos\theta_n\right]^T \tag{11}$$

$$P(\psi_n) = \frac{1}{\pi}, P(\phi_n) = \frac{1}{2\pi}, P(\theta_n) = \frac{1}{2}\sin(\theta_n). \tag{12}$$

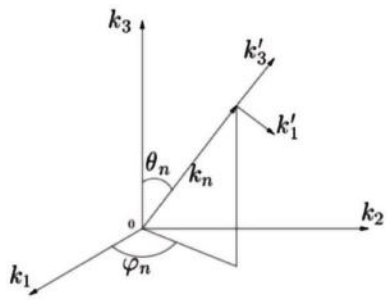

Fig. 2. Wave vector geometry of the nth Fourier mode [14].

The wavenumber direction vector is determined from the wavenumber vector. From applying the divergence operator to equation (1), it can be found that $\mathbf{k}_n \cdot \sigma_n = 0$ must hold in order to adhere to the continuity equation. This is the only requirement. To achieve this, σ_n is defined as the normalised cross-product between a random vector ζ_n, and the wavenumber vector, as shown in equation (13). Since the dot-product of a vector with the cross product of the same vector is always equal to zero, the continuity condition is met.

$$\sigma_n = \frac{\zeta_n \times \mathbf{k}_n}{|\zeta_n \times \mathbf{k}_n|}. \tag{13}$$

2.2.3 Time correlation and scaling

The procedure for calculating the non-dimensional fluctuations $\mathbf{w}_t(\mathbf{x})$ has been fully defined in the previous subsections. The next step is to create a space-time-dependent velocity signal $\mathbf{v}_t(\mathbf{x}, t)$, from the purely space-dependent signal. Two main phenomena have to be taken into account when constructing a time-correlated velocity field. Namely, the convection of turbulent eddies and the decorrelation due to the production and dissipation terms.

A method similar to Billson et al. [14] is used to introduce this time dependency. First, the fluctuations are convected by solving for equation (14). Here, $\mathbf{v}_t^{m-1}$ are the non-dimensional velocity fluctuations generated at timestep $m-1$, and U_j is the Reynolds-averaged velocity as calculated by the accompanied URANS simulation. Then in the second part, a new solution $\mathbf{v}_t^m$ is calculated from a combination of the (convected) previous solution $\mathbf{v}_t^{m-1}$, and a newly generated field $\mathbf{w}_t^m$, as shown in equation (15).

$$\frac{\partial \mathbf{v}_t^{m-1}}{\partial t} + U_j\frac{\partial \mathbf{v}_t^{m-1}}{\partial x_j} = 0 \tag{14}$$

$$\mathbf{v}_t^m(\mathbf{x}, t) = a\mathbf{v}_t^{m-1}(\mathbf{x}) + b\mathbf{w}_t^m(\mathbf{x}). \tag{15}$$

The coefficients a and b are defined in equation (16), where τ is the dissipation timescale determined from the URANS simulation, and f_τ is a modification factor for fine-tuning the correlation. For the latter, a value of $f_\tau = 17$ is used, in line with what was used in [14] for the simulation of a 3D jet. Tests showed that this value also gives a satisfactory correlation in the simulations of interest. The coefficients a and b are defined such that the squared mean properties of v_t are still respected, i.e. $v_t^2 = \delta_{ij}$.

$$a = e^{-f_\tau \Delta t/\tau} \qquad b = \sqrt{1 - a^2}. \tag{16}$$

Finally, the last step is to scale the dimensionless fluctuations, such that they replicate the Reynolds stresses. Since $\langle v_t \rangle^2$ is equal to the Kronecker delta, the fluctuations need to be scaled with a tensor a_{ij} such that $a_{ij}a_{ji} = R_{ij}$, as shown in equation (17). This can be realised with a Cholesky decomposition of the Reynolds stress tensor, which is shown in equation (18).

$$\mathbf{u}_t(\mathbf{x}, t) = a_{\mathrm{ij}}\mathbf{v}_t(\mathbf{x}, t) \tag{17}$$

$$a_{ij} = \begin{bmatrix} \sqrt{R_{11}} & 0 & 0 \\ \frac{R_{21}}{a_{11}} & \sqrt{R_{22} - a_{21}^2} & 0 \\ \frac{R_{31}}{a_{11}} & \frac{(R_{32} - a_{21}a_{31})}{a_{22}} & \sqrt{R_{33} - a_{31}^2 - a_{32}^2} \end{bmatrix}. \tag{18}$$

With this method, the AniPFM can reconstruct anisotropic Reynolds stresses. For flows with a constant pressure gradient, such as channel flows, linear Eddy viscosity models show isotropic Reynolds stresses. In order to improve the accuracy of these models, a correction is used to transform the isotropic tensor into an anisotropic tensor, based on the nonlinear Eddy viscosity model of Wilcox [16]. The Wilcox correction is shown in equation (19).

$$\overline{u'u'} = \frac{8}{9}k, \quad \overline{v'v'} = \frac{4}{9}k, \quad \overline{w'w'} = \frac{6}{9}k. \tag{19}$$

2.3 Model overview

This concludes the full model of the AniPFM. In Figure 3, the full model is summarised. First, the non-dimensional velocity fluctuations are calculated, based on the energy spectrum. Then the time correlation is performed. After this, the velocity fluctuations are computed by scaling with the Cholesky tensor. Finally, p' can be computed.

3 Simulation set-up

Two cases were simulated, in order to validate the AniPFM. First, a Homogeneous Isotropic Turbulent (HIT) box was simulated, which was used to verify the AniPFM in isotropic conditions, since an isotropic energy spectrum was used as input. Second, a turbulent channel flow was simulated, with the purpose of testing the accuracy of the AniPFM versus the PFM in anisotropic turbulence. The setup of these two cases is discussed in this section. The AniPFM is implemented in OpenFOAM 8, and thus all subsequent simulations have been performed with the same software.

3.1 Homogeneous isotropic turbulent box

A box of $L \cdot L \cdot L$ is created, which is discretized by a cartesian mesh of $N \cdot N \cdot N$ cells. All boundaries are periodic, and the domain has a zero-mean velocity. The experiment of Comte-Bellot and Corrsin [17] has been replicated, as well as the DNS of Gotoh and Fukayama [18]. In Table 1, the details of the replicated set-up of Comte-Bellot and Corrsin are shown. The DNS of Gotoh and Fukayama was specified in dimensionless numbers. The simulation with $\mathrm{Re}_\lambda = 287$ of Gotoh and Fukayama is replicated; the set-up is also shown in Table 1.

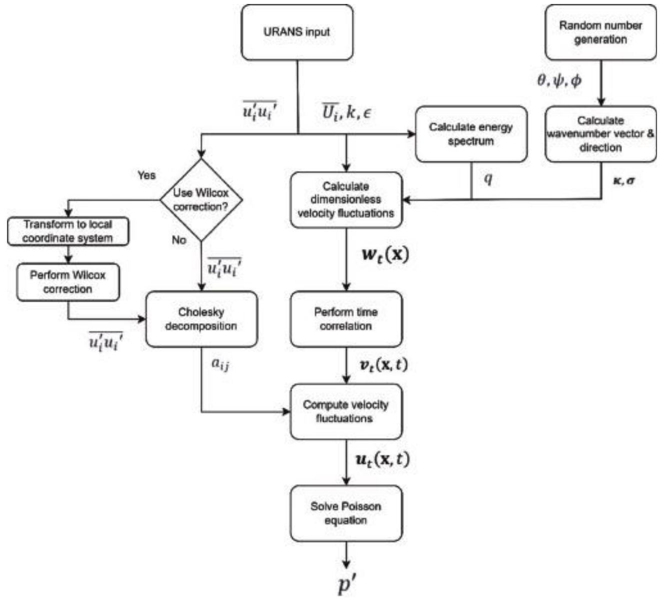

Fig. 3. Flow chart of the different computational steps of the proposed AniPFM.

Table 1. Details of the simulation replicating Comte-Bellot and Corrsin, Gotoh and Fukayama at $\mathrm{Re}_\lambda = 70$.

Turbulence Model	$k-\varepsilon$	$k-\varepsilon$
Initial k [m^2/s^2]	0.4740	0.012568
Initial ε [m^2/s^3]	0.07393	0.01377
Initial U [m/s]	0	0
Initial p [Pa]	0	0
v [m^2/s]	1.5e-5	1.5e-5
Time step [s]	0.001	0.001
Duration [s]	0.874	0.001

3.2 Turbulent channel flow

The results of the TCF are compared to the DNS results of Abe et al. [19]. The simulation with $\mathrm{Re}_\tau = 640$ is used for comparison. In this case, the flow between two infinitely long and wide stationary plates is simulated. The simulation domain used is equal to $6\delta \cdot 2\delta \cdot 3\delta$, where δ is the mid-channel height. The mesh has a size of $N_x \cdot N_y \cdot N_z$ cells, which are kept as variables. The mesh distribution is uniform in the stream- and spanwise-direction, and it is geometrically expanding to the mid-channel plane in the wall-normal direction. The mesh in the wall-normal direction is configured such that $y^+ \approx 1$ for the first grid cell from the wall. The setup is summarised in Table 2, and

Table 2. Details of the channel flow simulation set-up.

	URANS+AniPFM
Turbulence model	Variable
Wall model	n/a
$\mathrm{Re}_{\mathrm{bulk}}$ [–]	24 428
v [m^2/s]	2e-5
σ [m]	1
U_{bulk} [m/s]	0.24428

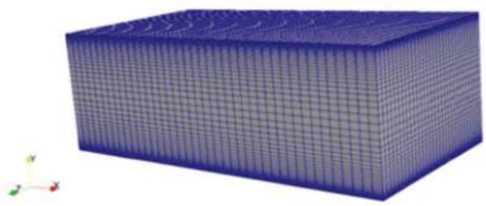

Fig. 4. Example channel flow mesh of $40 \cdot 64 \cdot 30$.

Table 3. All variables that have been compared against experimental and/or DNS results.

Case	V&V variables
HIT	TKE, p' spectrum, TKE spectrum, $p'_{\mathrm{rms}}\langle u'_i u'_j\rangle$ time correlation
TCF w/URANS input	$p'_{\mathrm{rms}}, R_{ij}$
TCF w/DNS input	$p'_{\mathrm{rms}}, R_{ij}, p'$ spectrum, TKE spectrum, p' frequency spectrum

an example mesh is shown in Figure 4. Simulations were performed with the $k - \omega$ SST turbulence model, along with the Wilcox correction. However, for several simulations, no URANS calculation was done, but rather the mean flow properties of the DNS of Abe et al. were used as an input to the AniPFM. This was used to isolate any errors that originate due to the AniPFM, and not due to the input.

4 Results discussion

The results of both cases are elaborated upon in this section. In Table 3, the V&V done for all variables of the test cases is shown. In this section, the most important results from this verification are shown and discussed.

4.1 Homogeneous isotropic turbulent box

In Figure 5, the simulated velocity fluctuations of the HIT box of Comte-Bellot Corrsin are shown, with a mesh size of $N = 128$. The velocity fluctuations on the left are from the AniPFM, whereas the results on the right are simulated through means of a Large-Eddy Simulation [20]. From Figure 5, it was concluded that the AniPFM can

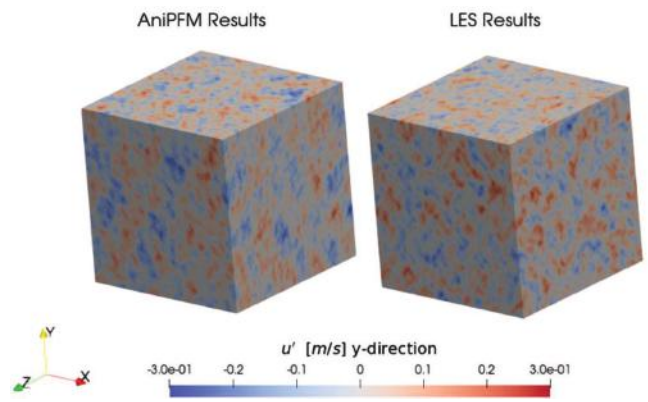

Fig. 5. The instantaneous velocity fluctuations of the AniPFM, compared to LES results.

qualitatively reconstruct similar flow structures as high-resolution methods.

In Figure 6, the energy spectra generated by both the AniPFM and the PFM of Kottapalli et al. are compared to the experimental spectrum of Comte-Bellot & Corrsin. The AniPFM results show a very good resemblance with respect to the experimental results, right up to the cut-off wavenumber. Compared to the results of the PFM, the peak of the energy spectrum is better predicted, and there is no unphysical accumulation of energy near the cut-off wavenumber. The latter difference is due to the fact that a cut-off filter is used in the AniPFM, which makes sure that the unresolved energy is not redistributed over the resolved part of the spectrum.

The effect of the cut-off filter can also be found in the root-mean-squared pressure fluctuations. With a mesh of $N = 64$, the AniPFM predicted p'_{rms} within a 2.4% error with respect to the results of Goth et al., whereas the PFM predicted a 3.7% error. The AniPFM showed an error of 1.1% when the mesh was refined $N = 128$.

4.2 Turbulent channel flow

For the turbulent channel flow, there are several sources of errors that cause a discrepancy between the AniPFM results and experimental/DNS data. Therefore, it is important that each source is carefully evaluated.

There exists an uncertainty range in the results of the AniPFM, which is due to the random numbers that are used throughout the simulation. For the chosen temporal correlation scheme, the random numbers gave an uncertainty range of ±0.25% for p'_{rms}, for a confidence interval of 95.4%. The number of modes did not seem to have a large effect on p'_{rms}, however, with a lower number of modes, the uncertainty went up, as fewer random numbers were used per iteration. For the presented simulations, 1024 wave number modes were used.

The amount of energy that is resolved by the AniPFM depends on the fineness of the mesh. There is no sub-grid model that models the effect of unresolved velocity fluctuations on the pressure fluctuations. Thus, the statistics of the pressure fluctuations only converge if a large part

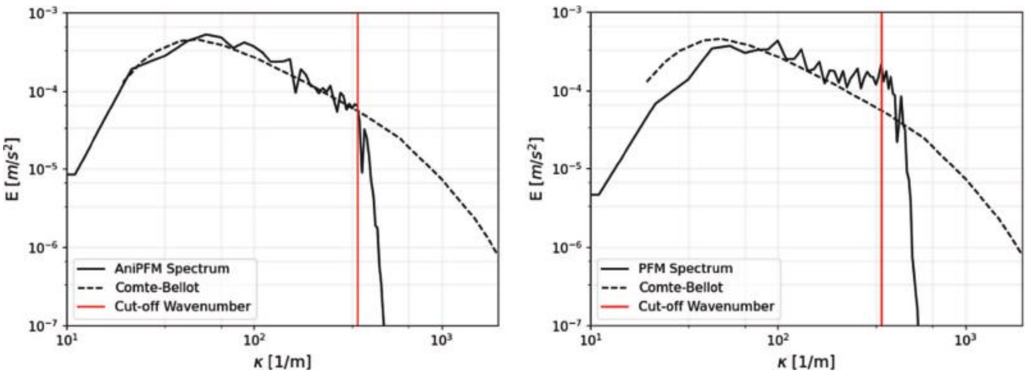

Fig. 6. The energy spectrum of AniPFM (left) and the PFM (right), compared to the experimental values of Comte-Bellot and Corrsin [17].

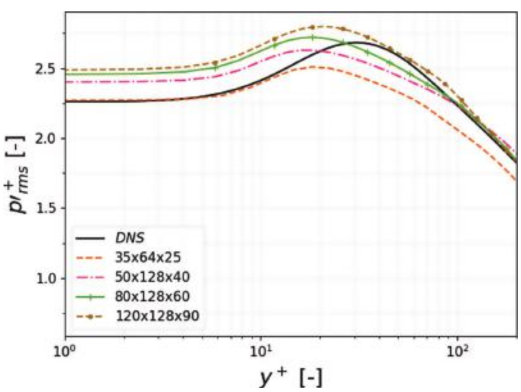

Fig. 7. The root-mean-squared pressure fluctuations along the wall-normal coordinate for various meshes, versus the DNS results of Abe et al. [19].

of the velocity fluctuations is resolved. Since $p'_{\rm rms}$ is the quantity of interest, this quantity is evaluated for several meshes. This is shown in Figure 6, in which the results were obtained using the $k - \omega$ SST turbulence model, together with the Wilcox correction. It can be seen that the meshes converge to a final solution when using finer meshes. At the second finest mesh, the results near the wall are within the given uncertainty range, thus deeming the solution converged.

The modelling error was found by performing a simulation of the turbulent channel flow on the finest mesh from Figure 7, but with the RANS input variables ($k, \varepsilon, \overline{u_i}$ and $\overline{u'_i u'_j}$) taken from DNS data. The replicated Reynolds stresses and $p'_{\rm rms}$ are shown in Figure 8. The Reynolds stresses are very closely approximated. The small underestimation is because the velocity fluctuations are not fully resolved. Nevertheless, it was found that these unresolved fluctuations had no effect on $p'_{\rm rms}$. From Figure 8 (right), it can be seen that near the midchannel plane, the AniPFM very closely approximates $p'_{\rm rms}$. This is because here the isotropic energy spectrum very closely approximates the actual energy spectrum. Near the wall, the energy spectrum is not approximated as accurately, due to the larger anisotropy in the flow. Thus, a larger discrepancy in $p'_{\rm rms}$ was found near the wall, with a maximum error of 4.4%.

When the $k-\omega$ SST turbulence model, together with the Wilcox correction was used as URANS input for the turbulent channel flow, an error of roughly 10% was found near the wall. This increase in error is due to the large difference in the Reynolds stress tensor between the selected RANS model and the DNS data. In comparison, the PFM showed an underestimation of roughly 47% at the wall. Thus, the AniPFM shows a sharp improvement in the prediction of $p'_{\rm rms}$ for anisotropic flows, with respect to the PFM.

5 Conclusion

In this paper, a new pressure fluctuation model was proposed, called AniPFM. This model improves the prediction of pressure fluctuations when using a URANS approach, which can be useful in particular for turbulence-induced vibration prediction. Several aspects of the AniPFM were adjusted with respect to the previous PFM of Kottapalli et al., namely the energy spectrum cut-off filter, the replication of anisotropic Reynolds stresses, and the method for time correlation.

Two test cases were performed to assess the performance of the AniPFM: namely, a homogeneous isotropic turbulent box, and a turbulent channel flow. From the HIT case, it was found that the prediction for $p'_{\rm rms}$ was slightly improved due to the addition of the cut-off filter. From the turbulent channel flow, it was found that the introduction of anisotropy gave a slightly higher model error. This is because the energy spectrum is still based on isotropic turbulence. Nevertheless, the AniPFM showed an improvement in the prediction of $p'_{\rm rms}$ at the wall, compared to the PFM of Kottapalli et al.

While the initial results give an optimistic view, there are still several challenges that need to be tackled. Further validation must be done, both for fluid-only cases, as well as for relevant use cases. While there is no consensus if the AniPFM two-way coupled approach would be an improvement with respect to the one-way coupled LES approach for determining fuel pin vibration, the research does show to be of interest for strongly coupled cases, such as full fuel assembly FSI simulations. For this, both the computational costs and accuracy of the AniPFM must be compared to LES or Hybrid URANS/LES FSI simulations,

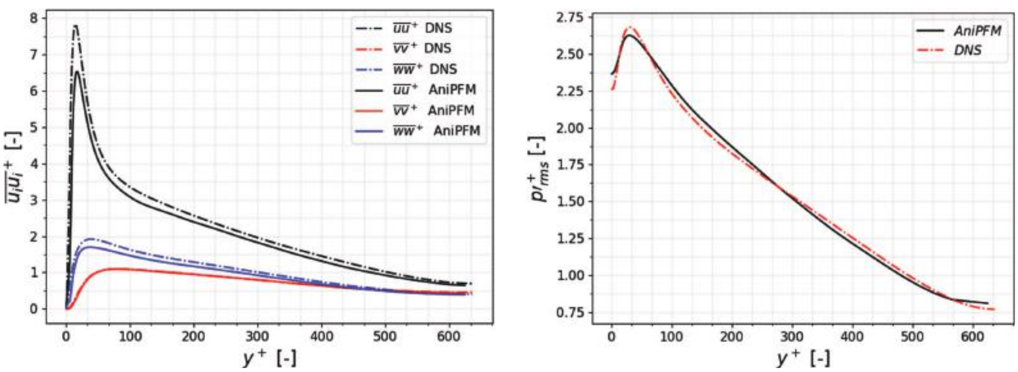

Fig. 8. The Reynolds stress profiles (left) and the RMS pressure fluctuations (right) along the wall-normal coordinate, versus the DNS results of Abe et al. [19]. DNS data is used as input.

to evaluate if the AniPFM is beneficial to use. Finally, there are still assumptions in the AniPFM which have to be evaluated, such as the use of an isotropic energy spectrum scaled to meet the Reynolds stress requirements. The construction of this spectrum is based on integral properties of the flow, with assumed isotropy, meaning that the energy distribution might not be well represented in areas of high anisotropy.

The next step is to apply the model to fluid flow cases that resemble nuclear fuel rod operating conditions more closely. While validation is still ongoing, the AniPFM shows potential for accurate, computationally cheap simulations of turbulence-induced vibrations in industrial nuclear applications.

Conflict of interests

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

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Data availability statement

The generated and analysed data associated with this paper is available, and it can be requested from the author K. Zwijsen.

Author contribution statement

All the authors were involved in the preparation of the article. All the authors have read and approved the final article.

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Regular Article — Open Access

On physics of a hypothetical core disruptive accident in Multipurpose hYbrid Research Reactor for High-tech Applications – MYRRHA

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Abstract. The sensitivity of the reactivity of a fast reactor core to changes in its geometry and/or fuel relocation calls for particular attention with regard to criticality events. A category of these events, the so-called Core Disruptive Accidents (CDAs), are intensively studied in the safety assessment of Sodium-cooled Fast Reactors (SFRs), and more recently also in the case of other systems. Differences between SFRs and Heavy Liquid Metal Fast Reactors (HLMFRs) are significant and therefore warrant an understanding of phenomena and the development of models specific to HLMFRs. This paper provides a qualitative overview of the physics relevant to the investigation of a CDA in HLMFR, with a particular application to the Multipurpose hYbrid Research Reactor for High-tech Applications – MYRRHA. At first, a core compaction mechanism viable for an HLMFR has been postulated. In what follows, simulation by an already existing severe accidents code, as well as modelling based on fundamental physics and engineering, have been performed. It is demonstrated that, for a linear insertion of reactivity due to hypothetical core compaction, the reversal of reactivity evolution happens due to the Doppler effect and the thermal expansion of core materials. Subsequent expansion by fuel melting terminates the prompt-critical event and makes the system delayed-supercritical. Successive fuel and/or coolant boiling is responsible for the hydrodynamic disassembly of the core and it therefore effectively terminates the transient.

List of acronyms

CDA	Core Disruptive Accident
HCDA	Hypothetical Core Disruptive Accident
HLMFR	Heavy Liquid Metal Fast Reactor
LBE	Lead-Bismuth Eutectic
MOX	Mixed-Oxide
MYRRHA	Multipurpose hYbrid Research Reactor for High-tech Applications
PRK	Point Reactor Kinetics
SFR	Sodium-cooled Fast Reactor
SIMMER	S_n, Implicit, Multifield, Multicomponent, Eulerian, Recriticality

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1 Introduction

The Multipurpose hYbrid Research Reactor for High-tech Applications (MYRRHA) is a flexible irradiation facility currently under development at the Belgian Nuclear Research Centre (SCK CEN). MYRRHA is a pool-type, fast-neutron-spectrum facility cooled by liquid Lead-Bismuth Eutectic (LBE) and coupled to a linear particle accelerator in order to enable its operation in subcritical mode. It can also operate in critical mode when the core contains enough fissile material to sustain a nuclear chain reaction [1].

Among the variety of goals MYRRHA aims to fulfil, there is the demonstration of the Accelerator-Driven System for the transmutation of high-level nuclear waste [1,2] and the Heavy Liquid Metal Fast Reactor (HLMFR) technology, provision for advanced material development aimed both at nuclear fission and fusion technology, and medical radioisotope production.

In the case of a severe accident, MYRRHA intends to rely on an in-vessel retention strategy as it is believed to be the most robust strategy in limiting the radiological consequences of a Core Disruptive Accident (CDA) for the population. This implies that it has to be confirmed that the reactor vessel can withstand the (potentially high) mechanical load caused by a prompt-critical severe accident. Since a fast reactor core, in contrast to a Light-Water Reactor core, is not designed to be in its most reactive configuration, a core degradation with a fuel relocation can result in core compaction that could increase the reactivity beyond the prompt-critical level [3,4]. This could further lead to a large power excursion that might expose the vessel to high mechanical forces, challenging its integrity and hence its confinement function.

This paper aims to establish the physics and phenomena relevant for the transition/secondary phase of a CDA in the core of MYRRHA, up to and not further than the neutronic disassembly of the reactor core (thus the mechanical energy release and structure loading assessment are not covered in the discussion). This is further backed up by the calculations performed with the S_n, Implicit, Multifield, Multicomponent, Eulerian, Recriticality (SIMMER) computer code and a numerical model currently being developed at SCK CEN, aimed at studying CDA scenarios in HLMFR cores. This paper focuses on a qualitative discussion of the relevant physics and phenomena, as well as a description of the employed models.

2 Core disruptive accident

The reactivity of a fast-spectrum reactor core can be very sensitive to the relocation of the core material. As already mentioned, this is due to the fact that the core of an intact HLMFR is not designed to operate in its most reactive configuration [3,4]. It is therefore theoretically possible that a change of geometry and/or rearrangement of the core material might result in a prompt-critical reactivity excursion (as an indication, the maximum value of reactivity observed in this work is ∼3$) and an explosive energy release inside the vessel.

A CDA represents a sequence of events that eventually leads to prompt-criticality followed by a core hydrodynamic disassembly and the corresponding neutronic shutdown [3]. Depending on the nature of the CDA, the released energy and the load on the vessel might differ significantly.

In the past, these CDAs have been intensively studied for Sodium-cooled Fast Reactors (SFRs). Although these accidents were always classified as “highly unlikely”, many designs of SFR containment structures were strongly influenced by the outcomes of these studies [3]. A CDA scenario hypothesized to occur in a fast reactor core was initially proposed by Hans Bethe and John Tait in 1956 [5], for the safety studies of the Dounreay Fast Reactor. The scenario assumed the following: upon loss of coolant, the metallic fuel, and its cladding, would melt and eventually collapse due to gravity, thereby forming a prompt-critical configuration. Bethe and Tait made a simplified, conservative model to estimate the energy released in such a case before the core would ultimately be disassembled by the pressure of fuel vapor generated as a consequence of the power excursion. In the years that followed, specialized computer codes were developed in order to describe CDAs in a best estimate approach, yielding less conservative estimations of the energy release. These codes also attempted to follow the whole sequence of events, from the initiating event up to the hydrodynamic disassembly of the reactor core, by coupling dedicated models of different phenomena at a mechanistic level. The aforementioned codes are, however, extensively validated only for SFRs.

The differences between SFRs and HLMFRs are significant and the development of dedicated models is necessary to assess the energy release of a CDA in an HLMFR core. For example, the boiling point of LBE is much higher than the one of Sodium; so in contrast to SFRs, no extensive coolant boiling prior to a prompt-critical event is expected in MYRRHA [3,6]. On top of that, the densities of Mixed-Oxide (MOX) fuel and LBE are similar. This implies that the core compaction mechanism commonly assumed in the case of SFRs, dominantly driven by the gravitational collapse of fuel, can be excluded as a compaction mechanism in HLMFRs.

Inspired by the approach and work of Bethe and Tait, research on CDA in an HLMFR core will start with a theoretical and simplified model. This model aims to identify which phenomena influence the disassembly of the reactor core and the extent of energy released in such an event. The experience accumulated and the tools developed for SFRs will provide an important reference and aid in this research.

2.1 Core disruptive accident in heavy liquid metal fast reactor

Due to the above-mentioned differences between SFRs and HLMFRs, many established sequences of events assumed to lead to a CDA in an SFR are not valid for an HLMFR. Recall that the typical scenario in SFR is the gravitational collapse and compaction of molten fuel and steel once the coolant is not present in the system. In an HLMFR, the coolant will be present in the system prior to and during the core compaction (due to its high boiling point, which largely exceeds the melting point of steel). Also considering the similar density of MOX fuel and the coolant, it is evident that a gravitationally driven fall and/or sinking cannot lead to a large reactivity insertion rate as in the case of SFR.

Taking this into consideration, a different core compaction mechanism for an HLMFR core has to be hypothesized. The compaction mechanism considered for the MYRRHA core and described in this paper is the one that is believed to lead to the maximum core compaction rate and therefore to the most conservative assessment of the thermal energy released during the event. Due to the extremely low probability of the hypothesized sequence of events happening, a CDA in an HLMFR is often referred to as a Hypothetical Core Disruptive Accident (HCDA).

Since gravity is not a credible core compaction force (due to the similar densities of fuel and LBE), the only external force left to be the driver of core compaction is believed to be the drag by the flow. In all possible events, including loss of forced flow and/or loss of reactor core protection (control and safety rod systems), the first degradation phenomenon in an HLMFR core is the melting (or dissolution) of the cladding [7]. The proposed bounding case assumes this to have happened instantly in the whole core, which is an extremely conservative hypothesis.

The hypothetical sequence of events leading to the core compaction in MYRRHA is assumed to be the following: the fuel in the reactor core is initially assumed to have lost all the cladding. Cladding is furthermore assumed to have been relocated, due to melting and subsequent freezing, to the region above the active core region and to have made a blockage there (the resolidified cladding material "floats" on top of the active zone). The porosity of this blockage is assumed to be such that it allows the LBE to flow through it but prevents the passage of the fuel (fragments). Fuel is furthermore assumed to be fragmented and suspended in the coolant (recall that the fuel itself has a similar density as the LBE). On top of previous assumptions, it is postulated that the primary circuit pumps are still running and hence creating a forced coolant flow that compacts the fuel against the blockage formed above the active zone of the core. This leads to fuel compaction and the consequent increase in reactivity.

In the opinion of the authors, the herein proposed (conservative) scenario maximizes the reactivity insertion rate in the MYRRHA core.

3 Modelling of a hypothetical core disruptive accident

Since the HCDA involves various physical phenomena, mostly in a non-linear coupled framework, the development of an accurate purely analytical model is deemed almost impossible. However, there is a variety of ways to assess the magnitude of the released energy in an HCDA.

The analytical model initially developed by Bethe and Tait for SFRs is based on a theoretical and simplified sequence of events: a prompt-critical sphere of molten metallic fuel heats up until the formation of fuel vapor at its center. This is followed by an expansion due to the buildup of internal pressure which ultimately inflates the sphere into a (deeply) sub-critical configuration. This model is subject to a number of simplifying and conservative assumptions that lead to the decoupling of the involved phenomena [5], therefore significantly simplifying the solution. Nonetheless, the model is suitable to provide a conservative assessment of the energy released during a CDA in an SFR.

In the years that followed, specialized computer codes were developed in order to estimate HCDAs in a best estimate approach. One of these severe accident codes is the SIMMER computer code. SIMMER-III is a two-dimensional, three-velocity-field (reactor core materials are assigned to one of the three existing velocity fields), multiphase, multi-component, Eulerian particle/fluid-dynamics code coupled with a space- and energy-dependent neutron-dynamics code [8]. Compared to the original Bethe and Tait model, SIMMER can address cases of significantly higher complexity. SIMMER was originally developed for use in the safety analysis of SFRs and was later adapted to be used for the same purposes in HLMFRs. The adaptations of the code include the introduction of the material properties of the coolant and the corresponding equation of state, as well as some additional minor modifications. Nonetheless, the majority of the physical phenomena and the corresponding modeling are as in the case of SFR. Some of these models were validated for applications to SFR safety analysis [9] but were, regrettably, never extensively validated for use in HLMFR.

Therefore, a simplified and conservative in-house model has been developed at SCK CEN and implemented in order to provide an assessment of the order of magnitude of the energy released during an HCDA in MYRRHA and to be further compared to SIMMER-III. This model couples the solution of the heat transfer problem, the mechanical-dynamics, and the neutron-dynamics. In addition, it involves a couple of simplifying assumptions that either have negliable impact or have a conservative impact on the solution.

3.1 Hypothetical core disruptive accident solver

In what follows, a brief description of the in-house developed model, from here on referred to as HCDA Solver, is provided. In addition, Figure 1 provides a simplified overview of the reactor pool (left), computational domain, and its anticipated state at the beginning and the end of the simulation (middle), as well as the corresponding legend (right). It is useful to return to Figure 1 while reading through this section.

In order to reduce the computational burden of simulations, the reactor core is initially assumed to be spherical.

The solution of neutron dynamics relies on the theory of Point Reactor Kinetics (PRK), whereas all necessary PRK parameters, as well as the corresponding reactivity feedback coefficients, are calculated by employing the Serpent 2 Monte Carlo code [10]. The set of PRK equations reads as in equation (1) [11]:

$$\begin{aligned} \frac{\mathrm{d}P\left(t\right)}{\mathrm{d}t} &= \frac{\rho\left(t\right)-\beta_{\mathrm{eff}}}{\Lambda}\cdot P\left(t\right)+\sum_{i}\lambda_i\cdot\zeta_i\left(t\right) \\ \frac{\mathrm{d}\zeta_i\left(t\right)}{\mathrm{d}t} &= \frac{\beta_i}{\Lambda}\cdot P\left(t\right)-\lambda_i\cdot\zeta_i\left(t\right) \\ \rho\left(t\right) &= \rho_{\mathrm{comp}}\left(t\right)+\sum_{i}\alpha_i\cdot SV_i\left(t\right) \end{aligned} \tag{1}$$

where P denotes the power, t the time, ρ the reactivity, β the delayed neutron fraction, Λ the neutron generation time, λ the decay constant of delayed neutron precursors, ζ the adjusted or "reduced" concentration of delayed neutron precursors [11], ρ_{comp} the reactivity inserted due to compaction of the reactor core, α the reactivity feedback

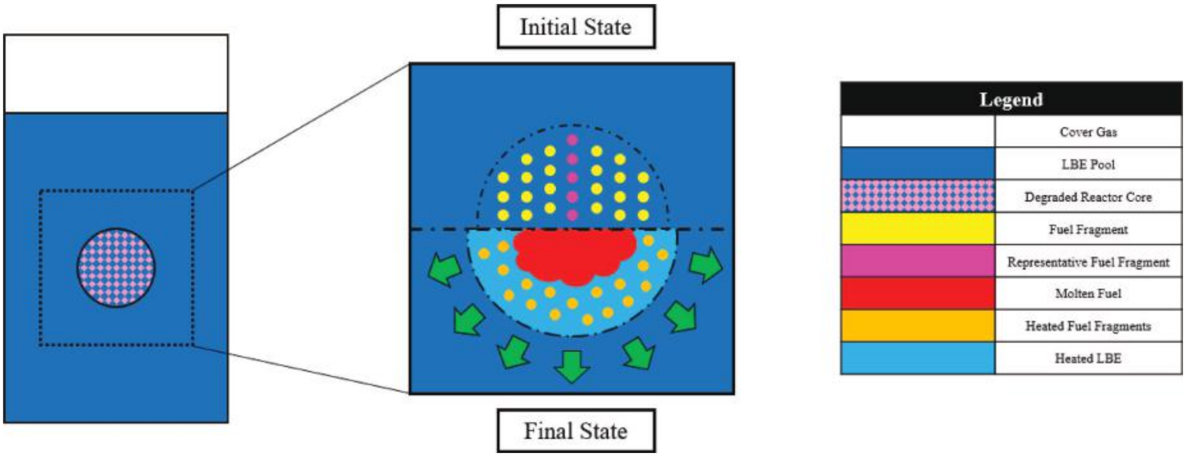

Fig. 1. Simplified overview of the reactor pool and the computational domain. The upper section of the computational domain represents the state of the core at the beginning of the transient, whereas the lower section represents the state of the core at the end of the simulation.

coefficient for a particular feedback effect and SV the state variable corresponding to the reactivity feedback effect.

Several reactivity feedback effects are considered: the nuclear Doppler effect, the thermal expansion of solid fuel, the thermal expansion of liquid LBE, the reactivity effect related to the fuel melting, and the thermal expansion of liquid fuel. The corresponding reactivity feedback coefficients are calculated by running a number of Serpent 2 cases and subsequently calculating the rate of change of reactor core reactivity with respect to the change of the corresponding state variable. The reactivity feedback coefficients are expressed either in $\frac{\text{pcm}}{K}$ or $\frac{\text{pcm}}{\%_{\text{vol}}}$.

Before and up to the hydrodynamic disassembly of the reactor core, heat transfer is solved at the fuel fragment level, under the assumption that the fuel fragment is spherical and that the heat transfer happens only due to conduction. The heat transfer equation in its general form reads as in equation (2) [12]:

$$\rho(T)\cdot c_p(T)\cdot\left(\frac{\partial T(t)}{\partial t}+\overrightarrow{v}(t)\cdot\nabla T(t)\right)=\nabla k(T)\cdot\nabla T(t)+q'''(t) \quad (2)$$

where ρ denotes the mean density, T the temperature, c_p the specific heat at constant pressure, t the time, v the flow velocity, k the thermal conductivity and q''' the volumetric heat generation rate. Equation (2) is reported in its general form, but some simplifications, allowed by the nature of the transient, can be introduced. For example, due to a low velocity of coolant with respect to the fuel fragments during the transient (i.e. $v \approx 0$), as well as due to the timescale of the entire transient, convective heat transfer can be neglected.

Since it plays an important role in an HCDA, a model of phase change, of both the fuel and the coolant are introduced. It relies on the so-called effective heat capacity method [13]. This method uses a pseudo material with an increased heat capacity near the melting temperature that simulates the latent heat of fusion so that the material absorbs the same amount of heat as the latent heat does during phase transition. By doing so, the latent heat of the phase change, along with the temperature-dependent thermal properties of different phases of the reactor core materials (e.g. density, thermal conductivity, etc.) are accounted for.

In order to feed the neutron-dynamics solver with the necessary state variables, information on the average reactor core state is required. The sought-average state is acquired by averaging results obtained for the representative fuel fragments. Since the reactor core geometry is assumed to be spherical, representative fuel fragments are identified as fuel fragments along the core radius and are indicated in magenta in Figure 1.

System pressure buildup is caused by the thermal expansion of core materials and phase changes [3,5]. Calculation of this pressure relies on the solution of the mass conservation equation and the simplified momentum conservation equation and is currently under further development. The conservation equations employed to calculate system pressure buildup are reported in their general form in equation (3) [14]:

$$\frac{\partial\rho(t)}{\mathrm{d}t}+\overrightarrow{\nabla}\cdot(\rho(t)\cdot\overrightarrow{v}(t))=0 \quad (3)$$
$$\rho(t)\cdot\frac{D\overrightarrow{v}(t)}{\mathrm{D}t}=-\overrightarrow{\nabla}p(t)+\rho(t)\cdot\overrightarrow{g}+\overrightarrow{\nabla}\cdot\overline{\overline{\tau}}$$

where ρ denotes the mean density, t the time, v the flow velocity, p the pressure, g the gravity acceleration and τ the deviatoric stress tensor.

A simplified coupling scheme of the above-described models (i.e. Eqs. (1) through (3)) is presented in Figure 2. It should be noted that the models presented in blue are related to neutron-dynamics, the models presented in red are related to heat transfer, and the models presented in green are related to mechanical-dynamics and pressure buildup.

Results obtained by the HCDA Solver have been compared to the results obtained by the significantly more complex and mature severe accidents code SIMMER-III and it has been verified that the HCDA Solver can perform comparatively well prior to boiling onset. By doing

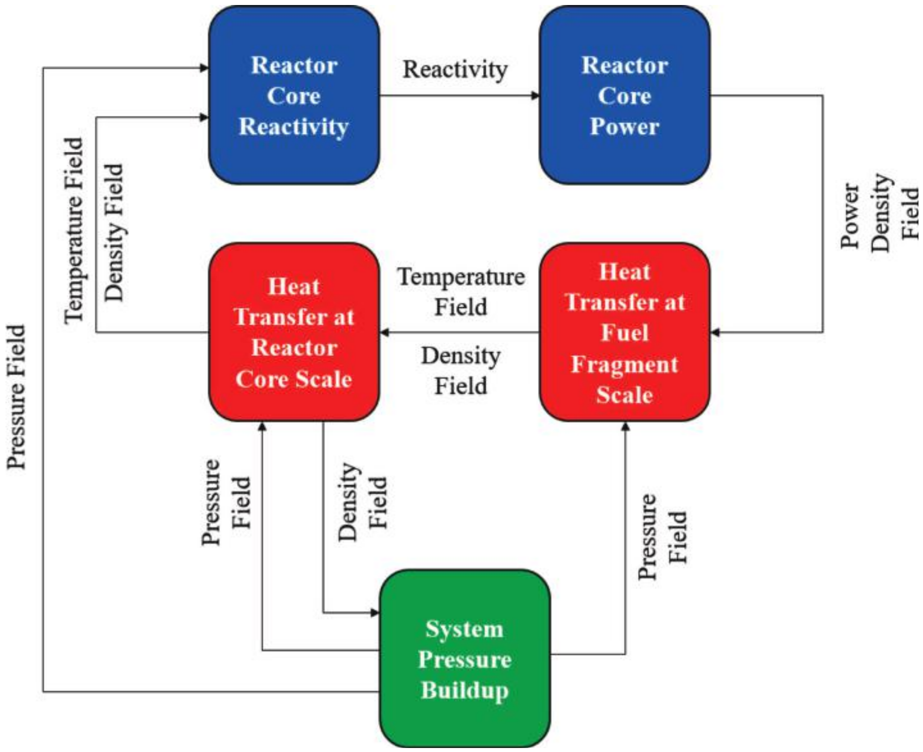

Fig. 2. Simplified coupling scheme of the described HCDA Solver.

this, code-to-code verification (for this specific transient) has been successfully performed. It can therefore be stated that the HCDA Solver seems to be able to model appropriately the physics relevant for an HCDA in an HLMFR core.

4 Phenomenology of a hypothetical core disruptive accident in a heavy liquid metal fast reactor

As already mentioned, this paper aims to provide a qualitative discussion of the physics relevant to an HCDA in an HLMFR core such as MYRRHA.

A postulated sequence of events leading to HCDA in an HLMFR has been reported in Section 2.1: *Core Disruptive Accident in Heavy Liquid Metal Fast Reactor*. The initial state of the system is that of a uniform mixture of fuel fragments and LBE (i.e. the *degraded* reactor core). Recall that the steel is presumed to have left the active core region by buoyancy and that it is not present in the system. The presented results are obtained by SIMMER-III and by the in-house developed model, HCDA Solver.

4.1 Core compaction and reactivity insertion

Since the core degradation phase is highly dependent on the specific core degradation scenario, the core compaction is currently modeled by a linear insertion of reactivity versus time. The linear reactivity insertion rate is the sole parameter used to describe the core compaction mechanism. Core compaction is therefore simulated by artificially increasing the reactivity of the core according to the compaction rate defined by the assumed compaction mechanism: degraded core compaction by a nominal forced flow. The core disruption by the prompt-critical power release is efficiently instantaneous and this justifies the assumption that it is independent of the actual compaction mechanism.

Results discussed and presented in the scope of this work are based on an input reactivity insertion rate that corresponds to the uniform compaction of the core by the nominal forced flow. By running two subsequent Serpent 2 calculations that correspond to a degraded core of nominal size and completely compacted degraded core (i.e. maximum theoretical packing density of spherical fuel particles) and by assuming this compaction to have happened at the flow velocity that corresponds to nominal forced flow (this is a conservative assumption), the amplitude of reactivity insertion rate is calculated to be 170\$/s.

4.2 Power buildup and reactivity reversal

An increase in the core reactivity results in an increase in core power. For as long as the reactivity of the core is below the effective fraction of delayed neutrons in the core (1\$), the power increase is mainly driven by the dynamics of delayed neutrons. This means that the power increase in this reactivity range (0\$–1\$), defined as delayed-supercriticality, is slow (i.e. dominated by the decay constant of delayed neutron precursors, λ, which is of the order of seconds, i.e. between 0.2 s and 55 s) [11]. In this phase, the reactivity feedback effects are small when compared to the reactivity inserted due to core compaction. This means that the reactivity evolution is dominantly driven by the core compaction.

When the core reactivity exceeds 1$, the nuclear chain reaction is dominantly driven by prompt neutrons and the power increase is much faster (i.e. dominated by the prompt neutron generation time, Λ, which is on the order of (fractions of) microseconds) [11]. This moment is defined as the moment of *super-prompt-criticality* and denotes the beginning of the power peak. Due to the high thermal energy input in the system, the reactivity feedback effects start becoming more important.

One of the important reactivity feedback effects is the Doppler effect, linked to the increase in the fuel temperature and the corresponding cross-section resonance broadening effect [4]. This effect results in the reduction of the core reactivity. An increase in the fuel temperature additionally leads to its thermal expansion and the consequent expansion of the entire reactor core. This core dimension augmentation leads to an increase in neutron leakage from the core and a corresponding reduction of the core reactivity. Heat transfer from the fuel to the surrounding LBE coolant results in thermal expansion of the coolant and reduction of the core reactivity due to the same reasons as mentioned above. As a consequence of very fast thermal feedback in the prompt-critical region, the sum of these reactivity feedback effects is of the same order of magnitude as the reactivity inserted in the system due to the hypothetical core compaction. The moment of *reactivity reversal* is defined as the moment when the overall reactivity reaches its maximum and starts reducing. It is important to remember that at the moment of reactivity reversal, the core reactivity is still above 1$. This means that the power increase rate remains high due to the fact that the nuclear chain reaction is still driven by the prompt neutrons.

4.3 Neutronic shutdown

Shortly after the moment of reactivity reversal, the fuel melting temperature is reached in the central regions of the core. *Fuel melting* introduces an additional negative reactivity feedback effect: since the phase change is associated with an increase in the fuel volume, it results in an increase in the core size, a decrease in the average core density, and additional neutron leakage. The reactivity feedback effect related to fuel melting is high enough to drive the overall core reactivity below 1$, into the delayed-supercritical zone. This occurs almost immediately upon the onset of the fuel melting. The moment when the core reactivity reaches the delayed-supercritical zone is the moment of the *neutronic shutdown*. At the moment of the neutronic shutdown, the power peak reaches its maximum [11].

4.4 Hydrodynamic core disassembly

Even though the reactor power has reached its maximum and is on the decrease after the reactor reaches neutronic shutdown, its absolute value is still very high. This means that the negative reactivity feedbacks continue to increase in magnitude and therefore continue to override the reactivity inserted due to hypothetical core compaction. The internal energy increase of the fuel and the heat transfer to the LBE eventually lead to *fuel* and/or *LBE boiling*. These two phenomena rapidly increase the system pressure and cause a *hydrodynamic disassembly* of the core, accompanied by a negative reactivity feedback of high magnitude that counters all the hypothetical reactivity insertion [3,5]. This results in the complete disassembly of the core and a corresponding dispersion of fuel. The reactivity feedback effect rated to the fuel dispersion is high enough to almost instantaneously reduce the core reactivity far below the critical state and make the entire configuration deeply subcritical.

The hydrodynamic disassembly of the core is assumed to override any hypothetical core compaction mechanism and will therefore effectively terminate the transient.

It should however be noted that the complete dispersion of the fuel might be prevented due to the presence of the supporting structures in the reactor pool. If that is the case, a sudden collapse of the created fuel and/or LBE bubble can lead to the new fuel compaction and therefore represents a viable recriticality mechanism. The potential for recriticality due to a variety of reasons will be addressed in the follow-up of this work.

4.5 Pressure buildup

Core compaction and the consequent power pulse result in a substantial pressure buildup in the system. This pressure buildup is caused by the expansion of core materials and the phase change.

As a brief reminder, the power profile of a reflected homogeneous critical sphere is parabolic [3,5]. As a consequence, the thermal expansion and phase change are more pronounced in the center of the core, as will the system pressure. Due to this pressure buildup in the center of the system, the location of the fuel and LBE boiling shifts towards the periphery of the core.

A simplified analytical model of the core material expansion (as a consequence of the thermal expansion or phase change from solid to liquid) shows that for as long as the system remains highly incompressible (i.e. does not contain non-condensable gas or vapor), no displacement inside the degraded reactor core is taking place at velocities higher than the speed of sound and no important local pressure is built up. This type of system is usually referred to as the “hard system”. The subsonic behavior of a (hard) system significantly simplifies the mechanical modeling of an HCDA.

It is important to stress that the full disassembly occurs by vaporization of the fuel and/or LBE and that a more complicated hydrodynamic model is required to describe this phase of the transient.

4.6 Importance of reactivity insertion rate

A parametric study has been performed with SIMMER-III, in which the reactivity insertion rate was varied up

Table 1. Initial conditions of degraded reactor core as employed in simulation of HCDA in MYRRHA. This simulation is performed by employing HCDA Solver.

Initial condition	Value
Power	100 MW
Reactivity	0$
Reactivity insertion rate	170$/s
Degraded core radius	0.71505 m
Fuel volume fraction	0.14
Fuel temperature	1700 K
LBE volume fraction	0.86
LBE temperature	600 K

Table 2. Timing of the most important events expected to occur during the HCDA in MYRRHA. These results are obtained by employing HCDA Solver.

Event	Timing [ms]
Beginning of reactivity insertion	0
Super-prompt-criticality	8.137
Reactivity reversal	21.074
Fuel melting	23.082
Neutronic shutdown	24.432
Fuel boiling	24.683
LBE boiling	/
Hydrodynamic core disassembly	>24.683

to the highest reactivity insertion rate that can physically occur in the core of MYRRHA. The scenario corresponds to the uniform compaction of a degraded reactor core by the nominal forced flow, as discussed in Section 2.1: *Core Disruptive Accident in Heavy Liquid Metal Fast Reactor* of this paper.

This parametric study showed that the released thermal energy increases with the increase of the reactivity insertion rate. The same study also showed that the sequence of the most important events expected to occur during the transient does not change as a function of the reactivity insertion rate. It should however be noted that the timing (relative to the beginning of the reactivity insertion) of the above-mentioned events does differ significantly.

5 Illustrative preliminary results

This section provides a brief, illustrative overview of the numerical results obtained for a reference test case. The presented preliminary results are obtained by application of HCDA Solver. The transient follows the phenomenology described in Section 4: *Phenomenology of Hypothetical Core Disruptive Accident in Heavy Liquid Metal Fast Reactor* of this paper.

Table 1 provides an overview of the initial conditions, whereas Table 2 contains the timing (relative to the beginning of the reactivity insertion) of the most important events expected to occur during the transient. The core reactivity and power evolution are represented in Figure 3. Since the HCDA Solver still does not include an appropriate hydrodynamic model of boiling, the simulation is terminated when the boiling onset is reached.

6 Future work

Concerning further developments in research of an HCDA in an HLMFR core, several points require attention.

It has been discovered that the 11 energy group structure, used as an input to the neutron-dynamics solver of SIMMER-III, is not suitable to accurately reproduce the neutron-dynamics of the prompt-critical event in the core of an HLMFR. By employing 72 energy group structure that accounts for seemingly important effects in the epithermal energy range, almost identical results to those of continuous-energy Monte Carlo simulation were achieved. Authors are therefore currently working on the development and generation of a better suited energy group structure and the corresponding cross-section library.

Furthermore, the in-house developed model used in this study is expected to perform accurately in a hard system until the onset of boiling. Due to the constraints imposed by the application of the PRK model [4,12], as well as the simplified treatment of the boiling process, further development of the model is currently being carried out to enable coverage of the transient beyond the boiling onset.

The herein described accident and the corresponding modeling are aimed at the assessment of the released thermal energy in a "hard system". It considers the complete absence of non-condensable gas that might be trapped inside the degraded reactor core, such that the expansion of the core materials directly translates into the expansion of the entire core. However, the presence of non-condensable gas in the system would delay the expansion of the core and increase the released thermal energy, since it would prevent the expansion of the core until the non-condensable gas is sufficiently compressed. The authors are currently investigating the potential for the presence of non-condensable gases and expansion of the current models to account for their presence.

Finally, a model will be developed for the conversion of the released thermal energy into mechanical energy and the calculation of the corresponding loads on the primary system. By doing so, an estimate of the viability of the in-vessel retention strategy will be performed.

7 Conclusions

This work provides an overview and a discussion of the physics relevant for an HCDA in an HLMFR, with the core of MYRRHA as an example. The work presented in

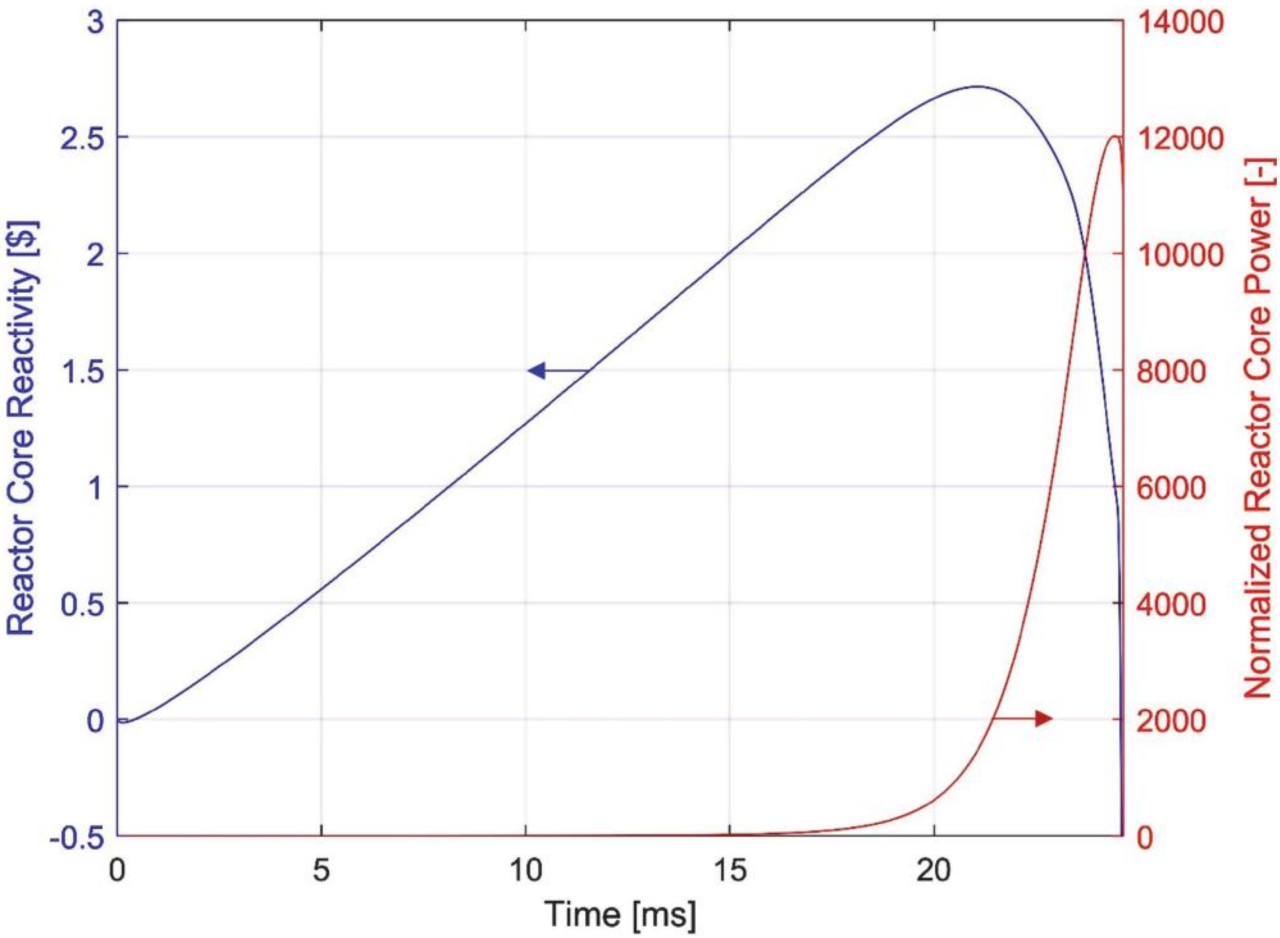

Fig. 3. Evolution of the reactor core reactivity and the corresponding reactor core power as calculated by employing the HCDA Solver.

the framework of this paper aims to support the mechanical calculation of the MYRRHA reactor vessel. In order to challenge the vessel's integrity and hence its confinement function, a conservative estimate of the energy released during an HCDA is to be used. To that goal, an assessment of the released energy during an HCDA is calculated by employing two codes: well-established severe accidents code SIMMER-III (originally developed for SFRs) and an in-house developed, simplified model describing multiphysics of such an accident.

In the framework of the above-described simplified model, some of the most important conclusions are as follows:

1. the sequence of events expected to occur during an HCDA in MYRRHA is as follows:
   i Super-prompt-criticality
   ii Reactivity reversal
   iii Fuel melting
   iv Neutronic shutdown
   v Fuel and/or LBE boiling
   vi Hydrodynamic disassembly;
2. reactivity feedback effects start playing a dominant role when super-prompt-criticality has been reached;
3. thermal expansion of the reactor core materials, together with the Doppler effect, exceed the maximized hypothetical reactivity insertion and results in the reactivity reversal;
4. fuel melting results in the neutronic shutdown of the reactor core;
5. fuel and/or LBE boiling results in the hydrodynamic disassembly of the reactor core;
6. for the range of reactivity insertion rates assumed to be possible in the case of an HCDA in MYRRHA, the sequence of events expected to occur during the accident does not depend on the reactivity insertion rate.

Even though classified as "highly unlikely", severe accidents need to be considered in the framework of the MYRRHA safety studies. The hope is that independent of the initiating event and the core compaction scenario, the physics of a CDA in an HLMFR core inherently limits the released thermal energy and the conversion to mechanical load to a level that can be sustained by the primary system.

Upon detailed analysis of the accident, this work identifies all the relevant processes and the corresponding physics necessary to provide a conservative upper-bound estimate of the released thermal energy during such an accident.

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.

Author contribution statement

The following authors have contributed to this research: Đorđe Petrović – model development, performing the calculations, processing the data, and writing the manuscript; Matteo Zanetti – research conceptualization, model development supervision, and manuscript revision; Guy Scheveneels – research conceptualization, model development supervision, and manuscript revision; Andrei Rineiski – model development, and manuscript revision; Xue-Nong Chen – SIMMER-III model development and manuscript revision; William D'haeseleer – manuscript revision.

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REactor Safety Analysis ToolboX RESA-TX

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Abstract. The REactor Safety Analysis ToolboX RESA-TX is a software and data package in development that combines the automatisation of all established procedures for deterministic safety analysis (DSA), the integration of expert know-how and a large database including the most relevant information required for conducting a DSA. In the current state of the art, DSA is a complex and thus error-prone process that is highly time-consuming and repetitive. The reliability of the result is strongly dependent on the availability of plant data and expert know-how. The idea of developing the RESA-TX toolbox arose at GRS to cope with these conditions. The innovative approach proposes an automated and standardised procedure, supported by a large database of plant design characteristics, plant behaviour, regulatory rules and DSA expert knowledge incorporated within the tool. Its application allows the end user to automatically generate and verify an input deck, as well as conduct design basis accident (DBA) calculations for a certain design with highly reduced manual intervention. The databases can be extended depending on available information or other boundary conditions. A heuristic approach is integrated into the model generation process, where users often suffer from a lack of information about the facility under consideration. These heuristics can be replaced when higher information quality is available or enhanced over time, which can lead to more reliable results with increasing usage of the tool. As a result, the application of RESA-TX could highly increase the efficiency of the DSA process, reducing both repetitiveness as well as user-induced errors. This in return will lead to an improvement in the quality of the analysis and reliability of the results. In consequence, RESA-TX will allow for a DSA to be conducted more frequently in situations where time or budget was a limitation before, thereby contributing to an increase in reactor safety.

1 Introduction

Every nuclear facility requires safety assessments. According to the IAEA [1], DSA is an essential part of this process, particularly to demonstrate the safety and adequacy of a reactor design within the defence in-depth concept. The main objective of DSA is to confirm that safety functions can be fulfilled and that the necessary structures, systems and components, in combination with operator actions, are effective in keeping the releases of radioactive material from the plant below acceptable limits.

A deterministic safety analysis is generally conducted using thermal-hydraulic system codes. Best-estimate thermal-hydraulic system codes like RELAP, TRACE, ATHLET or CATHARE have been developed and extensively validated during the last decades to analyse the thermal-hydraulic phenomena occurring in nuclear facilities during various scenarios.

The first step to being undertaken for analysing the plant behaviour by applying these system codes is the development of a model of the nuclear facility. This model is a simplified representation of the main plant systems, such as the reactor coolant system, secondary side, or safety systems. The different components are modelled and connected to each other to form a network of objects, known also as the nodalisation scheme (see Fig. 1). The model is described in an input deck having a code-specific format and syntax. To generate the thermal-hydraulic model, extensive plant data about the geometry of the main components, material properties, valve and pump characteristics, heat transfer, neutronic and control logic data, etc. are required. The input deck developers must have deep knowledge of thermal-hydraulic modelling of systems using code-specific syntax. Processing a large amount of data and translating it into a plant model is a time-consuming task, which may require a big effort in terms of man-hours (see Fig. 2).

Plant-specific thermal-hydraulic models are used for example by reactor manufacturers to analyse the complex thermal-hydraulic behaviour for abnormal operating conditions, or accidents and to demonstrate the safety of the plant concept. Technical support organisations (TSO) like GRS develop independently complex thermal-hydraulic

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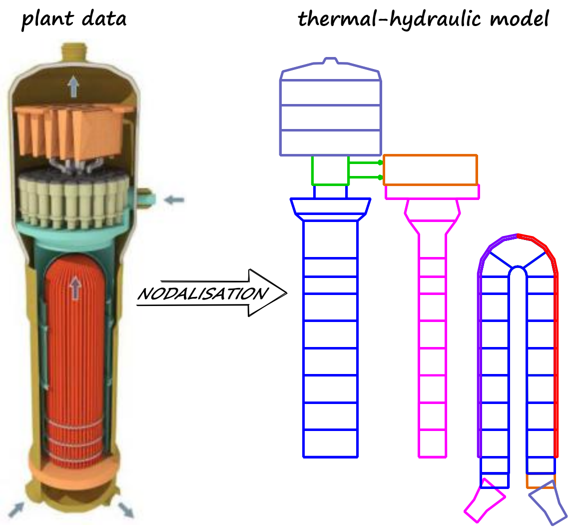


Fig. 1. Example of a steam generator model and nodalisation scheme.

models to support regulatory authorities in their safety assessment process of nuclear power plants (NPPs) by conducting confirmatory analyses. Thermal-hydraulic code developers use models of experimental facilities to assess the performance of their code and validate it by comparing the code results against these experiments, also comparing to other codes in benchmarking activities. In all cases, the generation of these models is manual and laborious, requiring a big effort in terms of time and cost.

The achieved result and thus the quality of a DSA depends not only on the system code but also on the quality of the plant model in the generated input deck. The quality of the model is limited by the availability of data and can be influenced by the so-called user effect. A user effect is related to the individual way of modelling certain plant components as well as errors when implementing the geometry and characteristics of the components. It can reflect badly on the robustness of the adopted system code and jeopardise the quality of the DSA.

2 Concept

RESA-TX was outlined at GRS to cope with the above-described problem. The innovative approach proposes an automated and standardised procedure supported by a large database of plant design characteristics, plant behaviour and DSA expert knowledge incorporated within the tool. Its application allows the end user to automatically generate and verify an input deck as well as conduct design basis accident (DBA) calculations for a certain design with highly reduced manual intervention.

The automatisation of each step using RESA-TX is supported by the inherent databases containing a pool of information about plant designs, plant behaviour, regulatory rules and expert know-how on DSA procedures. The databases can be extended depending on available information or other boundary conditions.

Heuristics are integrated into the model generation and verification process, where users often suffer from a lack of information about the facility under consideration. These heuristics can be replaced when higher information quality is available or enhanced over time which can lead to even more reliable results with increasing usage of the tool.

RESA-TX is intended for regulators and technical support organisations, for the nuclear industry as well as for nuclear code developers that can use either all or some of the tools for their own specific needs and purposes.

3 Methodology

The **RE**actor **S**afety **A**nalysis **T**oolbo**X** (RESA-TX) is a collection of three different tools corresponding to the three main steps of DSA. They support the end user:

(1) by the automatic generation of a thermal-hydraulic model of the desired facility in form of an input deck (Tool AMG – Automatic Model Generator). This is supported by a heuristic network in case of a lack of specific plant data;
(2) by the automatic verification process of the input deck to confirm the adequacy of the model (Tool AMV – Automatic Model Verify) based on a qualitative system behaviour evaluation and/or the NPP documentation if available;
(3) by the automatic generation of a safety analysis case (i.e., calculation of a basic set of design basis scenarios, e.g. a loss of coolant accident) with help of the ASAG tool – Automatic Safety Analysis Generator.

A schematic representation of the methodology is shown in Figure 3.

3.1 AMG – Automatic Model Generator

The Automatic Model Generator AMG is a tool which helps the user quickly generate a simple thermal-hydraulic model of the main plant components using code-specific syntax and automatically combining them to obtain a plant model.

An automatic and standardised approach for the generation of input decks is not available so far. The plant-specific input decks for the simulation of nuclear facilities are currently manually developed. For the modelling of the most relevant components of a plant, such as a reactor pressure vessel (RPV), Steam Generators (SGs) and Pressuriser (PRZ), system-specific drawings, plans and descriptions are taken into account. The input deck developers must have deep knowledge of both thermal-hydraulic system modelling and code-specific features and syntax. Generating a thermal-hydraulic model is a time-consuming task, which may require a big effort in terms of man-hours.

For the modelling of the main components, geometrical data is often not available, complicating the task of model generation. The current state of the art is that to overcome

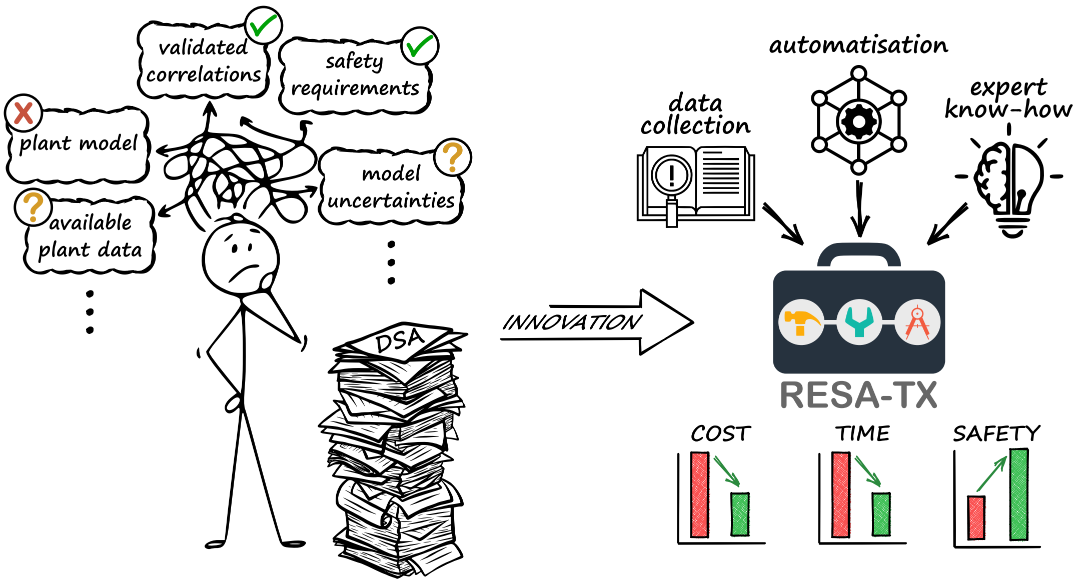


Fig. 2. State of the art DSA vs. innovative approach of RESA-TX.

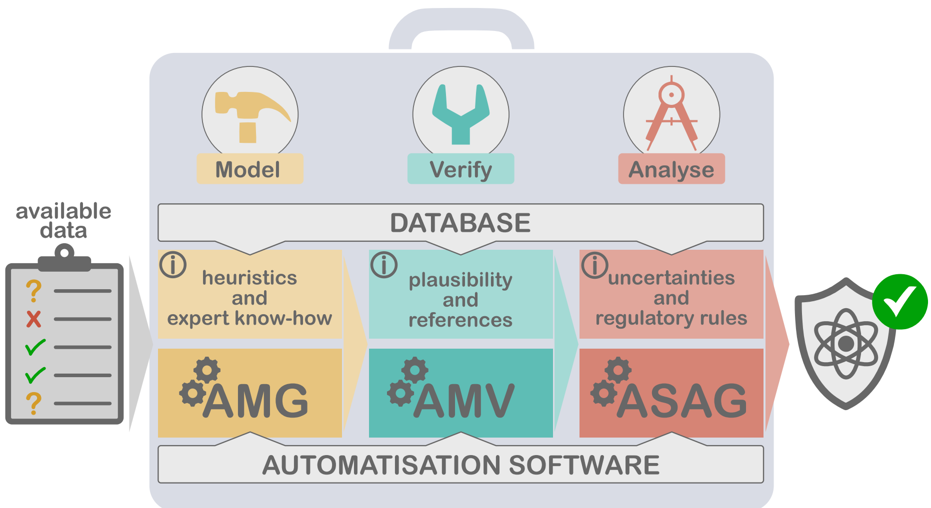


Fig. 3. The REactor Safety Analysis ToolboX (RESA-TX).

this lack of data, the user often needs to apply assumptions based on expert judgement, which requires not only time but also vast knowledge and experience. The innovative approach of RESA-TX strongly supports this step by automatically generating a plausible generic data set. This is done based on a network of heuristics, which represents a set of rules and mathematical relationships that help define the geometry and characteristics of a certain plant component and select the most likely configuration based on pre-defined plant databases. The previously required vast experience and user know-how are now in large part inherent to the tool. The developed algorithms in AMG are able to identify for instance the length of a certain component (e.g., fuel assembly) or the total number of components (e.g., number of fuel assemblies) by using the implemented mathematical relationships. If made available, the network of heuristics can be replaced with more specific plant data. With increasing plant knowledge, the model can be gradually refined.

By adopting this approach, essential systems and components of the plant are automatically generated as modules (RPV, SG, PRZ, ECCS). The modules are then automatically merged into one single data set constituting a plant-specific input deck. The complexity of the single components' modules is tailored to the respective level of knowledge about the plant and the DBA analysis to be executed. This approach has the potential to drastically reduce the user effect and user-induced errors during the modelling process by simultaneously decreasing the time necessary for the development.

Python is chosen for the automatic creation of the components modules, as it is an object-oriented programming language that enables the development of complex components in a modular way and is therefore suitable

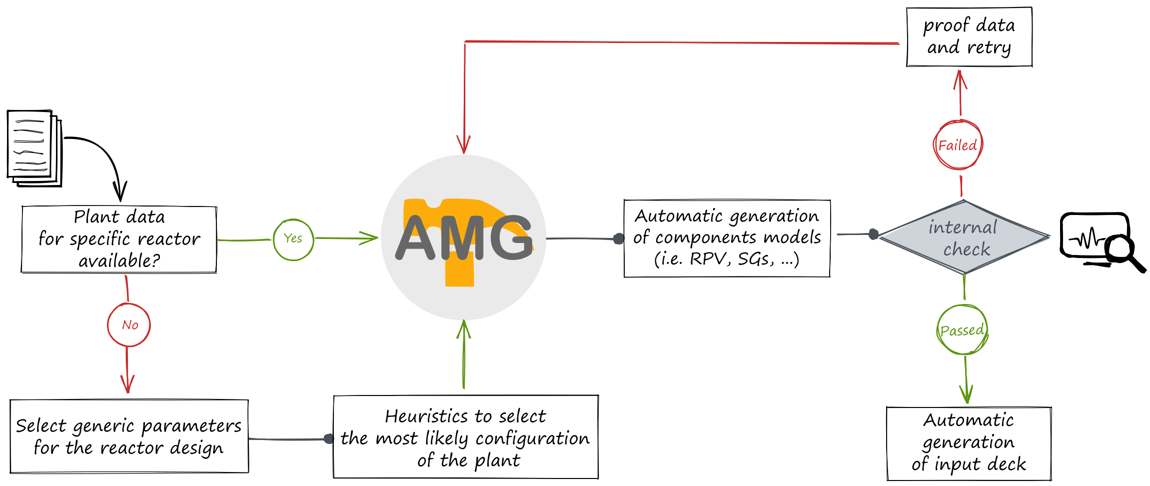


Fig. 4. Flow diagram for the Automatic Model Generator (AMG).

for the automatic generation of an input deck for system codes.

For the simulation of the relevant safety functions (e.g. SCRAM from reactor protection system) which are mandatory to prove that the reactor can cope with the accident scenario and reach a controlled state, control system models can be also automatically generated containing a simple network of logic signals.

Figure 4 depicts the procedure of automated model development using AMG Software.

Currently, code-specific python programs for the generation of components as objects in ATHLET system code are being developed at GRS [2]. The python programs can be adapted to other system codes, based on the specific syntax.

3.2 AMV – Automatic Model Verifier

The Automatic Model Verifier AMV is an automatic and continuous integration of reactor-related models which uses a set of parallel transient simulations in order to confirm the adequacy of the model or simulation code used as a prerequisite for deterministic safety assessment. The tool is based on a comprehensive systematic procedure to examine the correctness of an implemented model against a defined evaluation basis. It consists of three modules that communicate with each other during the verification process (see Fig. 5):

- the Verification Database Generator – VDG: algorithms are used to generate acceptance corridors from parameter progressions for a set of transients and accident scenarios (inherent database or user-provided) as an evaluation basis;
- the Simulation Controller – SC: sets boundary conditions (BCs) and controls operator actions or unintended plant behaviour for the assessed transient scenarios;
- the Continuous Integration Module – CIM: interacts with a global database infrastructure (repositories, input and result storage, etc.), automatically triggers and coordinates parallel simulations, and uses algorithms to evaluate their results using the verification database to generate a clear result report. Thanks to learning feedback loops, the verification database will be enhanced with increased usage.

The AMV is applicable for any level of model complexity and any code that evaluates transient behaviour (esp. thermal-hydraulic system codes, neutronic codes, subchannel codes, etc.). If minimal knowledge about an investigated plant is available, the progression of system parameters during a given transient is compared against qualitative value corridors which are provided by RESA-TX to verify a plausible model behaviour. Such approximation can be continuously replaced if more plant-specific data becomes available, which increases the result reliability. Transients and accidents are set up and controlled using control protocols which are accessed by the SC module. The SC intervenes in the simulation process to change BCs, setting plant malfunctions (stuck valve, leak initiation, etc.) and performs operator actions associated with the given list of transients or accidents to be investigated. These protocols are provided by RESA-TX for a minimal set of transients for thermal-hydraulic analyses but can also be created by the user according to specific needs and other deterministic codes.

A similar tool is in use at GRS to assess the reliability of system-specific analysis simulators that analyse the thermal-hydraulic behaviour for abnormal operating conditions, incidents and beyond design basis accidents in nuclear power plants, as well as for the verification of thermal-hydraulic code development (see [3] and [4]).

3.3 ASAG – Automatic Safety Analysis Generator

Once the input model has been automatically generated by the tool AMG and verified by the tool AMV the third

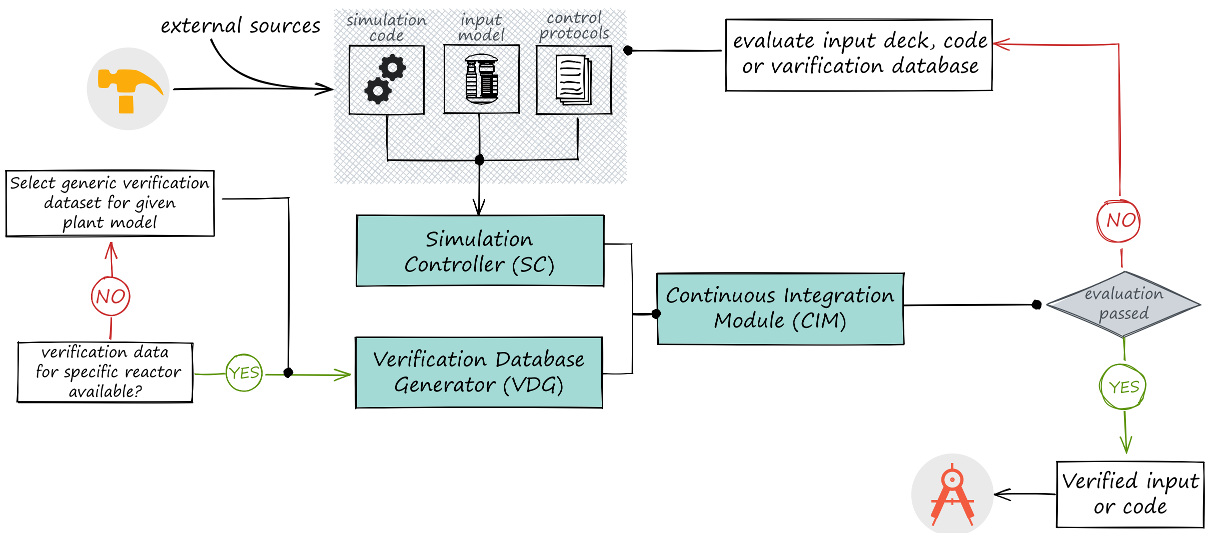


Fig. 5. Flow diagram for the Automatic Model Verifier (AMV).

tool can be used for the automatic generation of deterministic safety analysis. For this purpose, the Automatic Safety Analysis Generator ASAG uses the IAEA option 3 “best estimate plus uncertainty” approach [5]. A mix of best estimate and unfavourable initial and boundary conditions is proposed by the tool based on provided Phenomena Identification and Ranking Tables (PIRTs), taking into account the very low probability that all parameters would be at their most pessimistic value at the same time. Conservative assumptions on the availability of systems are suggested by ASAG depending on the considered scenario. To ensure the overall conservatism required in the analysis of design basis accidents, design-dependant uncertainties are identified, quantified and statistically combined. To do this, the ASAG picks up on the large statistical data storage for safety analysis of the different reactor designs provided by RESA-TX. For initial purposes, ASAG is limited to design basis scenarios. The process of the ASAG application is depicted in Figure 6.

ASAG combines the automatic transient calculation software already used in AMV with a database of transients and statistical data required for a safety assessment of the selected reactor design. It is not limited to a specific code. It builds on software tools already in use at GRS for the automatic start of several runs for uncertainty analysis tools like SUSA, combining these with a deep knowledge of safety analysis procedures inherent to the tool, e.g., information on which transients are required for safety assessment of a certain design, what are the most relevant plant systems for each transient, which boundary conditions should be applied for a correct BEPU assessment of this transient, which variables should be varied and what statistical behaviour should be assumed for them, etc.

In this way, ASAG will guide and support the user through the different steps of the analysis. The analysis may range from one case to the whole list of design basis scenarios available for selection within the tool for a specific reactor design (i.e. LWR or research reactors). The user can select the transient(s) desired, and ASAG will automatically prepare and run them. The transient results are then automatically assessed against a database of established acceptance criteria according to IAEA safety standards. With the increasing usage of the tool, a neuronal network could update boundary conditions and input parameters for the heuristic model generation with the AMG based on whether acceptance criteria are met.

Based on its safety assessment, ASAG will provide a list of the bounding transients for the selected reactor design and their safety margins accompanied by the selected analysis conditions and why they were assumed. Should there be changes or updates necessary, the whole analysis is easily rerunnable to deliver an updated result. This would be a big advantage in comparison to the current state of the art, in which repeating a safety case is often a very costly process and therefore often not undertaken.

4 Prototypical application of RESA-TX toolbox

The RESA-TX toolbox as well as its tools AMG, AMV and ASAG are software which undergoes continuous improvements and developments. Different single tests have been carried out till now to prove the correct implementation and the functionality of each tool.

In the following a prototypical application of the tools AMG and AMV will be presented.

4.1 Application of the AMG

To demonstrate the ability of the AMG tool to generate a code-specific thermal-hydraulic model of a specific component of the NPP, the automatic creation of a reactor

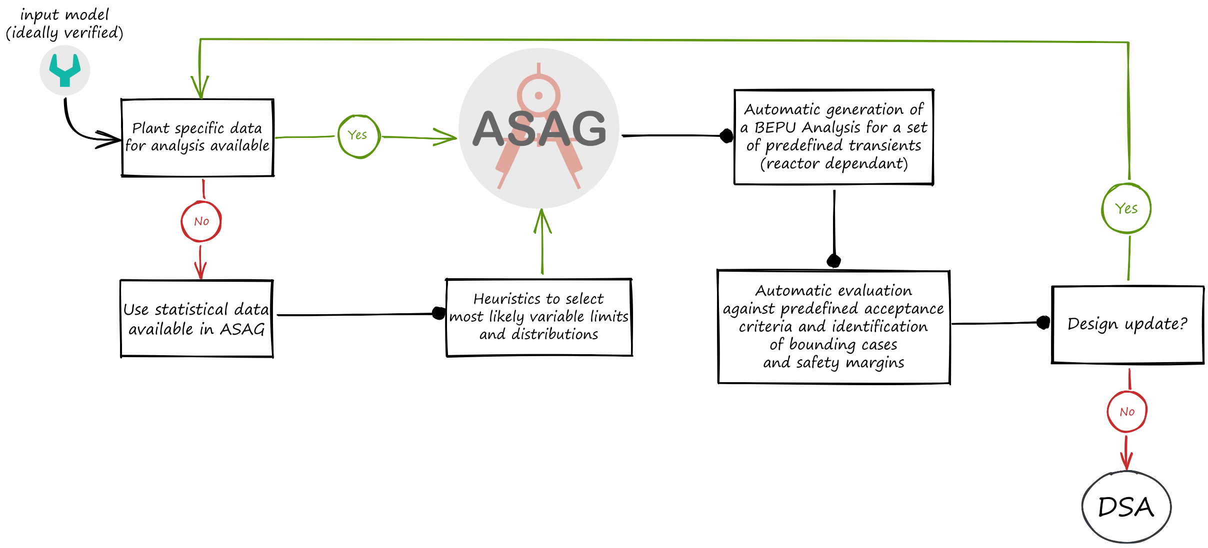


Fig. 6. Flow diagram for the Automatic Safety Analysis Generator (ASAG).

pressure vessels model for a KWU plant type using the ATHLET code is presented as a prototype.

Figure 7 shows a schematic representation of the steps required for the automatic generation of a simple thermal-hydraulic model of the RPV.

The implemented heuristic approach needs the following parameters which are defined by the RESA-TX user in order to start the generation process:

– reactor thermal power.
– Fuel assembly lattice.
– Number of fuel assemblies in the core.

In the example of Figure 7, a reactor thermal power of 4.0 GW, a fuel assembly lattice of 16×16 rods and a total number of 193 fuel assemblies in the core have been defined. Once the user inputs the parameter value in the AMG, the tool automatically selected the 4-loop geometry and generated the thermal-hydraulic RPV model for the ATHLET code. This is possible since every object, composing the RPV such as the upper and lower plenum or the core has been parametrized in the algorithm. The parameterization allows for a generation of even complex geometries on the basis of a few relevant dimensions using algebraic equations. An example is given in Figure 8 for the generation of a core channel model. The algorithm selects the core configuration for the 4-loop KWU-PWR and calculates every single parameter that describes the core channel geometry (e.g. length, cross-flow area and form losses) according to predefined equations. In the next step, the algorithm checks, if the calculated data for the core channel model is consistent with the geometry of the other sub-components of the RPV and if the data are exported in the code-specific data format (e.g. ATHLET ASCII-files). Some variables like the axial nodalisation are predefined and selected according to the validation report of the specific system code.

A further option in the AMG is available, which starts a test simulation for the generated geometry for check purposes. The results for the prototypical application are presented in Figure 9.

4.2 Application of the AMV

As a prototypical application of the AMV tool, each step of the automatic verification procedure for a generic PWR (KWU-type) input deck is presented in this chapter.

After generating the different thermal-hydraulic components of the primary and secondary sides, the input deck of the NPP has been loaded into a database structure (repository). A defined set of runs including plant transients (e.g. inadvertent opening of one main steam safety valve) and accident scenarios (e.g. intermediate break LOCA) has been selected and the verification process is initiated.

For each transient and accident, a protocol containing a list of the operator actions as defined in the operating manual is implemented (see Fig. 10). The manual actions are triggered when specific conditions are fulfilled. The file containing the listed actions as executable commands is loaded by the Simulation Controller which automatically executes and monitors the simulation.

The Continuous Integration Module, which is based on the GitLab [6] platform, automatically triggers and coordinates parallel simulations.

To prove the quality of the achieved results for each available transient the VDG module is automatically activated, which contains all the information of the acceptance corridors for each relevant thermal-hydraulic parameter (i.e. coolant temperature and pressure) and logical signal (i.e. coolant pump trip and SCRAM). This acceptance corridor for a specific parameter and a defined event is generated as a result of an algorithm, which evaluates the simulation results from previous runs stored in a database for the defined case using a 4-loop KWU-PWR.

Figure 11 shows as an example the results of the coolant pressure in the pressurised for the event

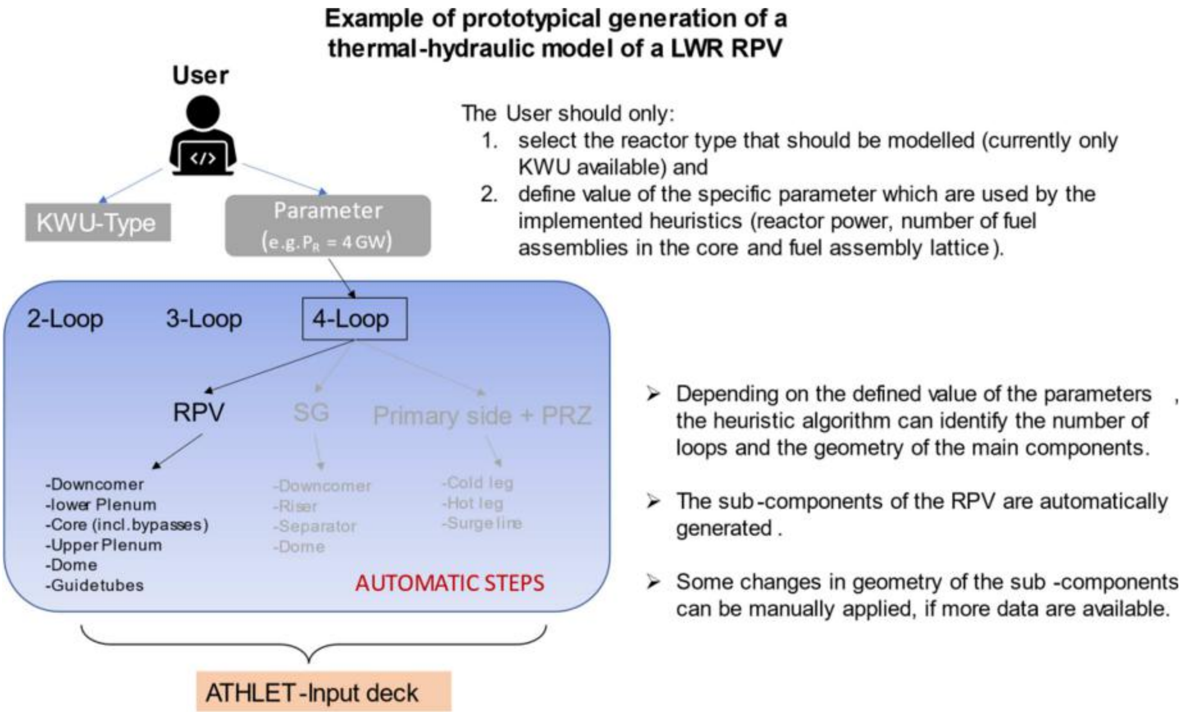


Fig. 7. Schematic representation of the steps required for the automatic generation of thermal-hydraulic models of a RPV.

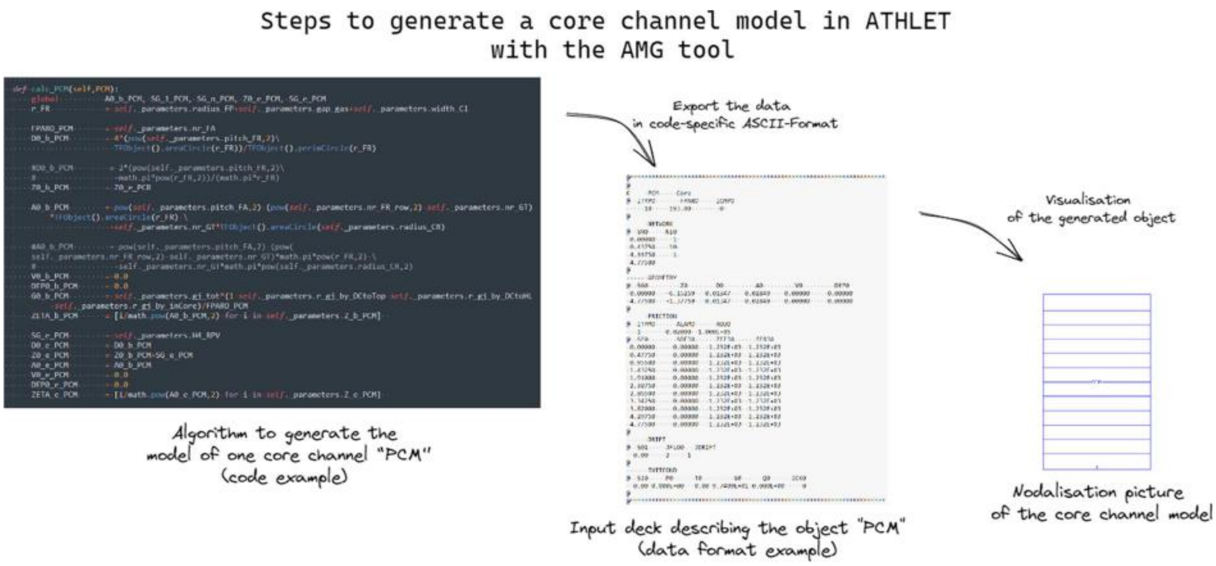
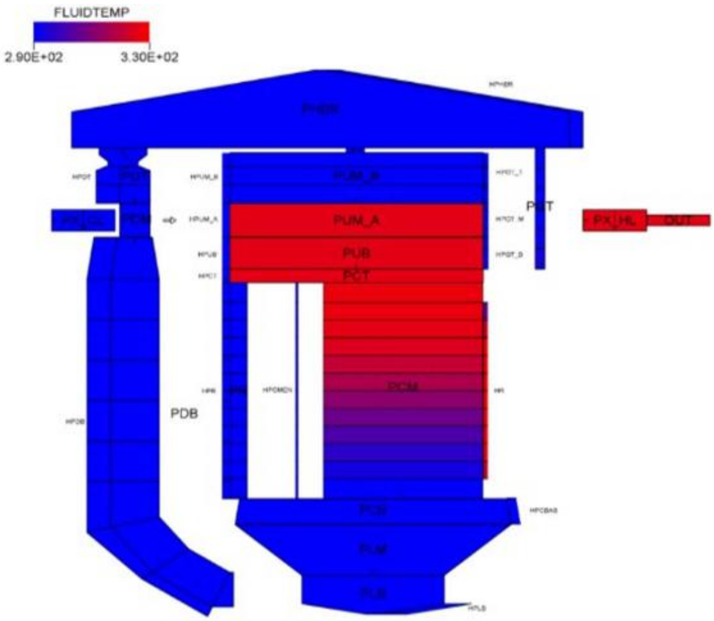


Fig. 8. Steps to generate one core channel model in ATHLET with the AMG tool.

"inadvertent opening of one main steam safety valve at full power". As soon as the failure occurs (t = 0 s), a sharp increase of the main steam flow takes place and temperature and pressure on the primary side decrease. The following increase of pressure up to 16.1 MPa is mainly due to the RCCA withdrawal, which is acted by the average coolant temperature control system to compensate for the temperature decrease of the coolant. The following decrease in the pressure is due to the RCCA insertion triggered by the power limitation system when the thermal power overcomes the 103% limit.

In the left plot of Figure 11, the results of different runs for this specific event are presented, which are stored in the VDG submodule. The implemented algorithm calculates the upper and lower bounds for the parameter "pressure" and additional limit curves, which have a gap of ±5% to the upper and lower bounds. The upper and lower bounds (blue curves) as well as the upper and lower limit curves (dashed curves) are plotted in the graphic on the right side. The graph also contains information on the current run (black curve) as well as the results from the last accepted verification run (pink curve). In this example,



Parameter	4-Loop
Thermal power [MW]	4000.0
Fuel assembly lattice	16x16
Number of spacer grids	9
Coolant inlet temperature [°C]	290.0
Coolant outlet temperature [°C]	325.17
Temperature increase [°C]	35.17
Total RPV mass flow [kg/s]	20 000
Pressure at RPV-inlet [bar]	160.3
Pressure at RPV-outlet [bar]	157.01
Total RPV pressure losses [bar]	3.29

Fig. 9. Automatically generated model of RPV (KWU reactor type) by the AMG tool using ATHLET-code and thermal-hydraulic parameters calculated by ATHLET using the RPV-model.

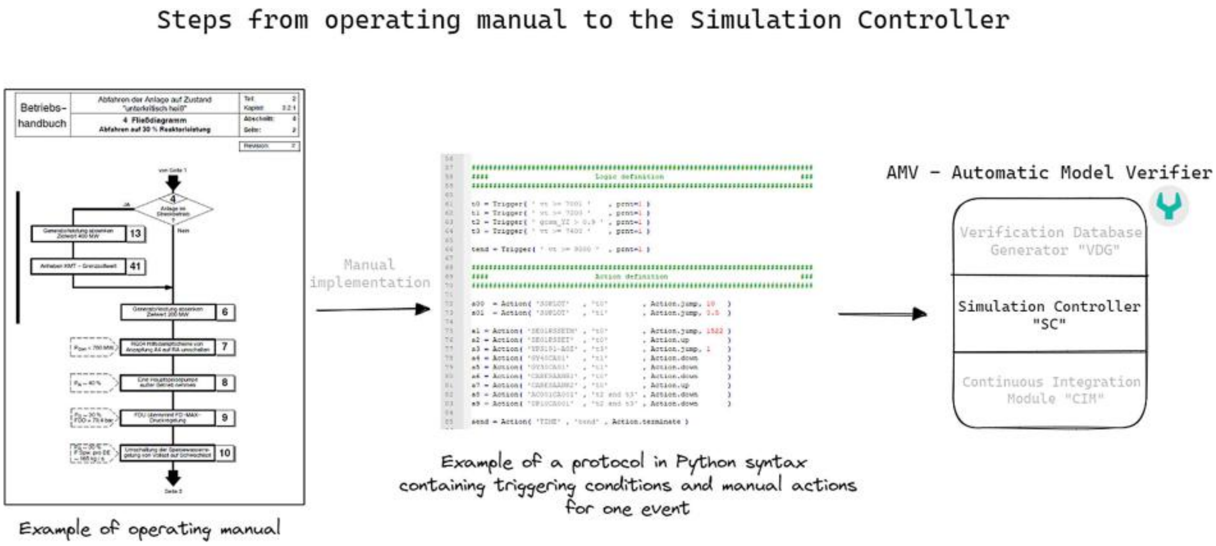


Fig. 10. Logging and implementation of manual actions in a protocol file for the automatic simulation control.

the results of the actual run differ from the previous ones at ca. $t = 500$ s. The violation of the upper bound is saved in a report and the user is informed to take action.

5 Main users and applications

The proposed idea of the automatic REactor Safety Analysis ToolboX RESA-TX has three main user groups and numerous applications:

- for nuclear regulators, RESA-TX can help support their assessment with a safety analysis, be it either in detail for confirmatory analysis purposes of a design assessment, or coarser to support an assessment that needs to be made with time constraints, e.g., a regulator reaction to an operational occurrence or an accident scenario. In the case of design assessment, the regulator would gain the ability to conduct a confirmatory safety analysis to support their assessment without necessarily requiring external services. In case of a quick safety assessment of an event, the regulator will gain the very powerful ability to conduct a fast but technically grounded analysis.
- For the nuclear industry, the applications of RESA-TX range from the initial generation of a safety case for licensees to the continuous (re)running of certain transients for nuclear operators after plant design

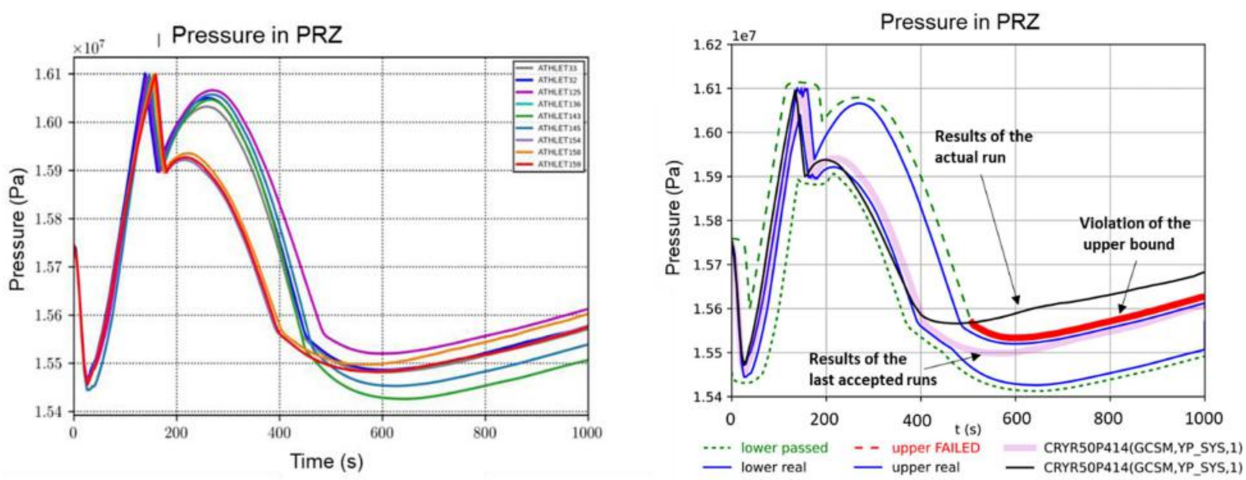


Fig. 11. Example of prototypical application of the AMV tool to the event "inadvertent opening of one main steam safety valve at full power".

enhancements. A plant operator could use the toolbox to generate a very detailed and highly verified plant model given large data availability. The result would be a precise and automated tool able to calculate or rerun all desired transients at any time, which could be used for decades into the future with minor maintenance requirements and allow the operator to conduct an updated safety analysis quickly and with minimal effort throughout the lifetime of the plant.

- For nuclear code developers, RESA-TX could translate into enormous time savings in the code validation and verification process given its automated and modular nature. As a code developer, a model of for example a research reactor or an experimental facility can be built with low effort using AMG and continuous code developments can be validated and/or verified automatically and regularly with AMV by clicking only a few buttons.

An example of market potential is the shortening of approval times in licensing projects. Applying RESA-TX would allow to a repeat of a safety analysis whenever necessary and quickly resolve any potential regulatory issue with low effort and increased added value, contributing to an increase in reactor safety.

6 Conclusion

GRS supports nuclear regulatory bodies worldwide, including the UK, the Netherlands, Switzerland and Germany. GRS regularly participates in operational safety assessments as well as licensing of new build designs. GRS are also code developers and have a large implication in nuclear safety research. Thanks to this valuable combination in our daily work, we have a good knowledge of the current state of the art in DSA and safety analysis code development. In the current state of the art, DSA is a complex and thus error-prone process that is highly time-consuming and repetitive. The reliability of the result is strongly dependent on the availability of plant data and expert know-how. The idea behind RESA-TX is based on our experience and knowledge accumulated over years of model development and conductance of DSA and complemented by powerful software that allows reaching a high degree of automatisation to counteract the issues described above. The resulting product is a toolbox made of three tools that base on our latest software developments and build upon them to achieve an advanced automated approach to DSA. The toolbox is flexibly applicable since the tools can be used independently. A centralised data source of information relevant to DSA ranking from plant design and characteristics to plant behaviour to safety analysis modelling and methods, conventions and acceptance criteria is inherent to the tool. To enable managing this large amount of information, big data algorithms are adopted. Thanks to learning feedback loops, the databases inherent to RESA-TX are enhanced with repeated usage. Through these innovations, a big increase in safety is achieved, since the automatic nature allows the frequent rerunning of a large set of safety analyses that would not be feasible otherwise. Also, an increase in the reliability of both codes and models is achieved due to the possibility of constant rerunning.

Conflict of interests

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

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Data availability statement

The data that support the findings of this study are not openly available due to the presence of restrictive plant data.

Author contribution statement

The authors confirm contribution to the paper as follows: study conception and design: A. Cuesta, S. Palazzo, S. Wenzel; data collection: A. Cuesta, S. Palazzo, S. Wenzel; analysis and interpretation of results: S. Palazzo; draft manuscript preparation: A. Cuesta, S. Palazzo, S. Wenzel. All authors reviewed the results and approved the final version of the manuscript.

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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

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
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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.

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)** **P11**: Open access of research infrastructures, **Rachel Eloirdi (JRC)**		
15:40	**Coffee Break**			
		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)**
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** **P7:** Robotics and drone program, **Anders Wik – Vattenfall** **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)** **P7:** Unique for SMR spent fuel and waste management, **Timothy Schatz (VTT)** **P8:** SRA documentation development from projects SHARE and PREDIS, **Anthony Banford (NNL) and Erika Holt (VTT)**
17:00			**P9:** AERACCESS, **Jean-Luc AYRAL** **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

Sustainable Nuclear Energy Technology Platform

SNETP REPORT

SNETP FORUM 2022 - Proceedings

SNETP Association

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The SNETP FORUM 2022 Proceedings report was prepared by the SNETP Association.

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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 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, **Yves Desbazeille (Foratom)** **P2:** Market analysis, **Bernard Dereeper** **P3:** Supply Chain, **Roberto Adinolfi (Ansaldo)**	**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 component integrity concepts for LWRs and activities of CEN Workshop 64 Prospective Group 1, **Bruno Autrusson (nuclear consultant), Manuela Triay (Framatome)** **P2:** Ongoing development activities on RCC-MRx and its enlargement to different Gen IV systems, **Karl-Fredrik Nilsson (JRC), Cecile Petesch (CEA)** **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)** **P2**: Introductory Scene Setter (new Euratom projects, NEA, GIF, IAEA), **Michael Fütterer (JRC)** **P3**: The European chemical industry on the path to climate neutrality, **Nicola Rega (CEFIC)** **P4**: Deployment of nuclear energy in deep decarbonization of the energy system, **Andre Faaij (TNO)** **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** **P5:** Core and Fuel - **Eric Hanus (CEA)** **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)** **P5**: Possibilities of the BR2 reactor as a support facility to materials and fuels R&D, **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), Pekka Valikangas (STUK), Tadeusz Szczesiak (ENSI), Alexis Courtois (EDF)** **P5:** Qualification of electrical equipment according to RCC-E **Benedict-John Willey (AFCEN)** **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)** **P7**: NOMATEN Centre of Excellence in Multifunctional Materials for Industrial and Medical Applications, **Jacek Jagielski (NCBJ)** **P8**: Exploring the deployment of advanced reactor systems for decarbonization of future energy generation: **Geert-Jan de Haas (NRG)** Wrap-up by **Ronald Schram (NRG)**
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** : Source Term Experimental Research - IPRESCA and OECD/NEA THEMIS Projects, **Sanjeev Gupta (Becker Technologies GmbH)** **P8**: COSMOS-H, **Stephan Gabriel (KIT)** **P9**: HFR / Pallas, **Ronald Schram (NRG)**	**P1:** The Nuclear Digital Nuclear Initiative, **Benoît Levesque/Chai Koren – EDF** **P2:** Combination between Digital Twin and AI for anomaly detection for industrial processes, **Aurélien Schwartz - Métroscope, EDF group** **P3:** Data based solutions & performance 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	**P11:** Energy Well – Czech molten salt SMR concept, **David Harut – CVR** **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)** **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** **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 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)**
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** **P7:** Robotics and drone program, **Anders Wik – Vattenfall** **P8:** AERACCESS, **Jean-Luc AYRAL**	**P6:** Advanced Separation for the Optimum management of spent Fuel – portioning, fuel fabrication, secondary waste streams, **Christophe Bruggeman (SCK CEN)** **P7a:** Unique for SMR spent fuel and waste management, **Timothy Schatz (VTT)** **P7b:** Towards harmonised practices, regulations and standards in waste management and decommissioning (EU-HARPERS), **Réka Szőke (IFE)** **P8:** SRA documentation development from projects SHARE and PREDIS, **Anthony Banford (NNL) and Erika Holt (VTT)**
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.

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
EURADWASTE'22
May 30 to June 3, 2022 | Lyon, France


L'ASSEMBLÉE
HÉMICYCLE GEORGES POMPIDOU


FISA 2022
EURADWASTE'22


FISA 2022
EURADWASTE'22
May 30 to June 3, 2022 | Lyon, France
10TH EDITION

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 Workshop on the achievements of EURAD-1 and the preparation of EURAD-2 On Monday 30 May 2022 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 Discussion and exchange of views 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** Lorenzo Malerba, CIEMAT, ORIENT-NM Coordinator **ORIENT-NM Vision and Strategic Research Agenda** Marjorie Bertolus, CEA **Partnership structure, governance and analysis of resources** Lorenzo Malerba, CIEMAT, on behalf of Petri Kinnunen, VTT **Partnership interaction with stakeholders and use of infrastructures** Angelika Bohnstedt, KIT
15:30 – 16:00	**Coffee Break**
16:00 – 17:00	**Member State Representatives' comments and recommendations** 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** All
18:00	**Workshop closure**

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FISA 2022

ORIENT-NM - 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*

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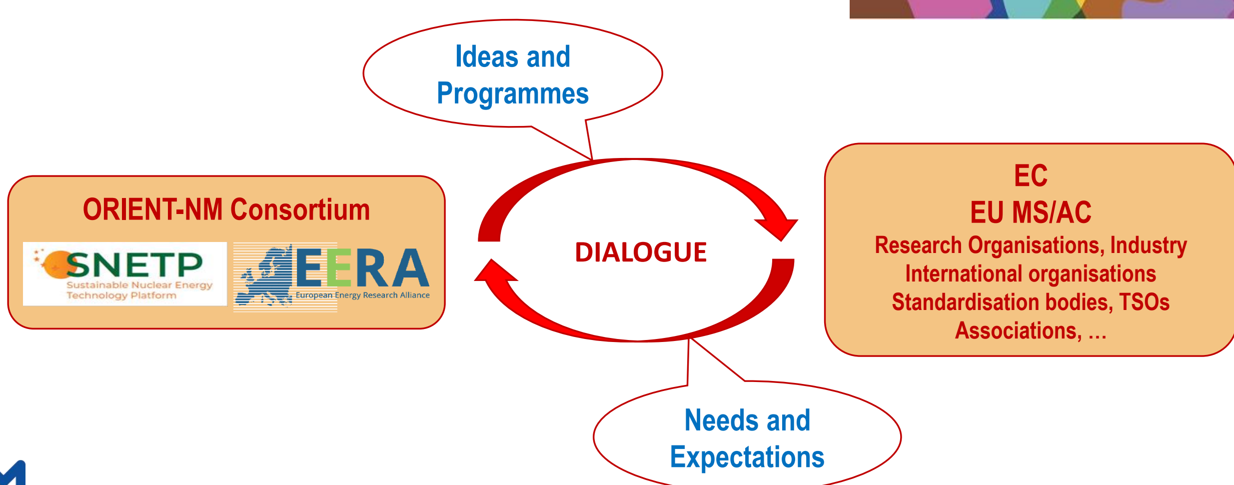
How is ORIENT-NM working?

Dialogue & Inclusiveness



ORIENT NM

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

Following Presentations

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

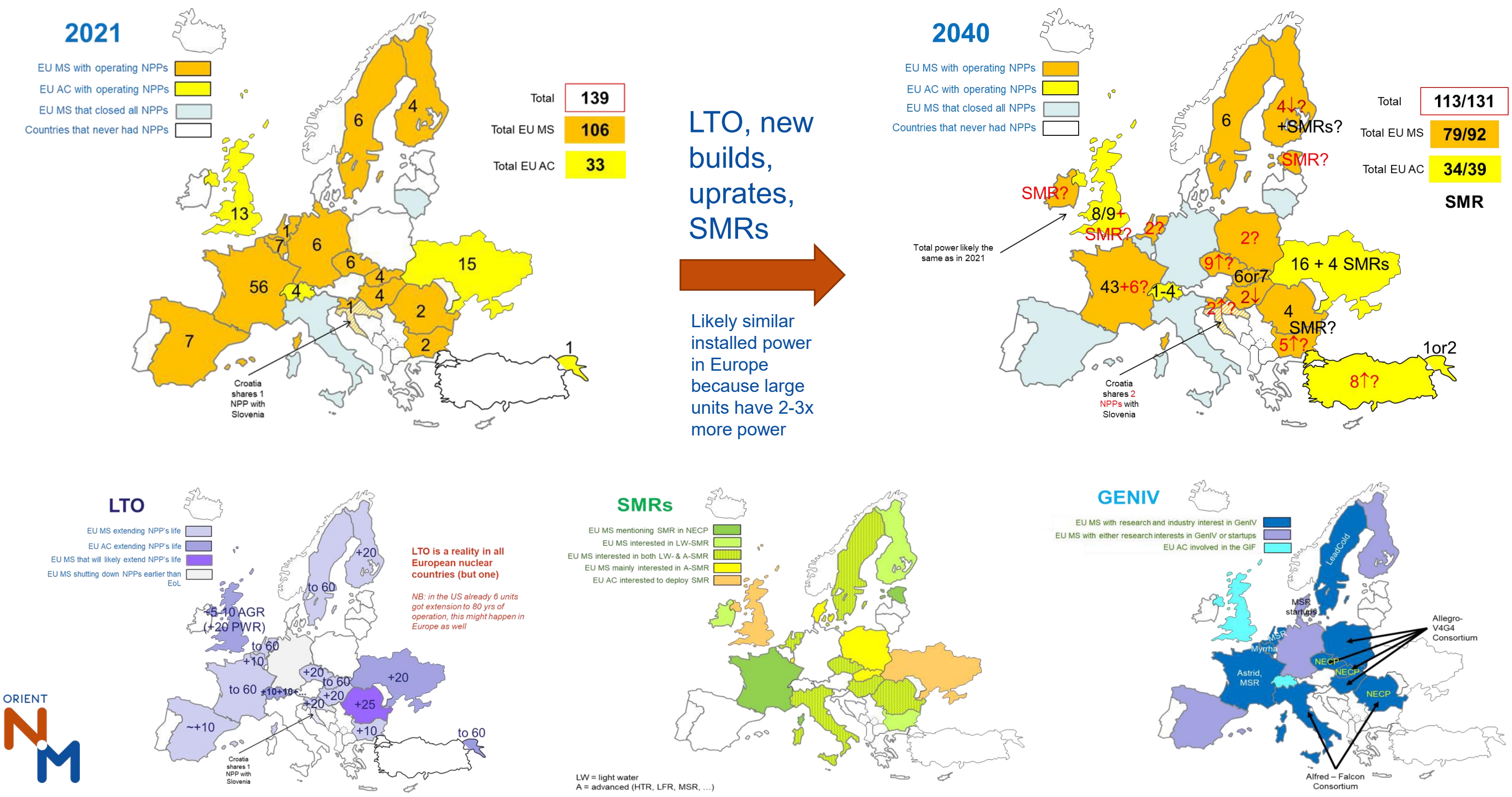
Coming up:

- 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

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

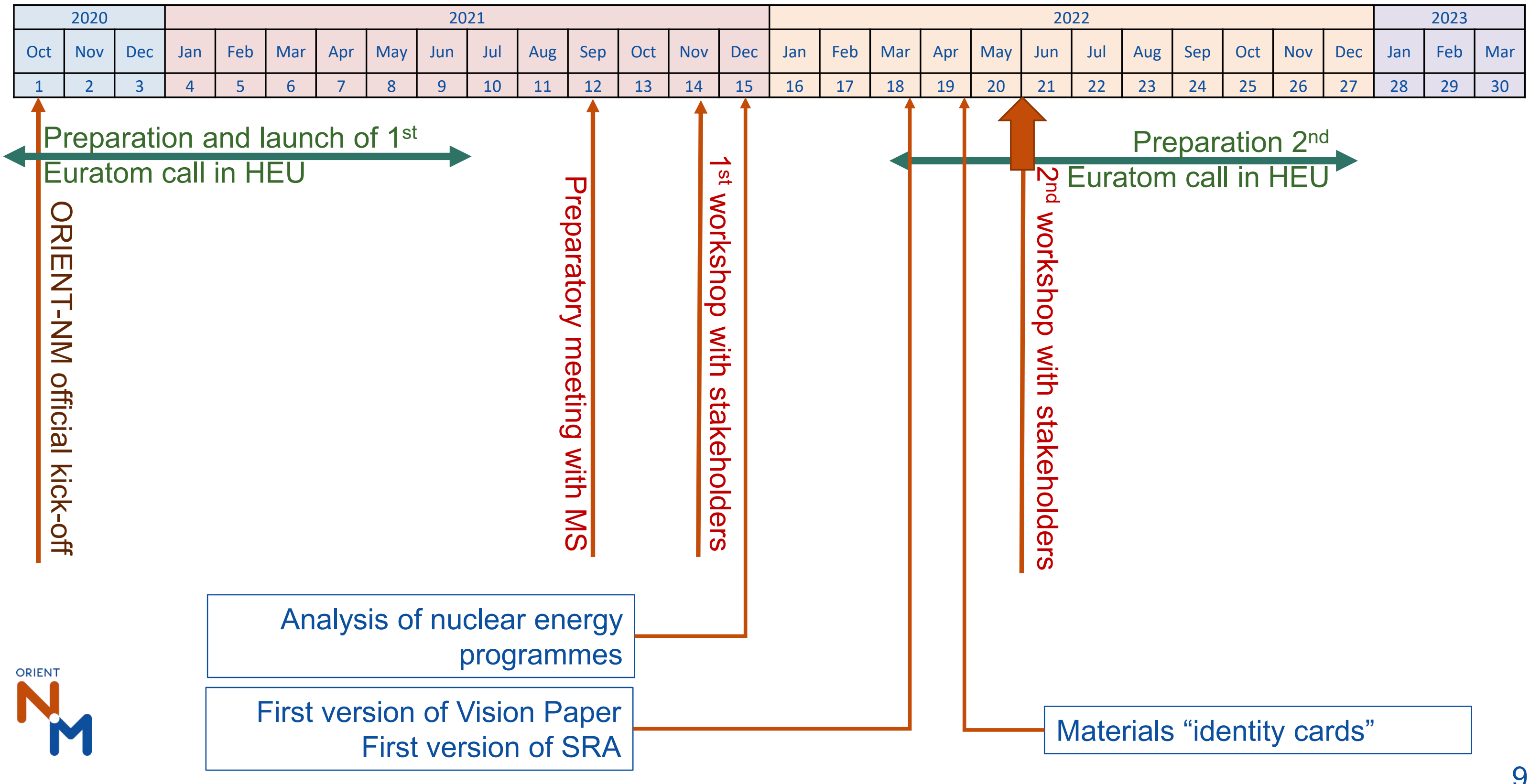
⇒ Deployment of light water SMRs within the next decade

⇒ 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

Timing of ORIENT-NM



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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:

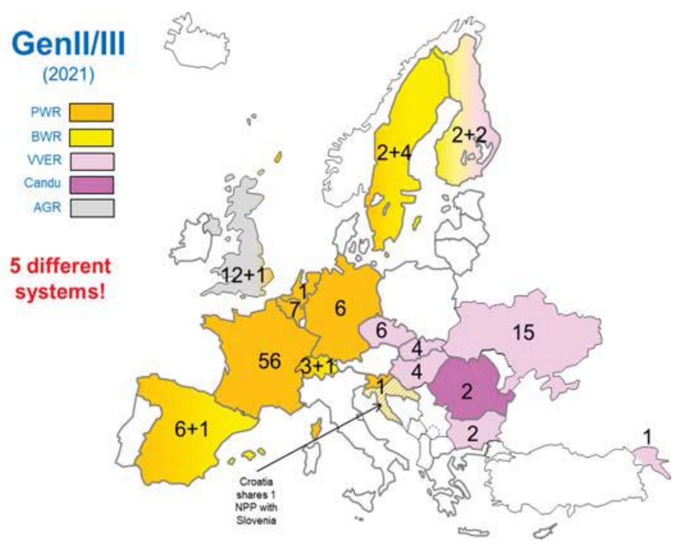
- Which systems
- Which materials: identity cards
- ORIENT-NM Vision
- Research lines and grand goals
- Perimeter of activities
- Timing and Planning
- Link with national programmes and other initiatives

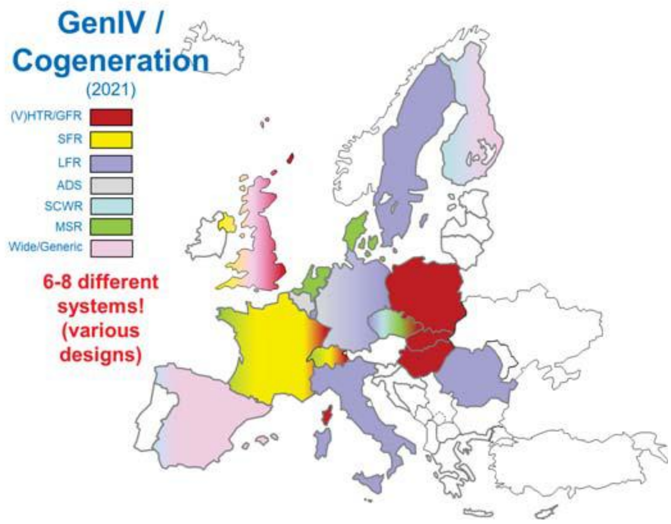
What is ORIENT-NM producing?

1. Single Vision Strategic Reasearch Agenda on Nuclear Materials 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

3

Which nuclear systems? Europe is united in diversity





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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 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! Defines neutron spectrum, burnup, etc.	Define neutron spectrum and criticality

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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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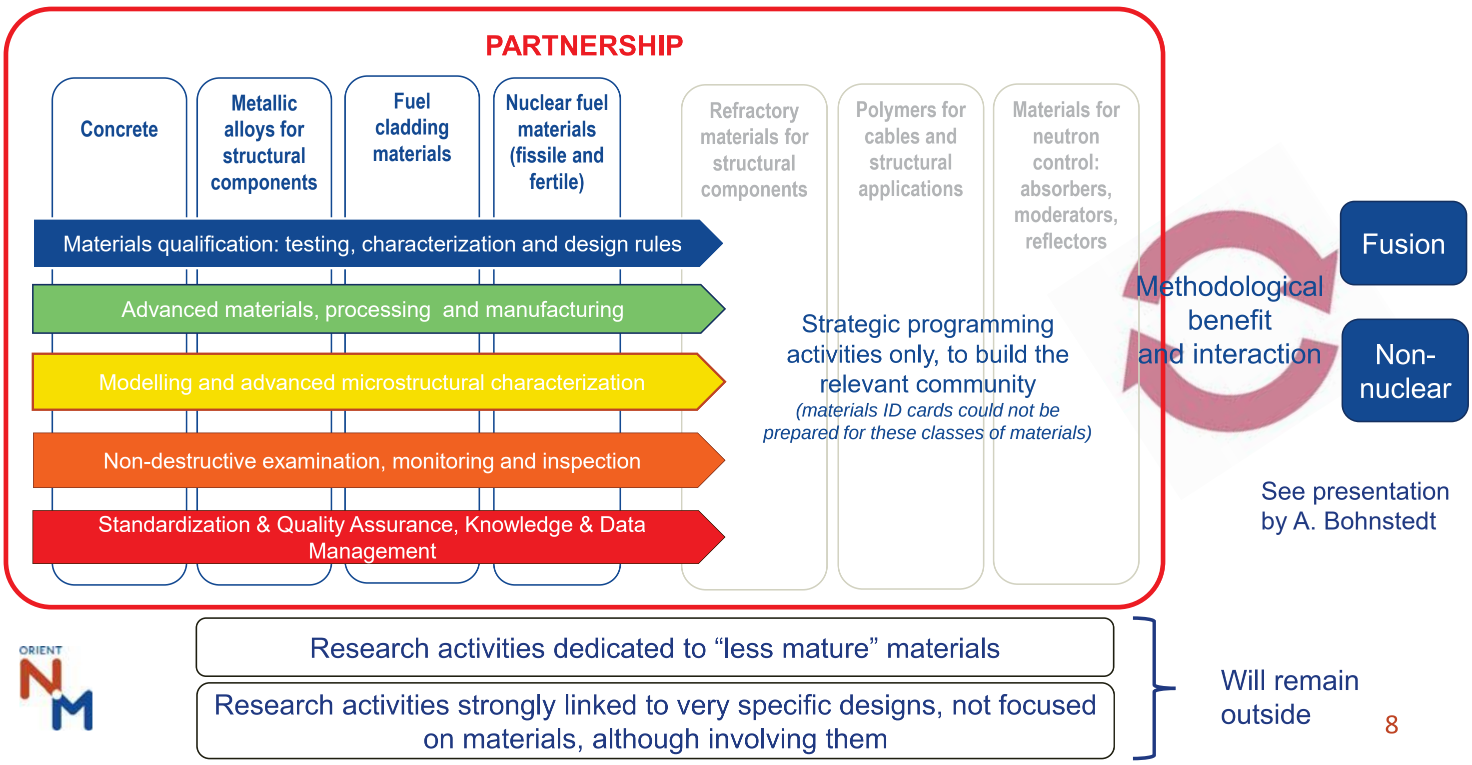
ORIENT-NM Vision

- **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

Grand goals will be reached on **case studies** with sufficiently ample validity

Criterion of success: **extensibility of methodology** rather than specific application

Infrastructures

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

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[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

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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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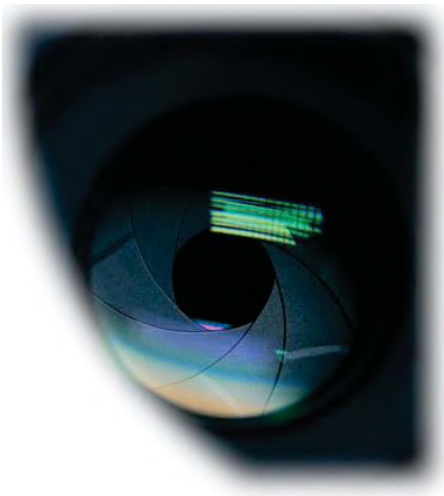
Work done in ORIENT-NM for structure and governance



- 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

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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 <u>co-funded</u> 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%**

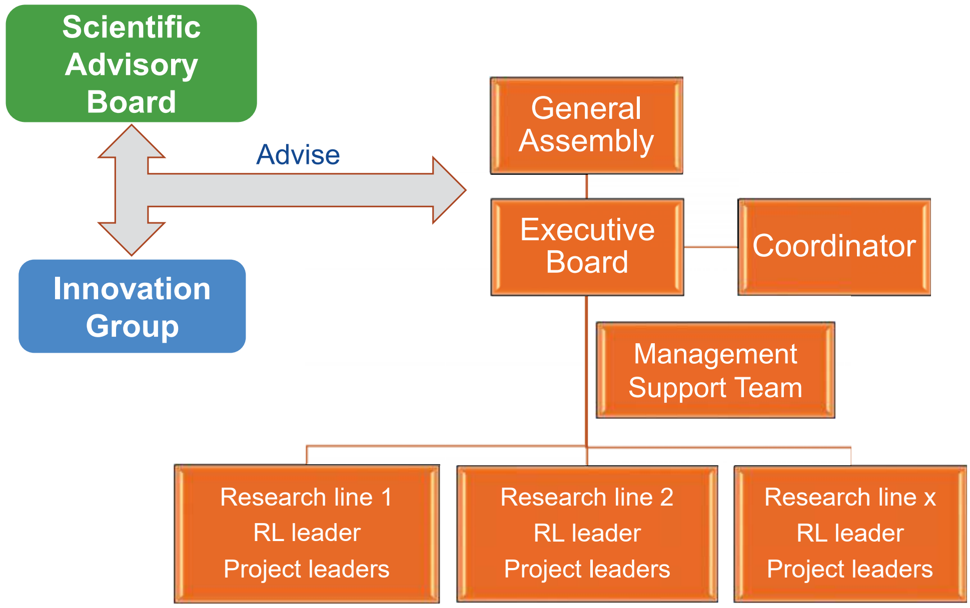
- **Co-funding scheme**
- The CEP agreement is signed by **Programme owners** (ministries, funding agencies...) and/or **Programme Managers** (usually large national research institutes), which receive a **clear mandate** from the Programme Owners
  - <u>This has not been successful in other CEP´s</u>: 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

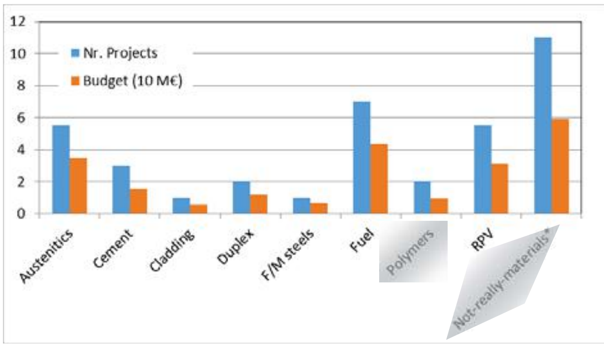
disadvantage: it may prove very difficult to agree on case-studies

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)

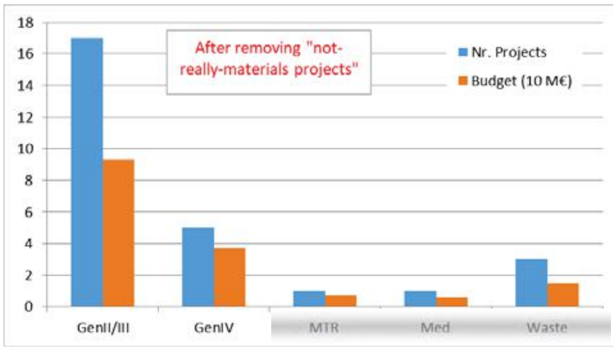


38 PROJECTS
217.5 M€

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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Side events

ORIENT-NM - Organisation of the European Research Community on Nuclear Materials

Partnership interaction with stakeholders and use of infrastructures

A. Bohnstedt, KIT, angelika.bohnstedt@kit.edu

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
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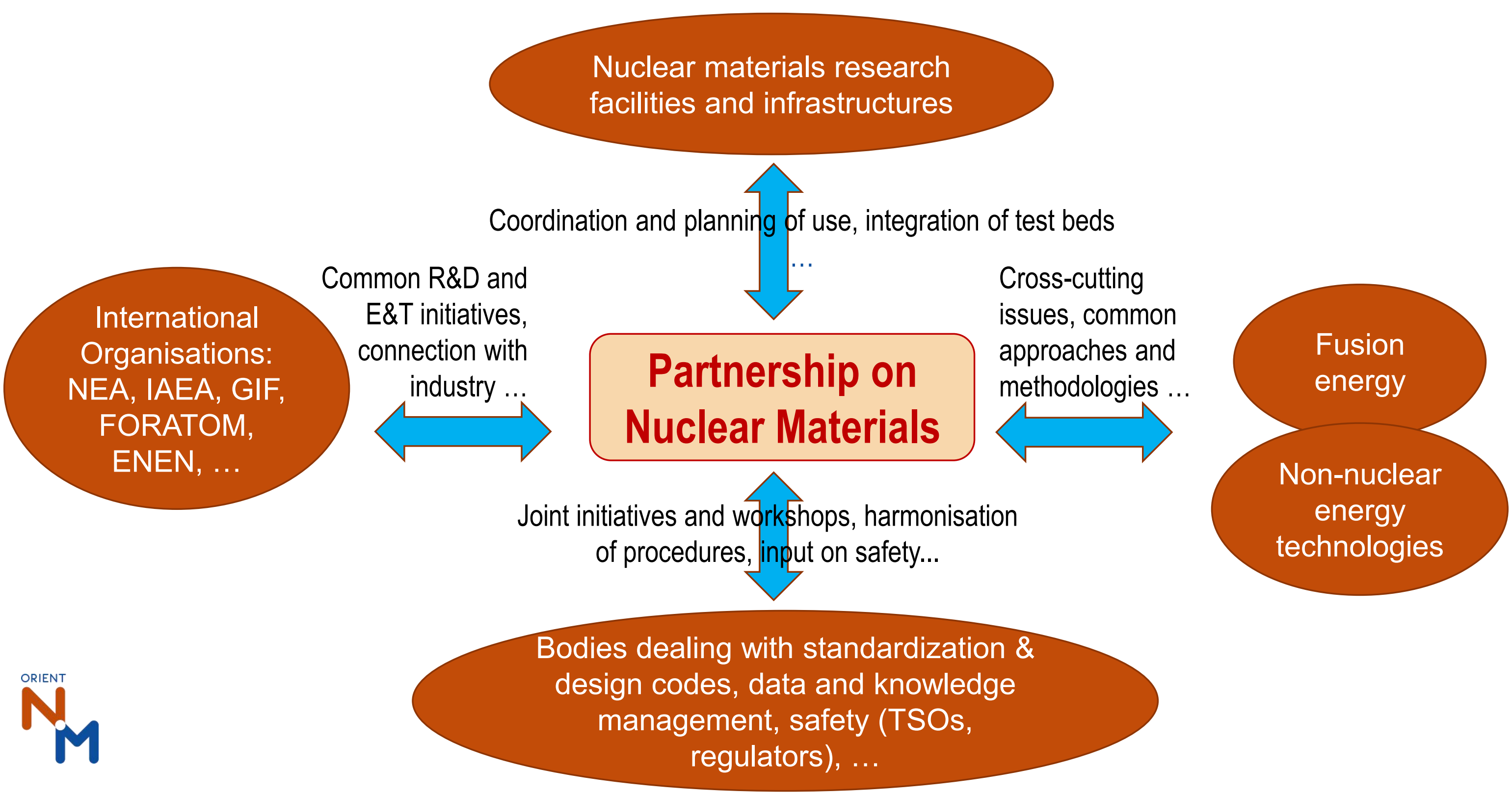
Partnership's expected interactions



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**.

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

NEA – NUCLEAR ENERGY AGENCY

IAEA: Possibility of agreeing on launching CRPs connected with CEP activities. Several sections potentially interested.

GEN IV International Forum – Expertise | Collaboration | Excellence: Collaboration through CEP experts participating in technical meetings of system steering committees.

FORATOM: FORATOM can act as springboard and amplifier of CEP activities towards industry. Networking events.

enen – european nuclear education network: ENEN may offer contact with students and universities. Collaboration through use of mobility programme and coordinated E&T initiatives on materials.

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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

ORIENT NM

Relationship with fusion

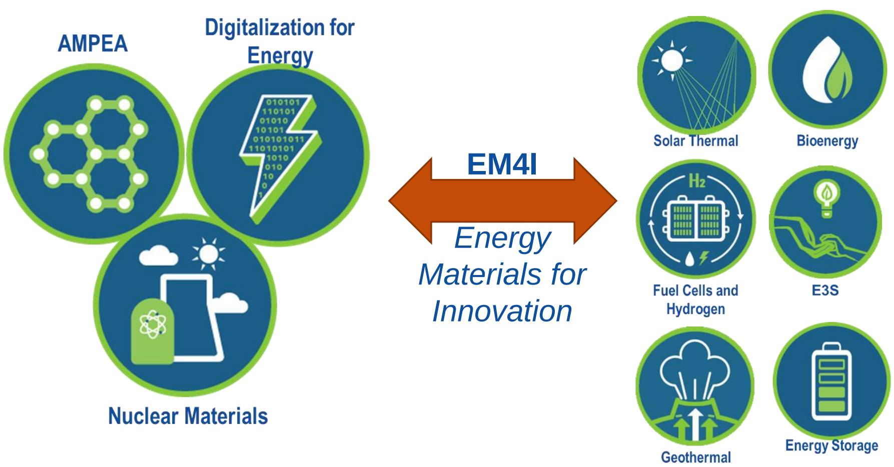
Outcome of the discussion during the 1st workshop: ***"The partnership should interact with the fusion community, by organising joint actions in which a structured dialogue for cross-fertilisation should be established between the two communities"***

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



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


MATERIALS 2030 MANIFESTO

Systemic Approach of Advanced Materials for Prosperity – A 2030 Perspective

7 February 2022

Vision

Materials, especially advanced materials, are the backbone and source of prosperity of an industrial society. In the context of the radical transformational changes of the 21st century, it is precisely these advanced materials that will play a decisive role.

Link was established with Materials Manifesto community

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

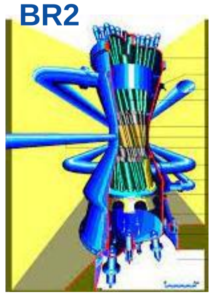
Nuclear-oriented materials qualification test-beds (n-test-beds)

Nuclear materials acceleration platforms (n-MAPs)

JHOP2040, OFFERR

FIDES (NEA-OECD)

BR2



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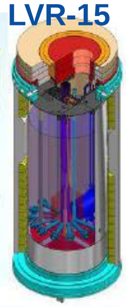
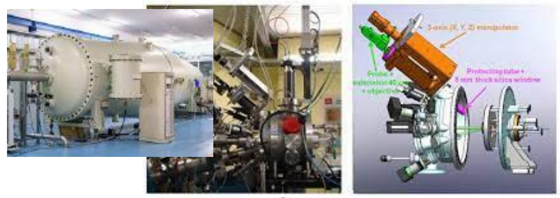


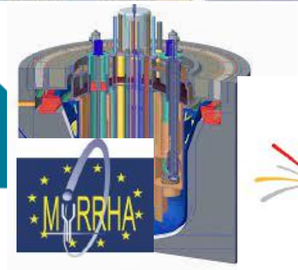
Neutrons in operation



Ions

PALLAS

JHR Jules Horowitz Reactor



IFMIF DONES GRANADA

Future neutrons (> 2030)

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Thank you!

www.eera-jpnm.eu/orient-nm

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FISA 2022, the 10th European Commission (EC) conference on Euratom Research and Training in Safety of Reactor Systems 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 EURADWASTE '22 conference on the management of radioactive waste and geological disposal in Europe. FISA 2022 technical sessions covered progress of the research carried out through 60 projects such as safety of existing nuclear installations; severe accidents prevention and mitigation including emergency management; advanced nuclear systems and fuel cycles for increased safety and sustainability, numerical simulation and digitalisation, innovative materials, low dose radiation protection, decommissioning, research infrastructures, education & training and mobility of researchers, as well as cross-cutting actions such as International Cooperation. The proceedings include written contributions from invited presentations and posters, session summaries and panel reports.

Studies and reports

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