European Commission

CONFERENCE PROCEEDINGS

Research and Innovation

Title of the publication

European Commission
Directorate-General for Research and Innovation
Directorate [Directorate letter] — [Directorate name *-see organigramme*]
Unit [Directorate letter.Unit number, *e.g. A.1*] — [Unit name *-see organigramme*]
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B-1049 Brussels

Printed by [Xxx] in [Country]

Manuscript completed in xxxx 201X.

Luxembourg: Publications Office of the European Union, 2019

Print	ISBN 978-92-79-98744-1	ISSN 978-92-79-98744-1	DOI: 10.2777/522041	Catalogue number: KI-01-19-009-EN-N
PDF	ISBN [number]	ISSN [number]	doi:[number]	[Catalogue number]
EPUB	ISBN [number]	ISSN [number]	doi:[number]	[Catalogue number]

EUROPEAN COMMISSION

PROCEEDINGS OF FISA 2019

[edited by A. Constantin]

Directorate-General for Research and Innovation
2019 [Name of the FP specific programme activity] EUR [number] EN

FOREWORD

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

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

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

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

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

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

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

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

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

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

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

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PATRICK CHILD

FISA 2019 – EURADWASTE '19

Keynote of Mr Patrick Child (EC, DG RTD), Deputy Director General, Research and Innovation, European Commission:

Euratom Research and Training and Horizon Europe framework programmes

Dear Minister,
Dear Senator,
Dear Honourable members,
Ladies and gentlemen,

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

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

Decarbonisation: Clean Planet for All

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

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

The EU committed to lead by example

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

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

Member States have very different views on nuclear energy

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

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

EURATOM as a platform to work together

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Future Euratom programme and Horizon Europe

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

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

- non-power applications such as the uses of ionising radiation, not only for medical applications, but also for industry, agriculture and space research.
- the creation of stronger synergies between nuclear research and other research areas through joint activities within the new research and innovation framework for 2021-2027, Horizon Europe.

- a single set of objectives, combining the indirect and direct action and we will also offer to all projects the possibility for access to our Joint Research Centre facilities and expertise.
- One overarching element of research is the human capital. It is imperative that we maintain and further enhance the number, the competences and the excellence of our research community, especially in the nuclear sector. For this reason, the Marie Skłodowska-Curie Actions will be opened up to Euratom researchers.

Conclusion

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

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

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

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

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

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

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

CHARLINA VITCHEVA

FISA 2019 – EURADWASTE '19

Keynote of Ms Charlina Vitcheva (EC, DG JRC), Deputy Director-General of the Joint Research Centre, European Commission:

JRC role in Euratom Research and Training and Horizon Europe

Dear Minister,
Dear Senator,
Distinguished guests,
Ladies and gentlemen:

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

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

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

The European Commission's Joint Research Centre

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

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

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

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

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

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

JRC research in nuclear safety, safeguards and security.

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

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

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

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

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

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

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

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

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

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

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

What lies ahead of us?

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

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

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

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

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

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

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

Thank you very much.

NICOLAE HURDUC

FISA 2019 – EURADWASTE '19

Keynote of Mr Nicolae Hurduc (Minister, RO)

Ministry of Research and Innovation of the Republic of Romania

Dear participants,

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

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

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

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

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

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

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

Nowadays the Romanian nuclear Agenda includes:

- operational safety of the the Nuclear Power Plant and other nuclear installations,
- the continuation of works at Cernavoda Unit 3 and Unit 4,
- Plant life extension for Cernavoda NPP Unit 1,
- Radioactive waste management (LILW repository construction, geological disposal strategy),
- ALFRED GenIV demonstrator implementation,
- Mining and environmental issues (site remediations).

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

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

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

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

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

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

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

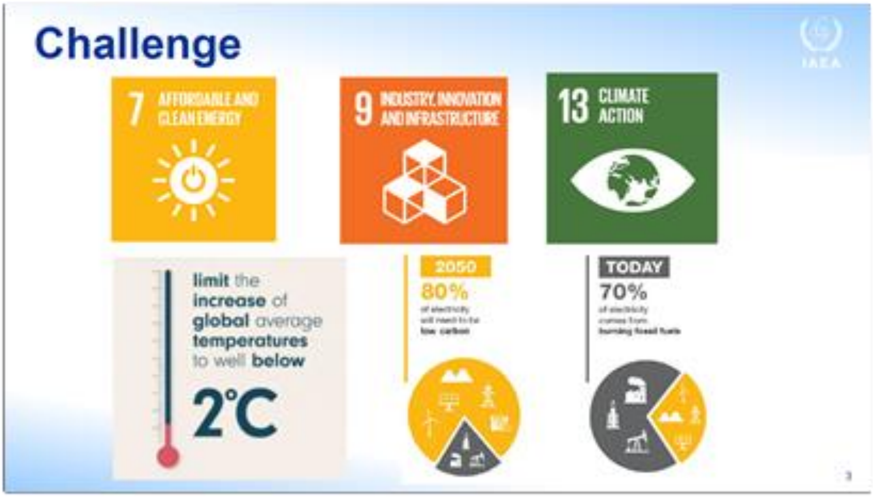
I wish a great success for your debate!

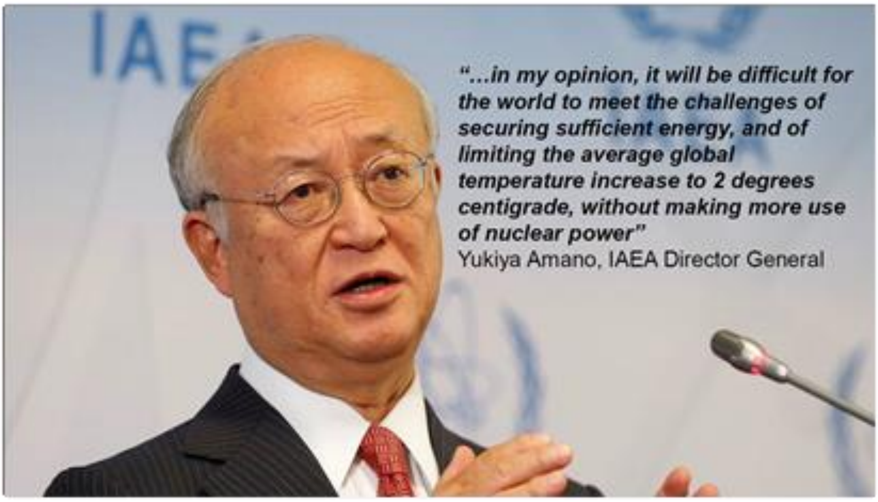
STEFANO MONTI

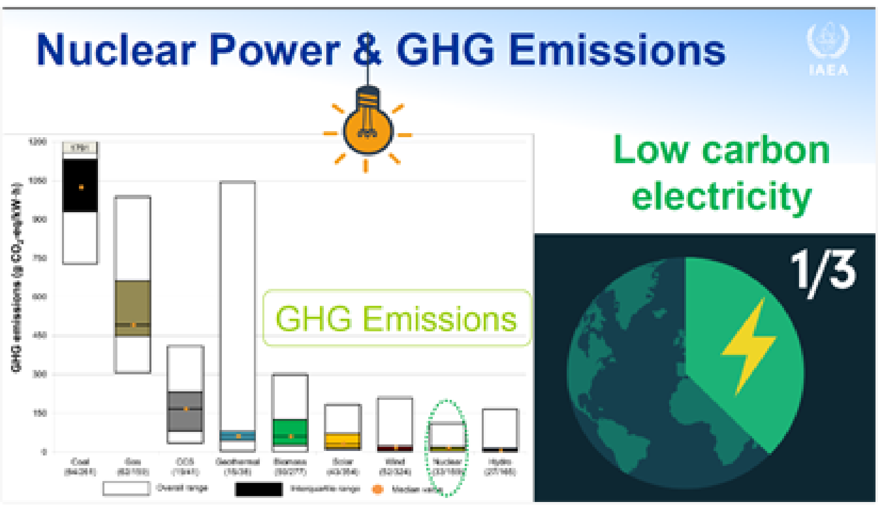
FISA 2019 – EURADWASTE '19

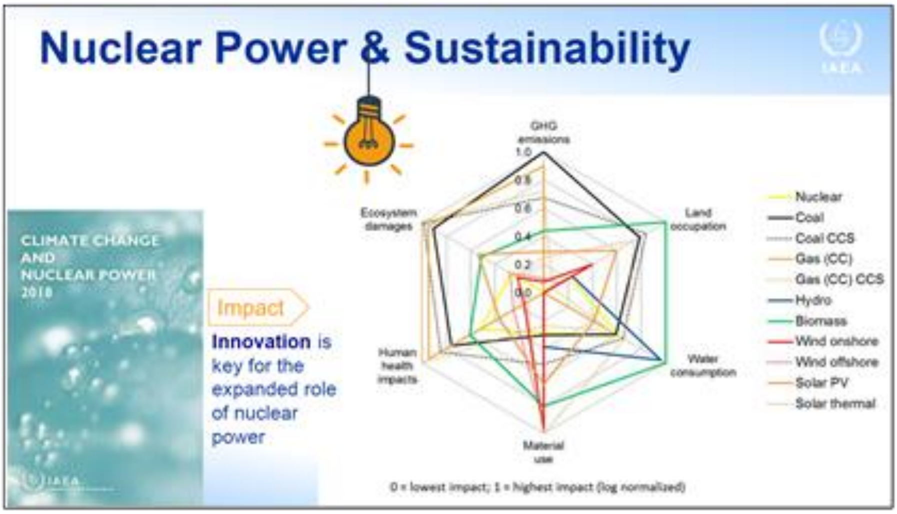
Keynote of Mr Stefano Monti (IAEA), Section Head, Nuclear Power Technology Development section, Division of Nuclear Power, Department of Nuclear Energy:

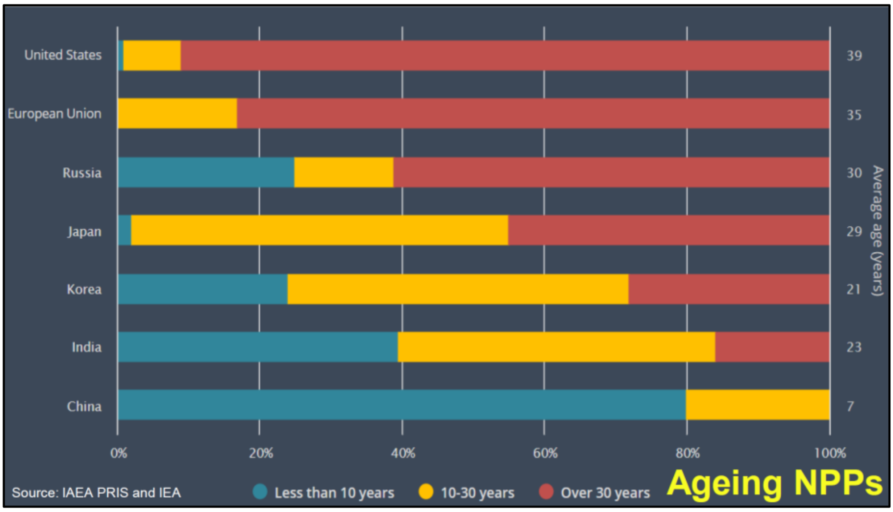
Research and Innovation for a safe, secure and safeguarded nuclear power in support of the UN Sustainable Development Goals


Challenge
7 AFFORDABLE AND CLEAN ENERGY
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE
13 CLIMATE ACTION
limit the increase of global average temperatures to well below
2°C
2050
80%
TODAY
70%


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


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

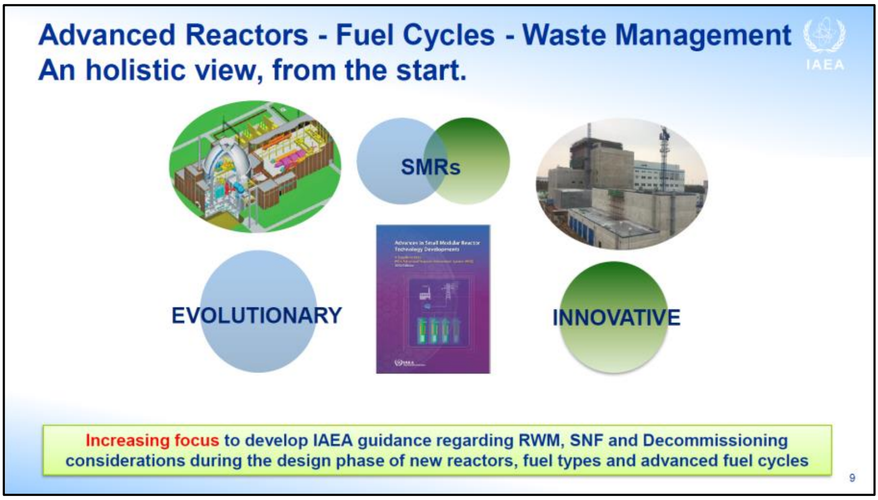




IAEA support of technical innovations to improve existing NPP fleet sustainability

IAEA

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


Advanced Reactors - Fuel Cycles - Waste Management
An holistic view, from the start.
IAEA
SMRs
EVOLUTIONARY
INNOVATIVE
Increasing focus to develop IAEA guidance regarding RWM, SNF and Decommissioning considerations during the design phase of new reactors, fuel types and advanced fuel cycles
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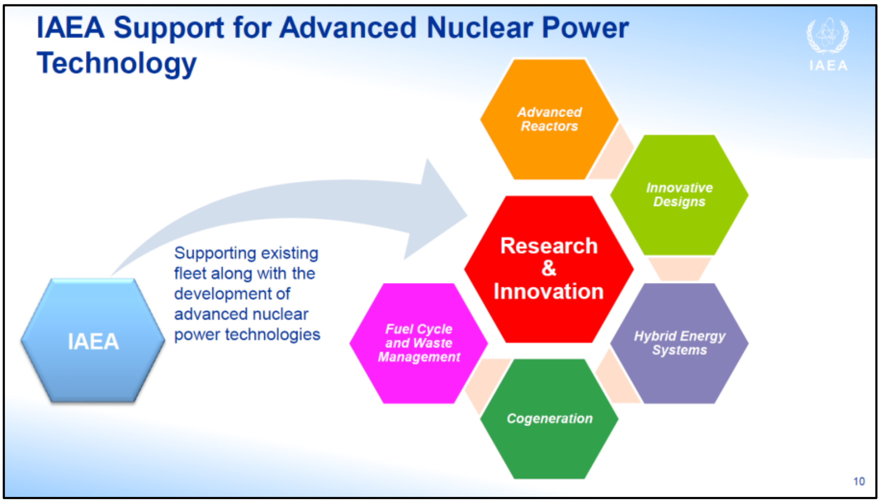
IAEA Support for Advanced Nuclear Power Technology
IAEA
IAEA
Supporting existing fleet along with the development of advanced nuclear power technologies
Advanced Reactors
Innovative Designs
Research & Innovation
Fuel Cycle and Waste Management
Hybrid Energy Systems
Cogeneration
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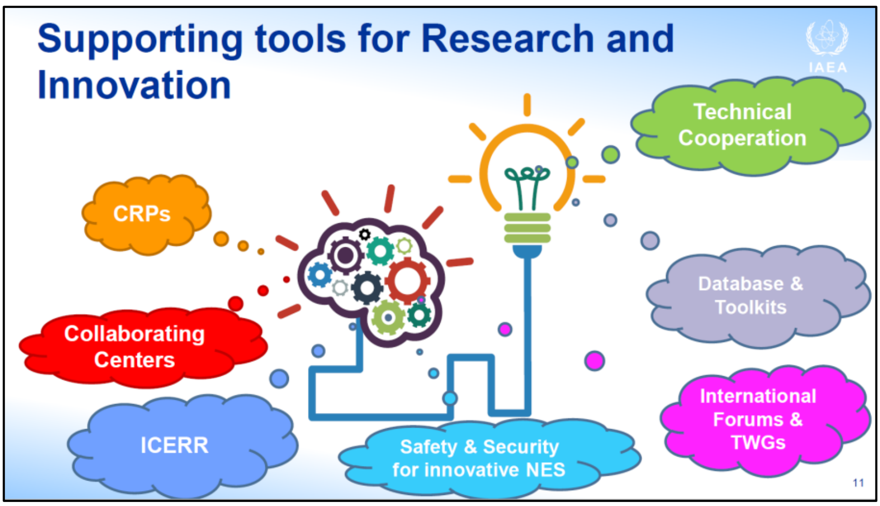
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IAEA
Technical Cooperation
CRPs
Database & Toolkits
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Coordinated Research Activities
IAEA
Uniting the World through Research
4
3%
44
36%
74
61%
~130 active CRPs (30 in NE), ~1600 research institutions involved
Nuclear Techniques for Development and Environmental Protection
Nuclear Power, Fuel Cycle and Nuclear Science
Nuclear Safety and Security
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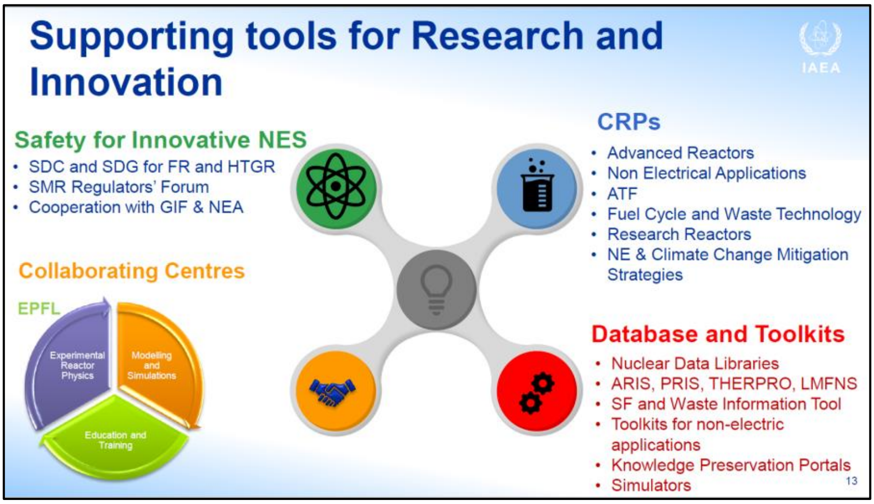

Supporting tools for Research and Innovation
IAEA
Safety for Innovative NES
SDC and SDG for FR and HTGR
SMR Regulators' Forum
Cooperation with GIF & NEA
Collaborating Centres
EPFL
Experimental Reactor Physics
Modelling and Simulations
Education and Training
CRPs
Advanced Reactors
Non Electrical Applications
ATF
Fuel Cycle and Waste Technology
Research Reactors
NE & Climate Change Mitigation Strategies
Database and Toolkits
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Investigate innovations in selected nuclear energy technologies, related R&D
Innovative institutional arrangements to facilitate their development and deployment.
02
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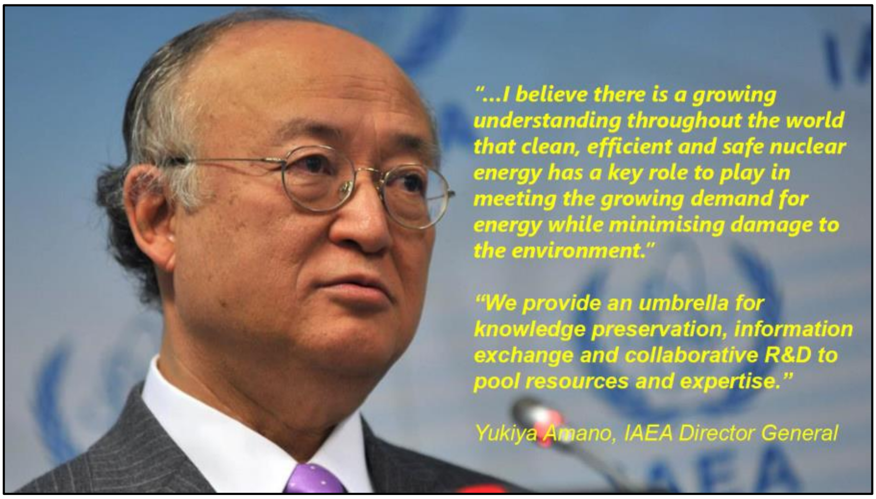
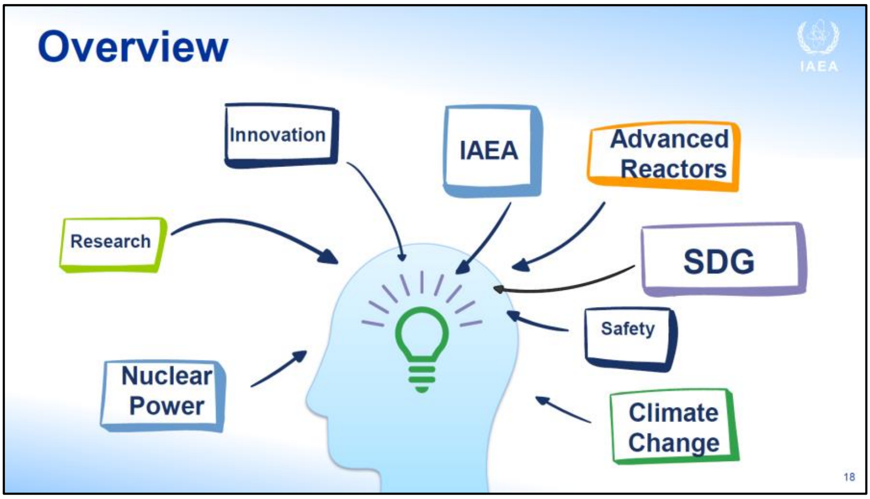
Sustainability assessment & strategies
Nuclear Energy System Assessment (NESA) using the INPRO Methodology
03
Dialogue and Outreach
INPRO Dialogue Forum
Regional Trainings
04


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


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


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
S.Monti@iaea.org
Atoms for peace and Development...


Overview
IAEA
Innovation
IAEA
Advanced Reactors
Research
SDG
Safety
Nuclear Power
Climate Change
18

DANIELA LULACHE

FISA 2019 – EURADWASTE '19

Keynote of Ms Daniela Lulache (OECD/NEA, FR), Head of Office of Policy and Coordination, OECD Nuclear Energy Agency

Nuclear Research and Innovation successes and accomplishments looking to the future

OECD BETTER POLICIES FOR BETTER LIVES

Nuclear Energy Agency

NEA NUCLEAR ENERGY AGENCY

The NEA Serves as a Framework to Address Global Challenges

The Role of the NEA is to:

- Foster international co-operation to develop the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes.
- Develop authoritative assessments and forge common understandings on key issues as input to government decisions on nuclear technology policy.
- Conduct multinational research into challenging scientific and technological issues.

33 NEA countries operate nearly 82% of the world's installed nuclear capacity

 3

OECD BETTER POLICIES FOR BETTER LIVES

Nuclear Energy Agency

NEA NUCLEAR ENERGY AGENCY

NEA Standing Technical Committees

Steering Committee for Nuclear Energy

- **CNRA** – Committee on Nuclear Regulatory Activities
- **CSNI** – Committee on the Safety of Nuclear Installations
- **RWMC** – Radioactive Waste Management Committee
- **CDLM** – Committee on Decommissioning of Nuclear Installations and Legacy Management
- **CRPPH** – Committee on Radiological Protection and Public Health
- **NLC** – Nuclear Law Committee
- **NDC** – Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle
- **NSC** – Nuclear Science Committee
- **MBDAV** – Management Board for the Development, Application and Validation of Nuclear Data and Codes

The NEA's committees bring together top governmental officials and technical specialists from NEA member countries and strategic partners to solve difficult problems, establish best practices and to promote international collaboration.

 3

OECD BETTER POLICIES FOR BETTER LIVES

Nuclear Energy Agency

NEA NUCLEAR ENERGY AGENCY

Major NEA Separately Funded Activities

NEA Serviced Organisations

- **Generation IV International F**
with the goal to improve sustai
effective fuel utilisation and mi
economics, safety and reliabilit
resistance and physical protec
- **Multinational Design Evaluat (MDEP)**
initiative by national safety aut
their resources and knowledge
design reviews.
- **International Framework for Cooperation (IFNEC)**
forum for international discussi
nuclear topics involving both d
emerging economies.

24 Major Joint Projects

tries from within
EA membership)

nd experimental data (e.g.,
haviour, severe accidents).

s (e.g., fire, common-cause

rmodynamics

gement (e.g., thermochemical

e.g., occupational exposure).

uels and materials, human

Ongoing Joint Projects

- **BSAF**, applying the scientific information gained from the Fukushima Daiichi accident to improve nuclear analysis tools
- **SAREF**, which will sample water from Fukushima Daiichi reactors and assess fuel debris characteristics

 5

OECD BETTER POLICIES FOR BETTER LIVES — Nuclear Energy Agency — NEA NUCLEAR ENERGY AGENCY

NEA: leading the way towards a robust nuclear energy future

An overview of current NEA projects/initiatives:

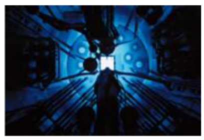
- **Nuclear Innovation 2050 (NI2050)**: focussing on increasing momentum in R&D and market deployment of new nuclear technologies
- **Multinational NEA Framework for In-pile Fuel and Material Testing**: focussing on future experimental capabilities
- **Nuclear Education, Skills and Technology (NEST) Framework**: focussing on the future generation

 6

OECD BETTER POLICIES FOR BETTER LIVES — Nuclear Energy Agency — NEA NUCLEAR ENERGY AGENCY

Nuclear Innovation 2050: moving ideas into reality

- Need for new nuclear technologies which are:
  - able to compete in future global energy markets
  - cheaper
  - more flexible and faster to deploy



- NI2050 involves industry and safety authorities to facilitate the transformation of R&D to market readiness → **all stakeholders need to be on board**

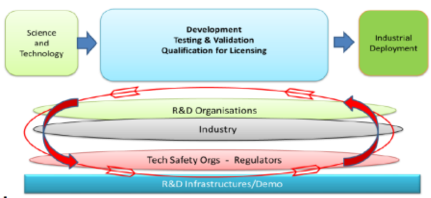
Three major barriers to overcome:
- Financing: nuclear innovation timeline is long; industry and private investors need to contribute
- Regulatory framework: not active in the technology development process; national dimension of regulatory processes can hinder wider market deployment
- Availability of infrastructure to support nuclear technology development

 7

OECD BETTER POLICIES FOR BETTER LIVES — Nuclear Energy Agency — NEA NUCLEAR ENERGY AGENCY

NEA "Nuclear Innovation 2050" (NI2050) Initiative

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



 8

OECD BETTER POLICIES FOR BETTER LIVES — Nuclear Energy Agency — NEA NUCLEAR ENERGY AGENCY

New Multinational NEA Framework for In-pile Fuel and Material Testing

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

OECD BETTER POLICIES FOR BETTER LIVES — Nuclear Energy Agency — NEA NUCLEAR ENERGY AGENCY

Proposed Framework Structure

Pursuant to Article 5 of the NEA Statute, the Framework will be established as an international joint undertaking

Framework for IrraDiation ExperimentS – FIDES[1]

- Being designed to provide stable, sustainable, reliable platform and an incentive for innovations for fuels and materials testing
- Encompasses **Joint Experimental Programmes** and the **Cross-cutting Activities**

Joint ExpErimental Programmes (JEEPs)

- **Enable in-pile experiments in test reactors and PIE**

[1] Fides (Latin: Fidēs) was the goddess of trust and bona fides (good faith)

[2] Country of the host organisation

OECD BETTER POLICIES FOR BETTER LIVES — Nuclear Energy Agency — NEA NUCLEAR ENERGY AGENCY

New NEA Framework: Added value and cross-cutting activities

The Framework is currently being established in order to

- provide continuity and sustainability in the strategic field
- build a collective awareness of needs and capabilities
- identify gaps requiring investments and facilitate related implementations
- create opportunities for cross-cutting activities
  - State-of-the-art instrumentation and modelling & simulation
  - **Preservation and quality management of experimental data**
  - Professional development and educational activities
- in collaboration with IAEA, address collectively practical issues of nuclear fuel transport and waste management

OECD BETTER POLICIES FOR BETTER LIVES — Nuclear Energy Agency — NEA NUCLEAR ENERGY AGENCY

NEA Nuclear Education, Skills and Technology (NEST) Framework

NEA member countries together represent the world's best nuclear expertise in the use of nuclear technology…

HOWEVER

…the scientists, engineers and technologists needed to ensure the safe and efficient use of nuclear technologies are declining in many countries leading to a potential loss of nuclear expertise and knowledge.

NEST Framework aims to:

- Attract, train and facilitate skills development of students and young professionals through transmission of practical knowledge and hands-on training
- Aid countries to maintain and strengthen academic nuclear-related education programmes by establishing international exchanges and collaborative activities between universities and other organisations (e.g., research institutions, regulatory bodies, etc.)

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OECD BETTER POLICIES FOR BETTER LIVES — Nuclear Energy Agency — NEA NUCLEAR ENERGY AGENCY

NEST: an investment in the next generation

Tacit knowledge needs to be preserved, transferred and shared with the next generation

To achieve this:

- Young generation needs to be exposed to challenging projects and real-world problems through hands-on training
- Leading experts in the field will work alongside the NEST Fellows (Masters, PhD, Postdoc students and young professionals)
- NEST Fellows will work within a network of organisations encouraging cross-fertilisation of ideas and development of new projects to advance new innovative nuclear technology

Photo Credit: Dean Calma / IAEA

OECD BETTER POLICIES FOR BETTER LIVES — Nuclear Energy Agency — NEA NUCLEAR ENERGY AGENCY

Entry into force of the NEST Agreement: 15 February 2019

OECD — BETTER POLICIES FOR BETTER LIVES

Nuclear Energy Agency

NEA — NUCLEAR ENERGY AGENCY

NEST current projects

PAUL SCHERRER INSTITUT PSI

NEST HYMERES (HYdrogen Mitigation Experiments for Reactor Safety, Phase 2) project:
- addresses safety relevant phenomena in containments during accidents; hands-on training at PANDA, one of the world's most advanced containment test facilities

McMaster University

SMR project:
- aims to integrate SMR research projects from individual participating organisation countries into a broader and more impactful program

CLADS

NEST-CLADS (Collaborative Laboratories for Advanced Decommissioning Science) project:
- dedicated to advanced remote technology for decommissioning under intense gamma-ray radiation environments (e.g robotics, virtual reality).

РОСАТОМ

NEST-PDC UGR (Pilot & Demonstration Center for Decommissioning of Uranium-Graphite Nuclear Reactors) project:
- addresses main issues of i-graphite management, including characterisation, decontamination and disposal

OECD — BETTER POLICIES FOR BETTER LIVES

Nuclear Energy Agency

NEA — NUCLEAR ENERGY AGENCY

Global issues require global solutions

What we know:
- Clima
- Nucl ... UT it need
- Much ... gies. Innov

What c
- Increa ... pertise has more value than a go-it-alone approach

The NEA can help lead the way

The NEA offers an ideal forum to advance the future of nuclear bringing together international experts who share and disseminate state-of-the-art knowledge in the field of nuclear energy.

The NEA's existing framework supports expertise and resources needed to enable multilateral co-operation.

OECD — BETTER POLICIES FOR BETTER LIVES

Nuclear Energy Agency

NEA — NUCLEAR ENERGY AGENCY

Thank you for your attention

More information @ www.oecd-nea.org

All NEA reports are available for download free of charge.

Follow us:

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TEODOR CHIRICA

FISA 2019 – EURADWASTE '19

Keynote of Mr Teodor Chirica (FORATOM, BE), President of the European Nuclear Industry Association

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

Membership

4

The membership of FORATOM is made up of 15 national nuclear associations representing more than 3,000 companies.

- Belgium
- Bulgaria
- Finland
- France
- Hungary
- Italy
- Netherlands
- Romania
- Slovakia
- Slovenia
- Spain
- Sweden
- Switzerland
- Ukraine
- United Kingdom

CEZ (Czech Republic) and PGE EJ 1 (Poland) are Corporate Members

Key topics

5

EU Energy Policy:
- Economics of nuclear
- EU energy mix
- Environment
- Euratom Treaty
- Security of energy supply
- Special projects - Brexit

Nuclear technology:
- Nuclear safety
- Nuclear transport
- **IRD**
- Supply Chain
- Waste disposal

Communication:
- Nuclear advocacy
- Perception of nuclear energy
- Promotion of nuclear energy
- Young generations in nuclear

What does nuclear contribute to the EU's economy?

7

126	100	1,100,000	26%	50%
NUCLEAR REACTORS IN OPERATION	TURNOVER € BILLION/YEAR	JOBS	ELECTRICITY PRODUCTION	LOW-CARBOM ELECTRICITY

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8

New build in the EU – construction & plans

Nuclear power plants under construction

- Finland – 1 reactor - 1 600 MW
- France – 1 reactor - 1 630 MW
- Slovakia – 2 reactors - 880 MW
- UK – 2 reactors - 3 200 MW

+

Countries preparing or considering new build

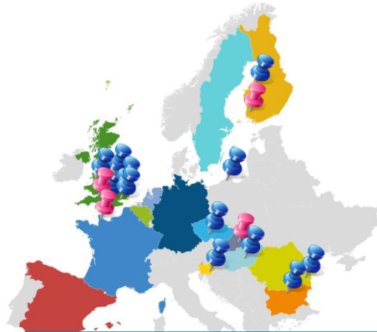
- ✓ Bulgaria
- ✓ Czech Republic
- ✓ Finland
- ✓ France
- ✓ Hungary
- ✓ Poland
- ✓ Romania
- ✓ UK

Each MS has the right to choose nuclear as part of its energy mix in line with the objectives of the Treaty on the Functioning of the EU

All nuclear projects, have been cleared by EC, in line with the objectives of the EURATOM Treaty and will be carried out.

Nuclear capacity "under construction" – ca. 7,500 MW

Nuclear capacity "planned" – between 10,000 - 20,000 MW



- nuclear power plants under construction
- nuclear projects being developed or planned

*Source: European Commission's PINC, May 2017

10

Key challenges at EU level

EC 2050 low-carbon strategy

EU energy & climate goals: CO_2 emissions goals vs. RES goals

UK leaving the EU (Brexit)

Balance of power pronuclear vs. antinuclear countries

New build projects facing opposition by selected EU members

Future of the Euratom Treaty

11

EU Energy Policy

EU Energy Policy Focus

Cutting GHG emissions	Contribution to the Paris Agreement	Affordable energy for consumers	Security of energy supply	Increasing the share of RES
Limiting the number of fossil fuel power plants	Robust EU-ETS system	New opportunities for growth and jobs	Reducing dependence on energy imports	Helping RES integrate into the system (network stability & flexibility)

ROLE FOR NUCLEAR

12

Nuclear energy in the EC strategy (Nov 2018)

EC Communication*:

"Renewables together with nuclear energy will be the backbone of a carbon-free European power system"

EC in-depth analysis:**

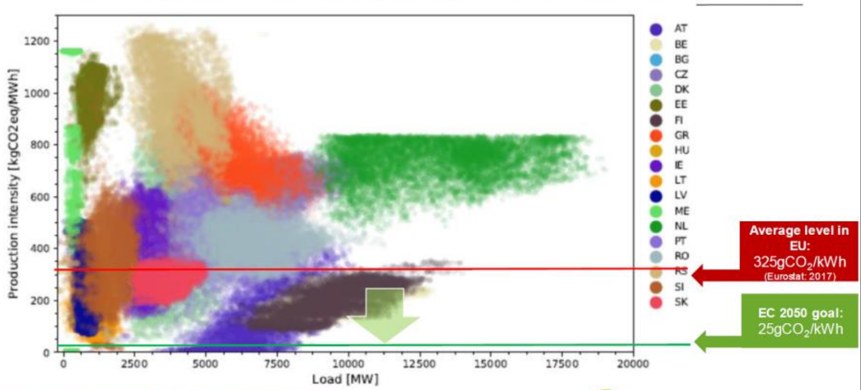
- Nuclear will **remain an important component** in the EU 2050 energy mix
- Capacity of nuclear in 2050 – **between 99-121 GW**
- Share of nuclear in the electricity mix in 2050 – **ca. 15%**
- *"The consumption of **natural gas** is expected to be severely reduced by 2050 in all scenarios"*
- *"In the baseline, **hydrogen** use develops only as a niche application for road transport and industry"*

Authors of the strategy referred directly to the study commissioned by FORATOM

* https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_en.pdf
** https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf

13

Hourly production intensity vs. hourly load by EU MSs



https://www.researchgate.net/publication/329734236_Real-Time_Carbon_Accounting_Method_for_the_European_Electricity_Markets

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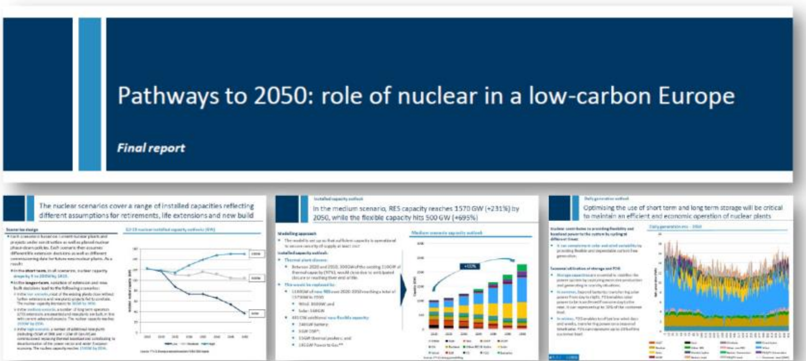
FTI CL Study (commissioned by FORATOM)



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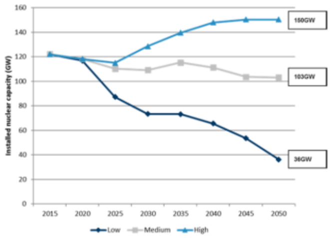
3 nuclear scenarios



3 nuclear scenarios:

1. **High** – 150 GW, share ~25% (maintaining the current one)
2. **Medium** – 103 GW, share ~15% (in line with the EC strategy)
3. **Low** – 36 GW, share ~4%

The study assesses the impact of each scenario on the key dimensions of Europe's energy policy:

1. security of supply
2. sustainability
3. economics

Benefits of having a 25% nuclear share in 2050*

Sustainability

- ✓ Allowing the EU to meet its **climate goals**
- ✓ **700 million t.** of CO_2 avoided per year (it emits **30x** less CO_2 than gas, **65x** less than coal, **3x** less than solar)
- ✓ Compliance with **air quality** standards
- ✓ **No need** for vast volumes of land / raw materials

Energy security

- ✓ **85-90%** capacity factor = a reliable source of electricity
- ✓ **Decreased dependence** on fossil fuels imports
- ✓ **System flexibility** much needed to support the RES developments
- ✓ **Limited reliance** on yet-to-be-proven technologies

Economy

- ✓ High residual investment value (avoiding reducing the value by **€1 trillion**)
- ✓ Mitigation of the cost impact of the low-carbon transition on customer cost by **€350bn**
- ✓ Reducing network & balancing costs by **160bn€**
- ✓ Positive & significant impact on **jobs, GDP, revenues,** etc.

Deloitte Study (commissioned by FORATOM)

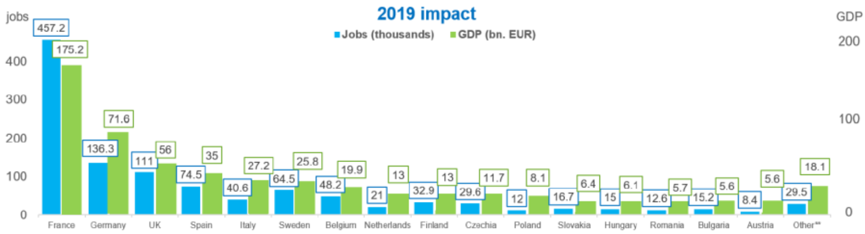
Key findings

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

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

Nuclear energy's economic impact

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



*Deloitte study "Nuclear energy: powering the economy – carbon-free growth, jobs and leadership in innovation
** Other = Ireland, Denmark, Greece, Slovenia, Luxembourg, Croatia, Lithuania, Latvia, Estonia, Cyprus, Malta combined

Different approaches towards nuclear R&D

Strategic areas for existing and future related technologies Small Modular Reactors (SMR) and Accident Tolerant Fuel (ATF).

over €1.1bn in 2019

R&D programmes & near-term innovation (floating nuclear reactor technology, advanced fuel cycle programme, focusing on the full recycling of fuel)

€1bn per year

Nuclear R&D (SMRs, advanced materials manufacturing, digitalization, large nuclear systems & component testing facilities, advanced fuel R&D programmes)

"Heavy investments" in R&D, but difficult to precisely estimate

?

Significantly less ambitious and of multiple orders of magnitude less than what is needed!!!

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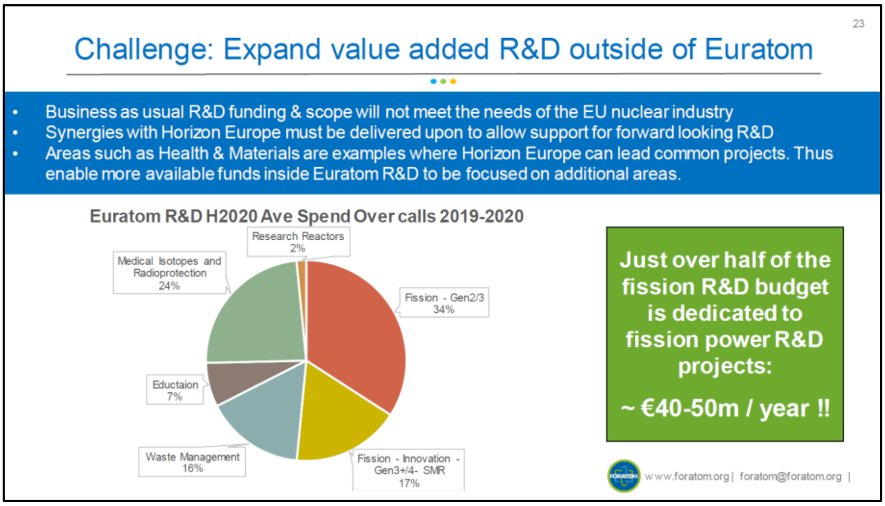
23
Challenge: Expand value added R&D outside of Euratom
• Business as usual R&D funding & scope will not meet the needs of the EU nuclear industry
• Synergies with Horizon Europe must be delivered upon to allow support for forward looking R&D
• Areas such as Health & Materials are examples where Horizon Europe can lead common projects. Thus enable more available funds inside Euratom R&D to be focused on additional areas.
Euratom R&D H2020 Ave Spend Over calls 2019-2020
Research Reactors 2%
Medical Isotopes and Radioprotection 24%
Fission - Gen2/3 34%
Eductaion 7%
Waste Management 16%
Fission - Innovation - Gen3+/4- SMR 17%
Just over half of the fission R&D budget is dedicated to fission power R&D projects:
~ €40-50m / year !!
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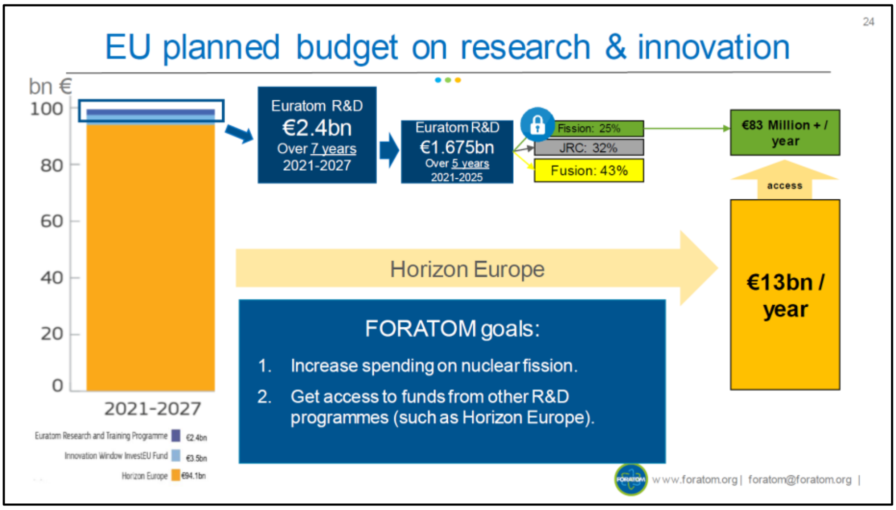
24
EU planned budget on research & innovation
bn €
100
80
60
40
20
0
2021-2027
Euratom Research and Training Programme €2.4bn
Innovation Window InvestEU Fund €3.5bn
Horizon Europe €94.1bn
Euratom R&D
€2.4bn
Over 7 years
2021-2027
Euratom R&D
€1.675bn
Over 5 years
2021-2025
Fission: 25%
JRC: 32%
Fusion: 43%
€83 Million + / year
access
€13bn / year
Horizon Europe
FORATOM goals:
1. Increase spending on nuclear fission.
2. Get access to funds from other R&D programmes (such as Horizon Europe).
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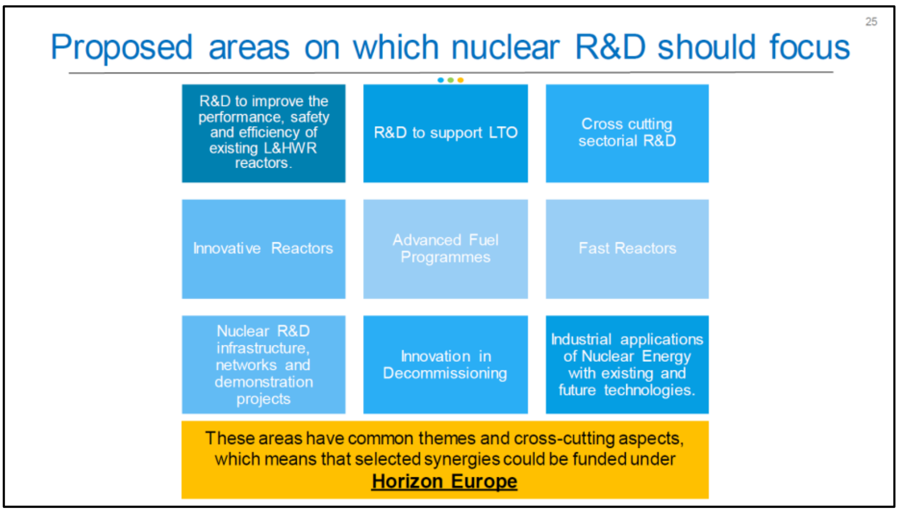
25
Proposed areas on which nuclear R&D should focus
R&D to improve the performance, safety and efficiency of existing L&HWR reactors.
R&D to support LTO
Cross cutting sectorial R&D
Innovative Reactors
Advanced Fuel Programmes
Fast Reactors
Nuclear R&D infrastructure, networks and demonstration projects
Innovation in Decommissioning
Industrial applications of Nuclear Energy with existing and future technologies.
These areas have common themes and cross-cutting aspects, which means that selected synergies could be funded under Horizon Europe

Colaboration outside of the Nuclear Sector: Case study – RIMA project

26

RIMA | Robotics for inspection and Maintenance

RIMA - European project to drive innovation in robotics for I&M by establishing a pan-European network of Digital Innovation Hubs.
The objective of RIMA is to **reinforce the leadership of Europe** in I&M robotics by connecting technology to industrial/sectorial needs and foster efficient cross border cooperation in Europe.

Project funded under the Digitising European Industry Call of **Horizon 2020**

FORATOM role

- Member of the RIMA consortium
- Bridge the gap between:
  - **SMEs within the robotics community**
  - Potential **end users within the nuclear industry** (licencees, I&M service providers, operators, etc.)

Importance of investing in nuclear R&D

28

The EU is lagging behind in nuclear R&D when compared to other international actors…
In order for the EU to maintain its technological leadership, which can help the EU decarbonise its power sector in line with the Paris Agreement:

1. Euratom 2021-2025 funding for fission R&I should be increased

2. Horizon Europe & Euratom 2021-2025 should be set up to complement each other (common themes & cross-cutting aspects)

3. Cohesion and synergy with R&D in the SET Plan Action 10 'Nuclear' must be considered & support given for shared benefits across R&D programmes

4. The scope of the WP Euratom 2021-2025 should be reflective of the direction of Member States, industry & academia stakeholders

FORATOM IRD WG planned activities

29

Release of a PP on "Opportunities for Euratom R&T 2021-2025 & Horizon Europe Programmes"

Innovation, Research & Development Working Group's industry view on the priority areas of R&D (9 fiches)

Position paper on IRD to meet the EU objectives (Q4 2019)

Direct engagement with key stakeholders (promotion of agreed messaging)

Participation in events (promotion of agreed messaging)

Participation in various projects, such as RIMA (promotion of agreed messaging)

Thank you

Join us on **26 June 2019** in **Bucharest** to discuss key challenges affecting EU's energy sector, the role of long-term operation of nuclear power plants and how to ensure that the industry has access to the skills it needs.

Registration: *events.foratom.org/nuclear-in-a-changing-world/*

Official hashtag: *#NuclearEurope2019*

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PIERRE JEAN COULON

FISA 2019 – EURADWASTE '19

Keynote of Mr Pierre Jean Coulon (EESC, EU), President of the Transport Energy and Networks section, European Economic and Social Committee

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

MISSING

DORU VISAN

FISA 2019 – EURADWASTE '19

Keynote of Mr Doru Visan (Secretary of State, RO)

Mr Minister,
Dear representatives of the European Commission,
Dear Participants,
Ladies and Gentlemen,

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

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

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

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

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

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

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

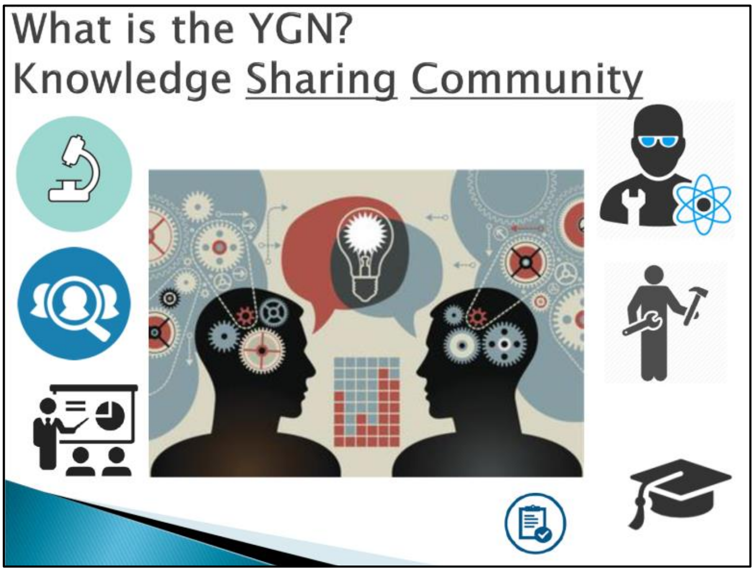
I wish a successfully Meeting!

NATHAN PATERSON

FISA 2019 – EURADWASTE '19

Keynote of Mr Nathan Paterson (ENS YGN, BE), Chair European Nuclear Society Young Nuclear Generation

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



21 Member Societies

Observer Partners

WANO · global WiN Women in Nuclear · World Nuclear Association · IYNC · IAEA

3

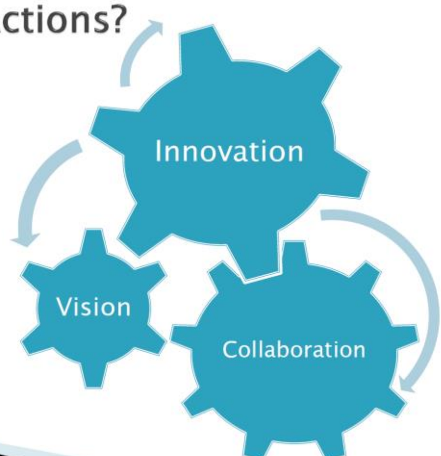
Who are we and what we stand for!!

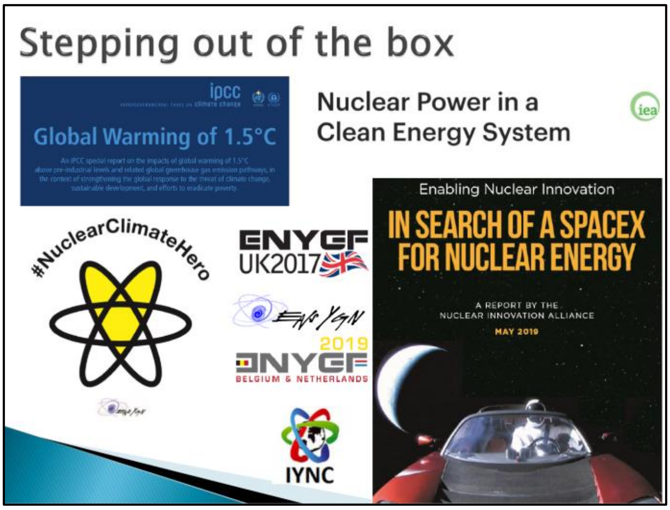
The global population is growing and the demand for **safe, clean** and **reliable electricity** is more important than it has ever been.

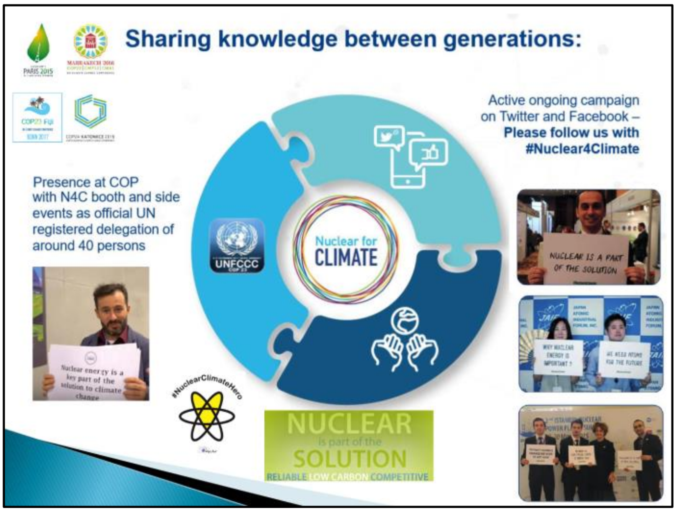
We must continue developing the global **nuclear industry** and strive for more **collaboration**, **innovative technologies** and **harmonization** of **best practices** to meet the needs of our **future**.

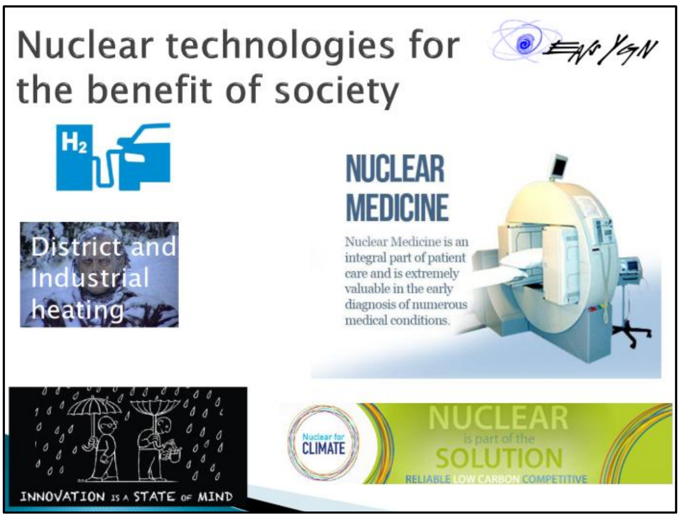
UN SDGs Extract

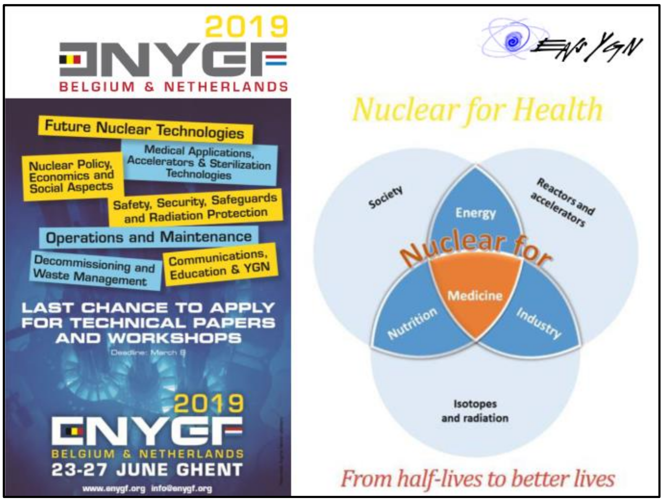
Words or Actions?

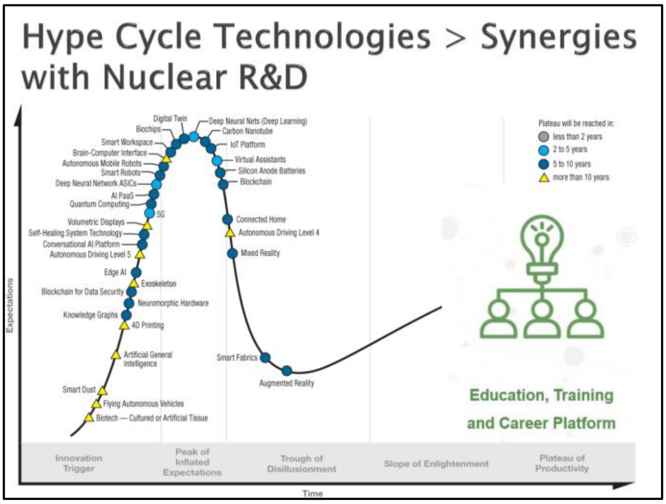


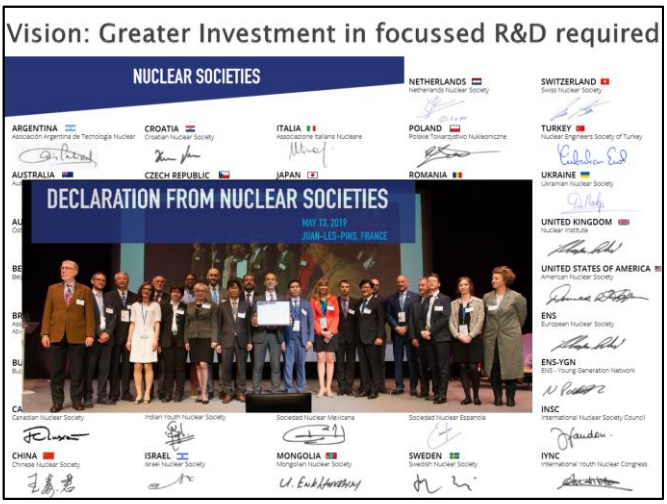

Stepping out of the box
ipcc
Global Warming of 1.5°C
Nuclear Power in a
Clean Energy System
iea
Enabling Nuclear Innovation
IN SEARCH OF A SPACEX
FOR NUCLEAR ENERGY
A REPORT BY THE
NUCLEAR INNOVATION ALLIANCE
MAY 2019
#NuclearClimateHero
ENYGF
UK2017
2019
ENYGF
BELGIUM & NETHERLANDS
IYNC


Sharing knowledge between generations:
Active ongoing campaign
on Twitter and Facebook –
Please follow us with
#Nuclear4Climate
Presence at COP
with N4C booth and side
events as official UN
registered delegation of
around 40 persons
UNFCCC
Nuclear for
CLIMATE
#NuclearClimateHero
NUCLEAR
is part of the
SOLUTION
RELIABLE LOW CARBON COMPETITIVE
NUCLEAR IS A PART
OF THE SOLUTION


Nuclear technologies for
the benefit of society
H_2
District and
Industrial
heating
NUCLEAR
MEDICINE
Nuclear Medicine is an
integral part of patient
care and is extremely
valuable in the early
diagnosis of numerous
medical conditions.
INNOVATION IS A STATE OF MIND
Nuclear for
CLIMATE
NUCLEAR
is part of the
SOLUTION
RELIABLE LOW CARBON COMPETITIVE


2019
ENYGF
BELGIUM & NETHERLANDS
Future Nuclear Technologies
Medical Applications, Accelerators & Sterilization Technologies
Nuclear Policy, Economics and Social Aspects
Safety, Security, Safeguards and Radiation Protection
Operations and Maintenance
Decommissioning and Waste Management
Communications, Education & YGN
LAST CHANCE TO APPLY FOR TECHNICAL PAPERS AND WORKSHOPS
Deadline: March 8
2019
ENYGF
BELGIUM & NETHERLANDS
23-27 JUNE GHENT
www.enygf.org info@enygf.org
ENS YGN
Nuclear for Health
Society
Reactors and accelerators
Energy
Nuclear for
Medicine
Nutrition
Industry
Isotopes and radiation
From half-lives to better lives


Hype Cycle Technologies > Synergies with Nuclear R&D
Digital Twin
Biochips
Deep Neural Nets (Deep Learning)
Carbon Nanotube
Smart Workspace
IoT Platform
Brain-Computer Interface
Virtual Assistants
Autonomous Mobile Robots
Silicon Anode Batteries
Smart Robots
Blockchain
Deep Neural Network ASICs
AI PaaS
Quantum Computing
5G
Volumetric Displays
Connected Home
Self-Healing System Technology
Autonomous Driving Level 4
Conversational AI Platform
Autonomous Driving Level 5
Mixed Reality
Edge AI
Exoskeleton
Blockchain for Data Security
Neuromorphic Hardware
Knowledge Graphs
4D Printing
Artificial General Intelligence
Smart Fabrics
Augmented Reality
Smart Dust
Flying Autonomous Vehicles
Biotech — Cultured or Artificial Tissue
Plateau will be reached in:
less than 2 years
2 to 5 years
5 to 10 years
more than 10 years
Education, Training and Career Platform
Expectations
Innovation Trigger
Peak of Inflated Expectations
Trough of Disillusionment
Slope of Enlightenment
Plateau of Productivity
Time


Vision: Greater Investment in focussed R&D required
NUCLEAR SOCIETIES
NETHERLANDS
Netherlands Nuclear Society
SWITZERLAND
Swiss Nuclear Society
ARGENTINA
Asociación Argentina de Tecnología Nuclear
CROATIA
Croatian Nuclear Society
ITALIA
Associazione Italiana Nucleare
POLAND
Polskie Towarzystwo Nukleoniczne
TURKEY
Nuclear Engineers Society of Turkey
AUSTRALIA
CZECH REPUBLIC
JAPAN
ROMANIA
UKRAINE
Ukrainian Nuclear Society
DECLARATION FROM NUCLEAR SOCIETIES
MAY 13, 2019
JUAN-LES-PINS, FRANCE
UNITED KINGDOM
Nuclear Institute
UNITED STATES OF AMERICA
American Nuclear Society
ENS
European Nuclear Society
ENS-YGN
ENS - Young Generation Network
Canadian Nuclear Society
Indian Youth Nuclear Society
Sociedad Nuclear Mexicana
Sociedad Nuclear Española
INSC
International Nuclear Society Council
CHINA
Chinese Nuclear Society
ISRAEL
Israel Nuclear Society
MONGOLIA
Mongolian Nuclear Society
SWEDEN
Swedish Nuclear Society
IYNC
International Youth Nuclear Congress


Thank you for listening
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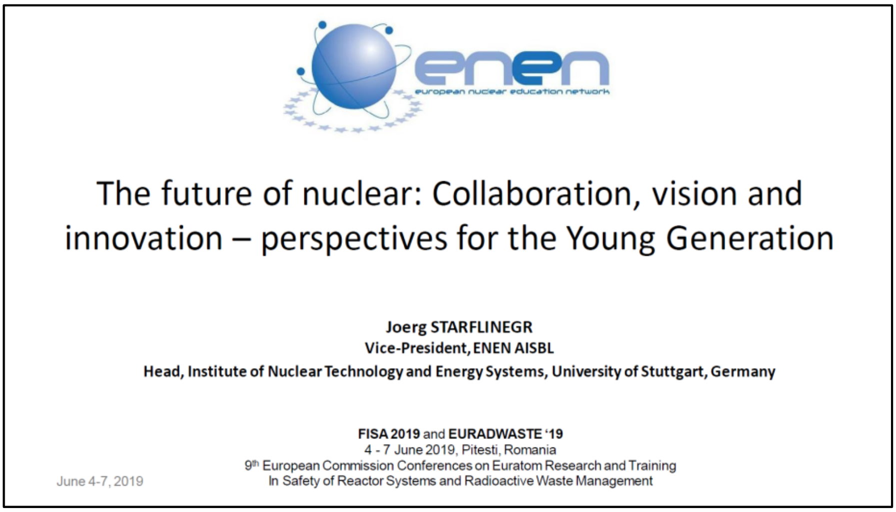
ENS-YGN group
ENS-YGN page
CREATIVE
EDUCATION
CAREER
VIBRANT
NUCLEAR
YOUNG
NETWORK
TRANSPARENCY
EUROPE
CLEAN
POWER
ATOM
OPENNESS
INSPIRING
DEVELOPMENT
Young Generation
creating the future

JOERG STARFLINGER

FISA 2019 – EURADWASTE '19

Keynote of Mr Joerg Starflinger (ENEN, BE), Vice-president of ENEN, University of Stuttgart, Germany

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



ENEN: European Nuclear Education Network

ESTABLISHED in 2003

Steady support by European Commission through projects

OBJECTIVE

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

ENEN Members in 2018

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

IAEA ENS NEA WORLD NUCLEAR UNIVERSITY FUSENET The European Fusion Education Network WFSJ

Selected Achievements of ENEN

Established

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

Ongoing: **Projects ANNETTE, ENEN+**

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

PhD Event & Prize and Mobility

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

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

Thank you for your attention

www.enen.eu

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

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

SERBAN CONSTANTIN VALECA

FISA 2019 – EURADWASTE '19

Keynote of Mr Serban Constantin Valeca (RATEN ICN, RO), President of the Scientific Council in RATEN ICN, Professor at University of Pitesti, Romania

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

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

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

Dear participants in FISA and EURADWASTE conferences,

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

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

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

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

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

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

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

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

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

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

Dear participants,

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

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

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

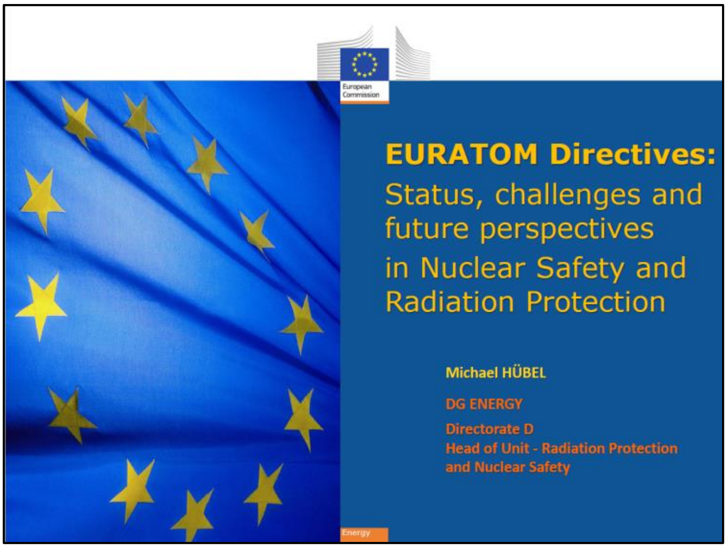
STATUS OF EU/ EURATOM DIRECTIVES

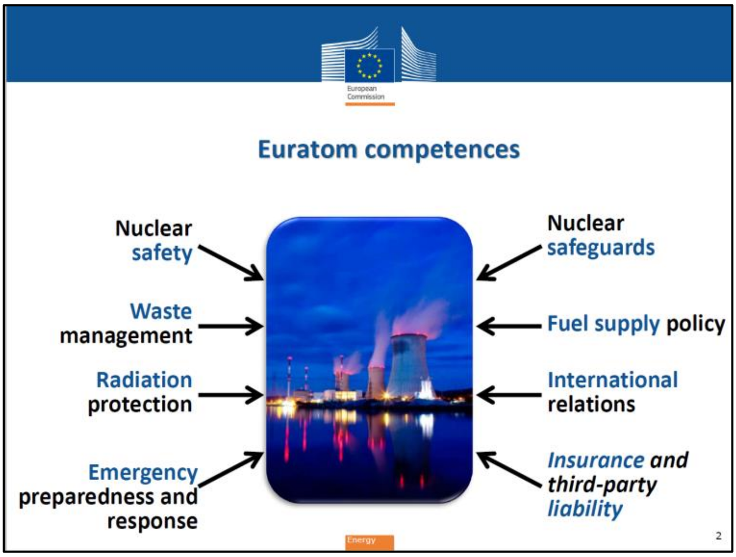
MICHAEL HUEBEL

FISA 2019 – EURADWASTE '19

Presentation of Mr Michael Huebel (DG ENERGY, DIRECTORATE D), Head of Unit - Radiation Protection and Nuclear Safety

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





Strengthening the legal framework

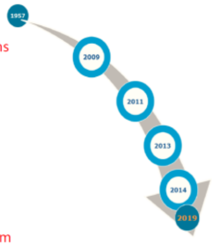
Directive 2009/71/Euratom
Nuclear Safety of nuclear installations

Directive 2011/70/Euratom
Spent Fuel and Waste Management

Directive 2013/51/Euratom
Euratom Drinking Water Directive

Directive 2013/59/Euratom
Basic Safety Standards

Directive 2014/87/Euratom
amending Directive 2009/71/Euratom



Energy

Nuclear Safety
Follow up to Fukushima nuclear accident

European Council 24-25 March 2011

2 mandates

- **Risk and safety assessments of nuclear power plants ("stress tests")**
- **Review of the legal and regulatory framework for the safety of nuclear installations – amended Directive**

Energy

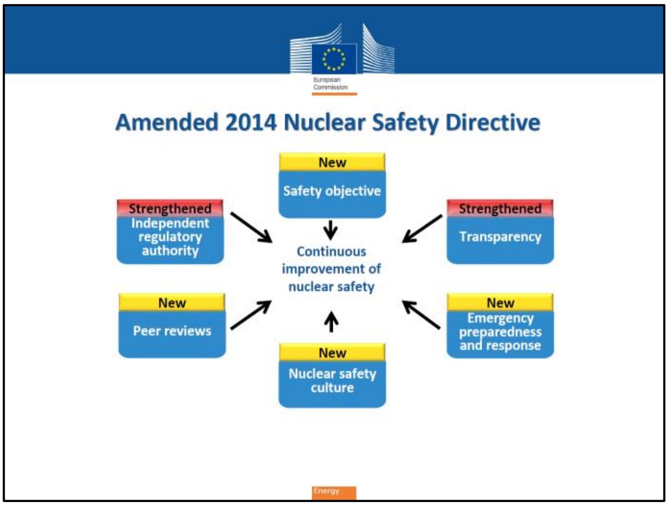
EU Stress Tests in 2012

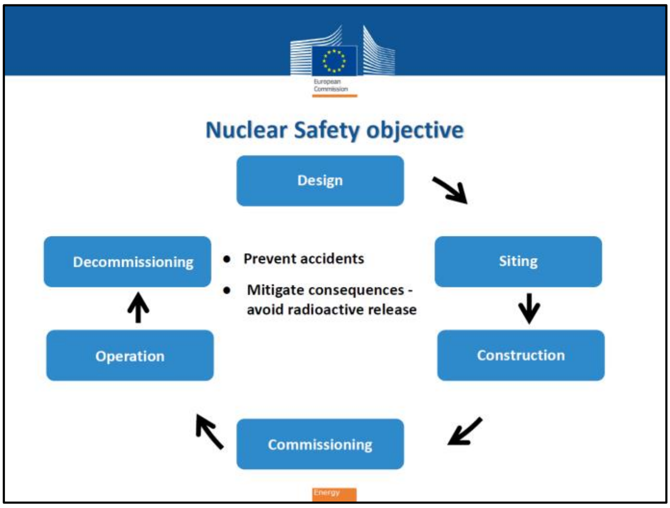
ENSREG

All 14 EU Member States that operate nuclear power plants, plus Lithuania, Switzerland, Ukraine. Additionally, Taiwan (2013), Armenia (2016) and Belarus (2018).

Planned in Turkey and Iran.

Energy


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


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


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

European Commission

European system of Topical Peer Reviews

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

http://www.ensreg.eu/sites/default/files/attachments/hlg_p2018-37_160_1st_topical_peer_review_report_2.pdf

Energy

European Commission

TPR 2018 findings, challenges

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

Energy

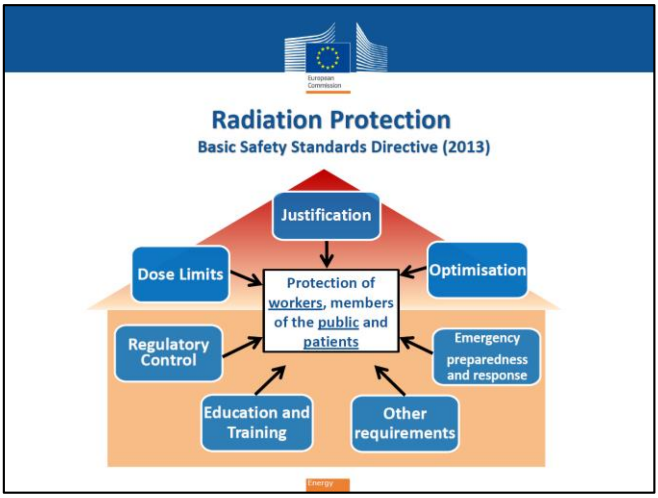
European Commission

Basic Safety Standards
Euratom Treaty (1957)

Chapter on health and safety

- Establish uniform basic safety standards for the protection of the health of workers and the general public against dangers arising from ionising radiations
  - ✓ ... and ensure that they are applied.

Energy



Motivation and Objective of the 2013 Revision

Modernisation

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

Consolidation and streamlining *– repealing :*

- ✓ *Basic Safety Standards, Directive 96/29/Euratom*
- ✓ *Medical Exposures, Directive 97/43/Euratom*
- ✓ *Public Information, Directive 89/618/Euratom*
- ✓ *Outside Workers, Directive 90/641/Euratom*
- ✓ *Control of high-activity sealed radioactive sources and orphan sources, Directive 2003/122/Euratom*
- ✓ *Radon, Commission Recommendation 90/143/Euratom*

15

Council Directive 2013/59/Euratom provides

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

16

Medical applications - radiology challenges

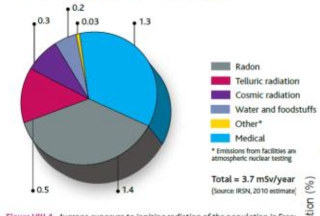
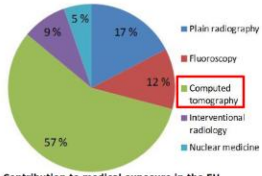
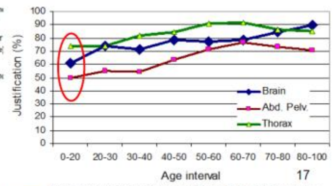


Figure VIII.1 - Average exposure to ionizing radiation of the population in France



Contribution to medical exposure in the EU
(RP 180, EC 2015)



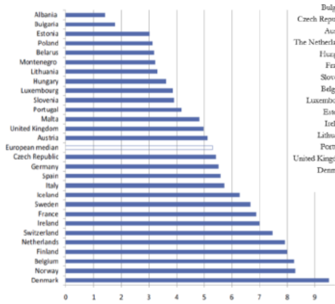
W. Leitz, A. Almén, S. Richter, A study on justification of CT examinations in Sweden

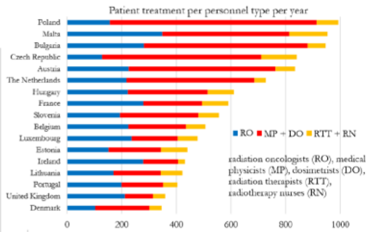
- BSS 2013/59/Euratom
- Commission COM/2010/0423
- Council Conclusions 2015 (LU)
- Implementation support

17

Medical applications – radiotherapy challenges

Radiotherapy machines per million inhabitants






LE FIGARO·fr

À Épinal, 5 500 personnes ont été victimes de surirradiation

18

BSS medical – main changes

Justification

- Transparency of justification for types of practice
- Equipment information – link with EU Medical Devices law
- Asymptomatic – guidelines, documenting, info to the 'client'

Optimization

- DRLs – mandatory, regular review, applicable to IR

Responsibilities / Procedures

- Stronger MPE involvement in IR, CT, paediatric, screening
- Information to patients on benefits and risks

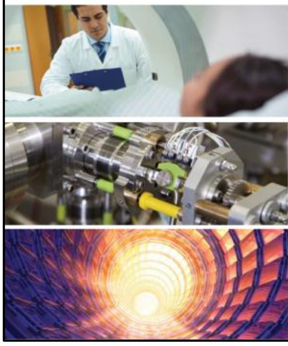
Equipment

- Dose-related information, transfer to examination record

Accidental and unintended exposures

- Risk assessments, recording, reporting, dissemination

SAMIRA = Strategic Agenda for Medical, Industrial and Research Applications



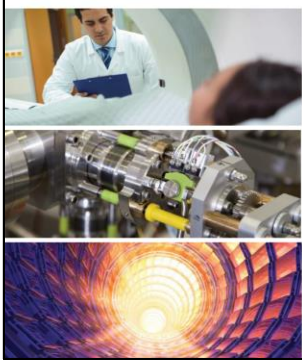
Objectives: *systematically* ***identify issues*** *relating to the use of nuclear and radiation technology outside the nuclear energy sector and* ***propose actions*** *to address them*

Cover: *security of* ***supply of radioisotopes****, radiation protection and safety, research and innovation*

20

Energy

Towards SAMIRA Action Plan

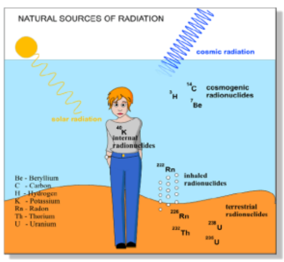


- **Where action is most needed**
- **EU could add real value to Member State actions**
  - Concentrated largely in the medical field
- **Secure supply of radioisotopes for Europe**
- **Improve radiation protection and safety for patients and medical staff**
- **Facilitate innovation in the medical practice**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

21

Protection from natural radiation sources

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



Energy

National radon action plan

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

Energy

Emergency preparedness and Response

The BSS Directive

Provisions of Basic Safety Standards Directive

- Assessment of emergency situations
- Management emergency exposures,
- Emergency response plans, protective measures, notification, emergency workers
- Cooperation across Member States
- Information to the public
- Transition from emergency to existing exposure situation

Council Conclusions on EP&R (Dec 2015)

- *Coherent protective measures along adjacent national borders,*
- *MS's cooperate closely on EP&R,*
- *MS's intensify efforts for joint training and emergency exercises,*
- *Better cross-border coordination of protective measures*

Energy

Emergency Preparedness and Response

The Amended Nuclear Safety Directive

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

Energy

Emergency Preparedness & Response

Commission role

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

Energy

26

The Euratom perspective

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

Energy

THANK YOU

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

Energy

MASSIMO GARRIBBA

FISA 2019 – EURADWASTE '19

Presentation of Mr Massimo Garribba (DG ENER, EUROPEAN COMMISSION)

Responsible and safe management of spent fuel and radioactive waste. The Community framework


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


DIRECTIVE ON RESPONSIBLE & SAFE MANAGEMENT OF SPENT FUEL AND RADIOACTIVE WASTE
Euratom Directive 2011/70 aims to improve the safety of radioactive waste and spent fuel disposal without undue burden on future generations.
WHY
Protects workers and EU citizens
Helps turn political decisions into actions
Avoids undue burden on future generations
Continued improvement of management systems, transparency, safety and public involvement
Commits Member States (MSs) to implement sustainable solution
Spent fuel and waste under the responsibility of the generators until disposal
EURATOM DIRECTIVE 2011/70
WHO
All MSs generate radioactive waste
21 manage spent fuel on their territory
14 MSs with 126 nuclear power reactors in operation
- 50 to be shut down by 2025
- 10 MSs plan new NPP projects
1 MS plans the first geological disposal expected around 2024
WHAT
3 481 000 m³ of radioactive waste
58 000 tHM of spent fuel generated in the EU by 2016
HOW
NATIONAL POLICIES
NATIONAL FRAMEWORK
NATIONAL PROGRAMMES
Energy


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


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


1st COMMISSION REPORT
Provides a comprehensive overview to the Council, European Parliament and EU citizens
Brings the principle of avoiding undue burden on future generations
Recognises MS' efforts and encourage pursuing them in several areas; policies, cost estimations, financing provisions and concrete projects for waste disposal.
Main report COM(2017)236
https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52017DC0236
Staff Working Document SWD (2017)159 on MS implementation
https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1531085795800&uri=CELEX:52017SC0159
Staff Working Document SWD (2017)161 on inventories, prospects
https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1531085865514&uri=CELEX:52017SC0161
Energy


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

IMPORTANCE OF THE R&D ON THE DIRECTIVE

Member States shall ensure that the national framework (for spent fuel and radioactive waste management):

Article 5 Obligations (5.2)
- is improved ...taking into account … **the development of relevant technology and research**.

Article 8 Expertise and skills
- require all parties to make arrangements for …**research** and development activities to cover the needs of the **national programme…**

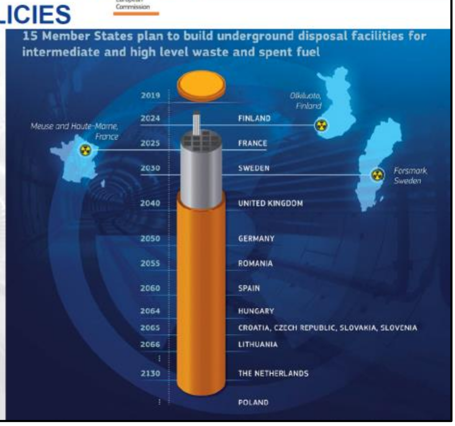
Article 12 Contents of national programmes (12.1(f))
… shall include:
the **research**, development and demonstration activities that **are needed in order to implement solutions**

Energy

UNDERGROUND RESEARCH LABORATORIES

NATIONAL POLICIES

DEEP GEOLOGICAL DISPOSAL



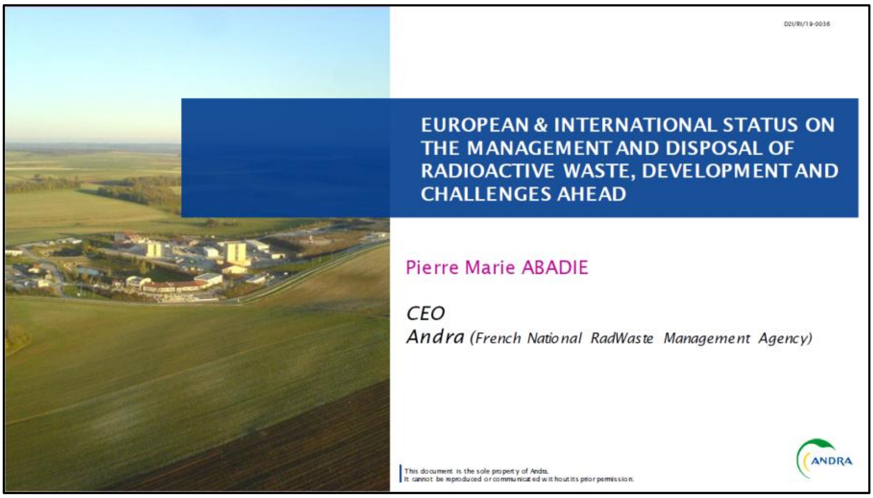
RADIOACTIVE WASTE MANAGEMENT

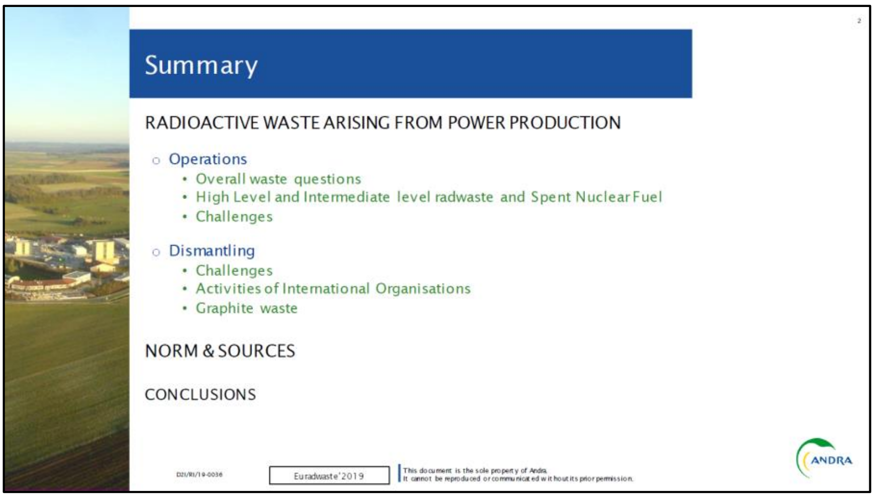
PIERRE MARIE ABADIE

FISA 2019 – EURADWASTE '19

Presentation of Ms Pierre Marie Abadie (ANDRA, FR), CEO

European and International status of the management and disposal of radioactive waste, developments and challenges ahead





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The overall waste question (I)

Currently **446 reactors operating worldwide** in **31 countries**, and 4 new comers are in the process of joining that club (Turkey, United Arab Emirates, Bangladesh and Belarus)

Radwaste arising from operations:

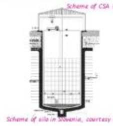
- Operating waste, mainly low activity (LLW), and mainly short lived
- Spent Nuclear Fuel and/or waste from reprocessing mainly high activity and including a significant amount of long lived elements

Radwaste management **routes** and many **disposal facilities exist for Majority of LLW** (short lived), but different concepts:

- **Surface disposal**, centre de l'Aube (France) **(1)**
- **Shallow disposal**, silo (planned in Slovenia) **(2)**
- **Underground** type, SFR (Sweden) **(3)**

Scheme of CSA in France

(1)


Scheme of silo in Slovenia, courtesy of ARAO

(2)


Scheme of SFR in Sweden, courtesy of SKB

(3)

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The overall waste question (II)

Long term management of spent nuclear fuel and/or radwaste from reprocessing: a challenge for the industry since the birth of nuclear power generation

A main consensus for long term management: Deep Geological Repository as appropriate solution

- This solution does not burden future generations. In this sense long term storage, although technically sound, does not completely answer the question
- Other possible envisaged solutions such as partitioning and transmutation do not completely satisfy requirements either
- Acceptance of such a DGR by local and national populations: a constant issue

A large set of knowledge available on DGR, resulting for more than 40 years of research

- mainly focussed on long term safety of a DGR and construction (clay, granite…): host rock, engineered barriers (buffer, backfill, seal, plugs), radwaste…

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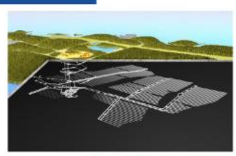
HLW, ILLW and Spent Nuclear Fuel: Situation regarding the DGR at 2019

Significant variety of situations

- For 3 countries, established projects for disposal exist:
  - Finland has a license for excavating a facility (SNF in Crystalline host rock)
  - Sweden has applied for a license and the approval is pending (SNF in Crystalline host rock)
  - France has a target date for submitting a license application in 2020 (HLW and ILLW in clay host rock)
- Other countries have started the sitting process/work:
  - UK: government (BEIS) kicked off the sitting in December 2018
  - Switzerland: sitting process ongoing
  - Japan: METI produced a map of suitable sites in the summer of 2016
  - China and Russia: Underground Research Laboratories (URL) are being excavated in Crystalline rock
  - And URL's exist in Belgium, Switzerland and Hungary.

With different schedules (can be very distant)


Scheme of DGR in Finland (Courtesy of posiva)


Scheme of Cigéo project in France

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The challenges a waste manager faces

In all cases, the management of HLW/SNF lead up to R&D intensive projects:

- A common development/realisation project duration: > 20-30 years
- A common long operational duration: > 100 years
- A significant oversight cost in the tens of billion Euro range, depending on inventory size

It also leads to managing an organisation that will have to adapt to the successive project phases:

- Phase 0 : policy, framework and program establishment
- Phase 1 : Site evaluation and site selection
- Phase 2 : Site characterization and Design
- Phase 3 : Facility construction
- Phase 4 : Facility operation and closure
- (Phase 5 : Post-closure)

- The feedback from the Swedish, Finn and French projects all point to the transition from 2 to 3
  - There is a needed adaptation of the organisation to go from science to design to realisation
  - This in turn requires changes in both skills and organisation
    - But RD&D/innovation remains for optimization and adaptation of DGR, long term Knowledge Management…

Dismantling - Challenges (I)

The challenges differ between facilities

- One of kind dismantling operations (ex. research facilities)
- Repetitive dismantling of an homogeneous fleet of NPP's

However in all cases, **characterization** is a key issue

- for a better sorting and an identification of the most suited management route

Dismantling - Challenges (II)

Strong need for **optimization of waste stream**

- Optimization based on safety, waste volume and cost criteria

Requirement for a holistic approach of waste management chain and strong interaction between waste producer, operator and waste manager

Options that lead to optimization cover:

- Waste valorization (of scrap metal, of rubble)
- Volume reductions (metal fusion, incineration and compaction) including at the waste generation phase
- Reorientation of waste streams to more appropriate solutions (ex. In situ disposal)
  - Options to be assessed as to their technical, economic, environmental efficiency and to their social acceptability
  - Existence of clearance levels must also be taken into account
  - These options are supported by a significant R&D effort

George Besse facility (France)

Disposal of a vapour generator at French surface disposal centre for VLLW (CIRES)

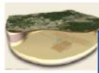
The specificities of graphite waste

Low Level but Long Lived (LL-LL) waste

- Originating from the dismantling of first-generation graphite-gas cooled NPP's
  - Ex. in France
    - (70,000m³)
    - Total activity ~ 21 200 TBq in 2013, the strongest activities being represented by C14, by H3 and by Co60
    - Significant Cl36 inventory

Many solutions still under studies for all or part of graphite Inventory

- Treatment
- DGR
- Surface or shallow disposal



Moderate specific activity not requiring deep disposal

Content in long lived RN compatible with CSA?

Technical and economical optimization of waste disposal routes

Shallow disposa l

Example of french process

Other elements in the LL-LL inventory in France

Part of legacy bituminized waste (40,000m3)

- Originating from the treatment of liquid effluents, embedded in bitumen, in the process of being taken over by the CEA in Marcoule

Uranium - bearing waste (50,000m³) resulting from natural uranium conversion

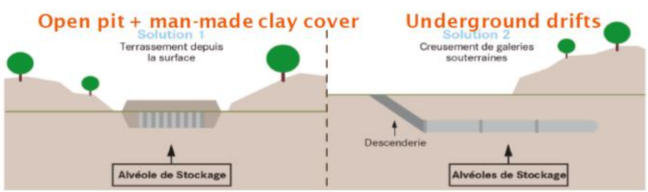
NORM waste (2,000m³)

Disused sealed sources

- Smoke sensors: ^{241}Am, ^{226}Ra
- Surge protectors: ^{3}H, ^{226}Ra...

A solution for disposal of LL-LL waste

Shallow disposal options in a geological layer with low permeability: 2 design options are under investigation



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Sources and NORM (I)

NORM and sources are present in many countries

- Sources:
  - Generally sources that have been used either for industrial or health linked applications (Disused Sealed Sources)
  - Classified by IAEA on 1-5 scale (level 1 being the most active)
  - To be dealed in countries that are not nuclear countries
- NORM waste
  - Waste arising from the processing of natural materials that are naturally rich in radionuclide content but that are not used for their radioactive properties
    - extracting materials from the underground (water, oil, coal, rare earth...) or from the ground (phosphate...),
    - Processing materials (coal, rare earth...)
    - ...

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Sources and NORM (II)

Difficulty to Handle these different categories of waste in countries were the nuclear and radioactive waste management culture is not present

In addition the volumes can range from very small to significant

Promising solutions are being investigated by the IAEA for Disused Sealed Sources, based on borehole technology.

- Solution that also could be used for small volumes of other type of waste, and this is being examined by the IAEA

Issues to identify solutions that are adapted to these waste streams:

- Environmentally safe
- Affordable for the country
- Adequate proportionality from a waste management point of view (holistic view)

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Conclusions (I)

LLW from NPP operations are disposed adequately in ***many existing facilities*** throughout the world

HLW, ILLW and SNF from NPP operations can be disposed of via ***DGR***'s, and the development of this type of solution is progressing with ongoing or planned license applications in 3 countries and siting projects in many countries

- A strong knowledge base is available
- The evolution of project from design and demonstration to construction and operation requires deep evolution of skills and organization
- The long duration and the progressive development of projects allow optimization and innovation, supported by RD&D

Forecast Radioactive waste from decommissioning of NPP's is a significant issue, for the next decades, according to large volume: ***characterization*** is a ***key point to optimize the waste routes in an holistic approach (recycling, disposal)***

- R&D on characterization, treatment and conditioning is required to support optimization

Low Level but Long Lived radwaste, such as graphite, (should) remain(s) an issue to address the ***appropriate route***, depending of country policy (long term storage, DGR, shallow or surface disposal)

Other types of waste (NORM, DSSS...) are to be considered: frequent in all countries and appropriate solutions are to be deployed in particular in ***countries without nuclear culture/NPP*** (borehole...)

Whatever type of radwaste, but in particular HLW/ILLW and SNF, the ***long duration of projects*** (more than a century) highlights the need of a **strong Knowledge Management process**

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Conclusions (II)

In addition to efforts produced by each country, international organizations strongly contribute in a complementary and consistent way

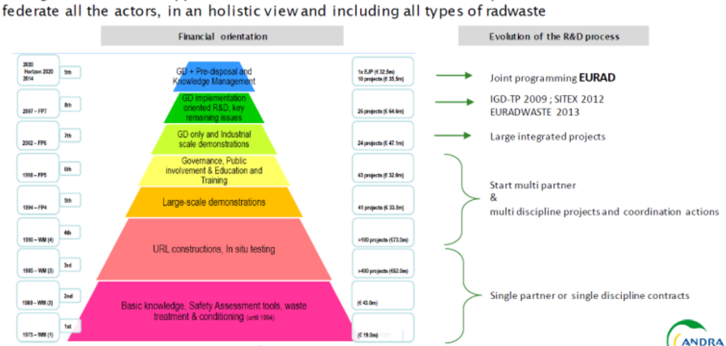
- to radioactive waste management:
  - IAEA: numerous initiatives (joint convention, production of safety standards and guides, supporting exchange networks…)
  - NEA: Radioactive Waste Management Committee that in turn has organized many instances to share information on waste management (The Integration group for the safety case (IGSC) ; Forum on Stakeholder Confidence (FSC)…
  - EC: Directive, Euratom R&D projects
- in dismantling:
  - IAEA: recent Decommissioning & Environmental Remediation Section inside the department of nuclear energy
  - NEA: creation of an independent Committee on Decommissioning of Nuclear Installations and Legacy Management (CDLM) since 2018
  - EC: Directive, Euratom R&D projects

In addition, international initiatives exist to address the complex subject of the disposal of HLW, ILLW or SNF for countries with a limited inventory (Netherlands, Slovenia…)

- The previously mentioned significant financial needs associated to such projects naturally lead to looking at the sharing of such facilities

Conclusions (III.1)

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



Conclusions (III.2)

A positive evolution of EC support to RD&D:

- To consider all Radwaste types
  - Including countries without NPPs
- To consider all management solutions
- To consider radwaste routes from cradle to grave
  - From predisposal to disposal
- To federate all actors: Radwaste Producers, WMOs, TSOs, and REs, in close link with Civil Society
  - To promote sharing between all actors
    - Joint Strategic Research Agenda
    - Collaborative RD&D
    - Joint Knowledge Management and Training processes
    - Joint Strategic studies
- To be complementary with IAEA and NEA and to promote common work on Knowledge Management, Training and Strategic studies

⇨Toward an **European community on Radwaste**, whatever each national policy and level of progress

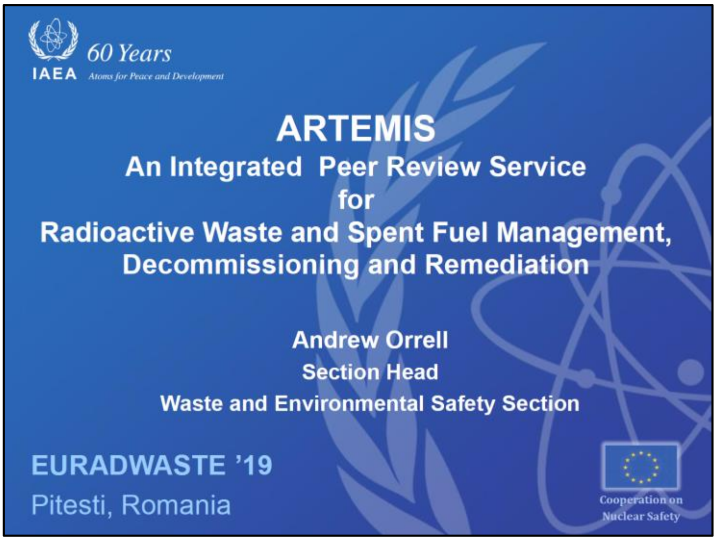
- EURAD Joint Programming
- (future) project on predisposal (characterization/treatment/conditioning) in close link with EURAD

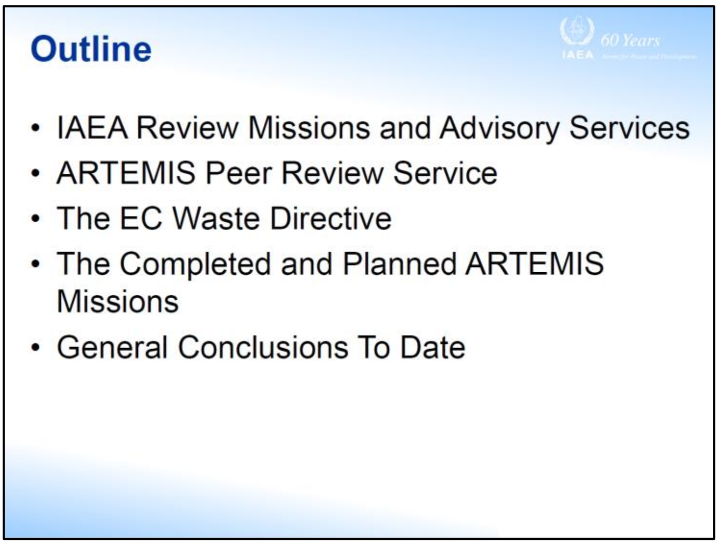
ANDREW ORRELL

FISA 2019 – EURADWASTE '19

Presentation of Mr Andrew Orrell (IAEA), Section Head of Waste and Environmental Safety

ARTEMIS in Europe, the Integrated Review Service for Radioactive Waste and Spent Fuel Management, Decommissioning and Remediation





IAEA Review Missions and Advisory Services

IAEA offers Member States a wide array of review services

- ImPACT (an integrated mission of PACT otherwise referred to as an imPACT Review)
- Operational Safety Review Team (OSART)
- International Physical Protection Advisory Service (IPPAS)
- Integrated Regulatory Review Service (IRRS)
- Integrated Review Service for Radioactive Waste and Spent Fuel Management, Decommissioning and Remediation (ARTEMIS)
- Safety Aspects of Long-Term Operation (SALTO)
- Integrated Nuclear Infrastructure Review (INIR)
- Quality Management Audits in Nuclear Medicine Practices (QUANUM)
- Occupational Radiation Protection Appraisals (ORPAS)
- Construction Readiness Review (CORR)
- Emergency Preparedness Review (EPREV) Service
- Integrated Safety Assessment of Research Reactors (INSARR)
- Site and External Events Design Review Service (SEED)
- Independent Safety Culture Assessment (ISCA)
- Knowledge Management Assist Visit (KMAV)
- Education and Training Appraisal (EduTA)
- Operation and Maintenance Assessment for Research Reactors (OMARR)
- Technical Safety Review (TSR)
- State Systems of Accounting for and Control of Nuclear Material mission (ISSAS)
- Quality Improvement Quality Assurance Team for Radiation Oncology (QUATRO)
- Safety Culture Continuous Improvement Process (SCCIP)
- Independent Engineering Review of I&C Systems (IERICS)
- International Nuclear Security Advisory Service (INSServ)
- Quality Improvement Quality Assurance Audit for Diagnostic Radiology Improvement and Learning (QUAADRIL)
- Integrated Nuclear Infrastructure Review for Research Reactors (INIR-RR)
- Advisory Mission on Regulatory Infrastructure for Radiation Safety (AMRAS)
- Uranium Production Site Appraisal Team (UPSAT)
- Safety Evaluation of Fuel Cycle Facilities during Operation (SEDO)
- Transport Safety Appraisal Services (TranSAS)

https://www.iaea.org/services/review-missions/calendar

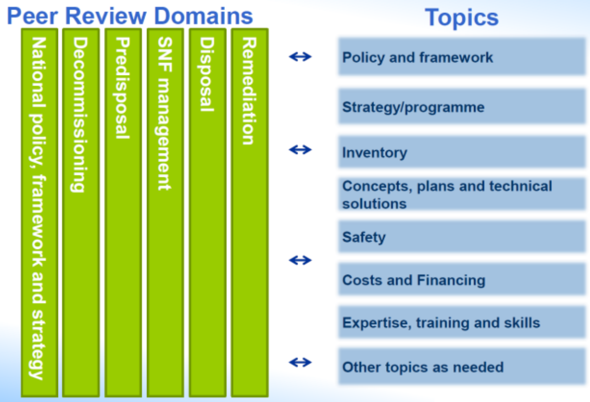
ARTEMIS Review Service

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

ARTEMIS

Integrated Review Service for Radioactive Waste and Spent Fuel Management, Decommissioning and Remediation

Structure of ARTEMIS



ARTEMIS Review Process

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

Definitions

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

ARTEMIS on GNSSN Platform

https://gnssn.iaea.org/main/ARTEMIS

The EC Waste Directive

The EC Waste Directive

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

Article 5 National framework

1. Member States shall establish and maintain a national legislative, regulatory and organisational framework ('national framework') for spent fuel and radioactive waste management that allocates responsibility and provides for coordination between relevant competent bodies. The national framework shall provide for all of the following:

   (a) a national programme for the implementation of spent fuel and radioactive waste management policy;

   (b) national arrangements for the safety of spent fuel and radioactive waste management. The determination of how those arrangements are to be adopted and through which instrument they are to be applied rests within the competence of the Member States;

   (c) a system of licensing of spent fuel and radioactive waste management activities, facilities or both, including the prohibition of spent fuel or radioactive waste management activities, of the operation of a spent fuel or radioactive waste management facility without a licence or both and, if appropriate, prescribing conditions for further management of the activity, facility or both;

   (d) a system of appropriate control, a management system, regulatory inspections, documentation and reporting obligations for radioactive waste and spent fuel management activities, facilities or both, including appropriate measures for the post-closure periods of disposal facilities;

   (e) enforcement actions, including the suspension of activities and the modification, expiration or revocation of a licence together with requirements, if appropriate, for alternative solutions that lead to improved safety;

   (f) the allocation of responsibility to the bodies involved in the different steps of spent fuel and radioactive waste management; in particular, the national framework shall give primary responsibility for the spent fuel and radioactive waste to their generators or, under specific circumstances, to a licence holder to whom this responsibility has been entrusted by competent bodies;

   (g) national requirements for public information and participation;

   (h) the financing scheme(s) for spent fuel and radioactive waste management in accordance with Article 9.EN 2.8.2011 Official Journal of the European Union L 199/53

Article 6 Competent regulatory authority

1. Each Member State shall establish and maintain a competent regulatory authority in the field of safety of spent fuel and radioactive waste management.

2. Member States shall ensure that the competent regulatory authority is functionally separate from any other body or organisation concerned with the promotion or utilisation of nuclear energy or radioactive material, including electricity production and radioisotope applications, or with the management of spent fuel and radioactive waste, in order to ensure effective independence from undue influence on its regulatory function.

3. Member States shall ensure that the competent regulatory authority is given the legal powers and human and financial resources necessary to fulfil its obligations in connection with the national framework as described in Article 5(1)(b), (c), (d) and (e).

Article 11 & 12 National Programmes

1. Each Member State shall ensure the implementation of its national programme for the management of spent fuel and radioactive waste ('national programme'), covering all types of spent fuel and radioactive waste under its jurisdiction and all stages of spent fuel and radioactive waste management from generation to disposal.

2. Each Member State shall regularly review and update its national programme, taking into account technical and scientific progress as appropriate as well as recommendations, lessons learned and good practices from peer reviews.

Contents of national programmes

1. The national programmes shall set out how the Member States intend to implement their national policies referred to in Article 4 for the responsible and safe management of spent fuel and radioactive waste to secure the aims of this Directive, and shall include all of the following:

   (a) the overall objectives of the Member State's national policy in respect of spent fuel and radioactive waste management;

   (b) the significant milestones and clear timeframes for the achievement of those milestones in light of the over- arching objectives of the national programme;

   (c) an inventory of all spent fuel and radioactive waste and estimates for future quantities, including those from decommissioning, clearly indicating the location and amount of the radioactive waste and spent fuel in accordance with appropriate classification of the radioactive waste;

   (d) the concepts or plans and technical solutions for spent fuel and radioactive waste management from generation to disposal;

   (e) the concepts or plans for the post-closure period of a disposal facility's lifetime, including the period during which appropriate controls are retained and the means to be employed to preserve knowledge of that facility in the longer term;

   (f) the research, development and demonstration activities that are needed in order to implement solutions for the management of spent fuel and radioactive waste;

   (g) The responsibility for the implementation of the national programme and the key performance indicators to monitor progress towards implementation;

   (h) an assessment of the national programme costs and the underlying basis and hypotheses for that assessment, which must include a profile over time;

   (i) the financing scheme(s) in force;

   (j) a transparency policy or process as referred to in Article 10;

   (k) if any, the agreement(s) concluded with a Member State or a third country on management of spent fuel or radioactive waste, including on the use of disposal facilities.

2. The national programme together with the national policy may be contained in a single document or in a number of documents.

ARTEMIS Reviews Status

Mission	Member State	Date
ARTEMIS Mission to SOGIN	Italy	3-Jul-17
ARTEMIS Mission to Poland	Poland	1-Oct-17
ARTEMIS Mission to France	France	14-Jan-18
ARTEMIS Mission to Bulgaria	Bulgaria	10-Jun-18
ARTEMIS Mission to SOGIN	Italy	24-Jun-18
ARTEMIS Mission to Luxembourg	Luxembourg	24-Sep-18
ARTEMIS Mission to Eletronuclear	Brazil	1-Oct-18
ARTEMIS Mission to Spain	Spain	14-Oct-18
ARTEMIS Mission to Estonia	Estonia	24-Mar-19
ARTEMIS Mission to Germany	**Germany**	**22-Sep-19**
ARTEMIS Mission to Latvia	**Latvia**	**3-Dec-19**
ARTEMIS Mission to Denmark	**Denmark**	**7-Jun-20**
ARTEMIS Mission to Romania	**Romania**	**2019 Q4***
ARTEMIS Mission to Cyprus	**Cyprus**	**2020 Q4***
ARTEMIS Mission to Slovenia	**Slovenia**	**2021 Q1***
ARTEMIS Mission to Hungary	**Hungary**	**2021 Q2***
ARTEMIS Mission to Lithuania	**Lithuania**	**2021 Q2***
ARTEMIS Mission to Croatia	**Croatia**	**2021 Q3***
ARTEMIS Mission to Ireland	**Ireland**	**2021 Q3***
ARTEMIS Mission to Sweden	**Sweden**	**2022 Q1***
ARTEMIS Mission to Finland	**Finland**	**2022 Q1***
ARTEMIS Mission to Greece	**Greece**	**2023 Q1***
ARTEMIS Mission to the Netherlands	**Netherlands**	**2023 Q1***
ARTEMIS Mission to the Czech Republic	**Czech Republic**	**2023 Q3***

Requested combined IRRS and Artemis:

- Slovenia 2021
- Sweden 2022
- The Netherlands 2023 (tbc)

General Conclusions

INTEGRATED REVIEW SERVICE FOR RADIOACTIVE WASTE AND SPENT FUEL MANAGEMENT, DECOMMISSIONING AND REMEDIATION (ARTEMIS)

MISSION

TO

FRANCE

PARIS, FRANCE

14 to 24 January 2018

DEPARTMENT OF NUCLEAR SAFETY AND SECURITY
DEPARTMENT OF NUCLEAR ENERGY

ARTEMIS

CONTENTS

60 Years
IAEA Atoms for Peace and Development

Thank you!

ARTEMIS.Contact-Point@iaea.org

CHRISTOPHE DAVIES

FISA 2019 – EURADWASTE '19

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

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

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

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

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

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

In the early 2000's, after 25 years of R&D, there was still no scheduled date for start of operation of the first underground repositories in Europe and no country was still foreseeing a date of submission of an operation license application to its regulatory authority. Disposal of high-level and long-lived radioactive waste

(HL&LL W) and spent fuel (SF) in deep underground repositories was and still is the most important challenge in all national programmes, which have to manage SF.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Summary:

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

SAFETY OF REACTOR SYSTEMS

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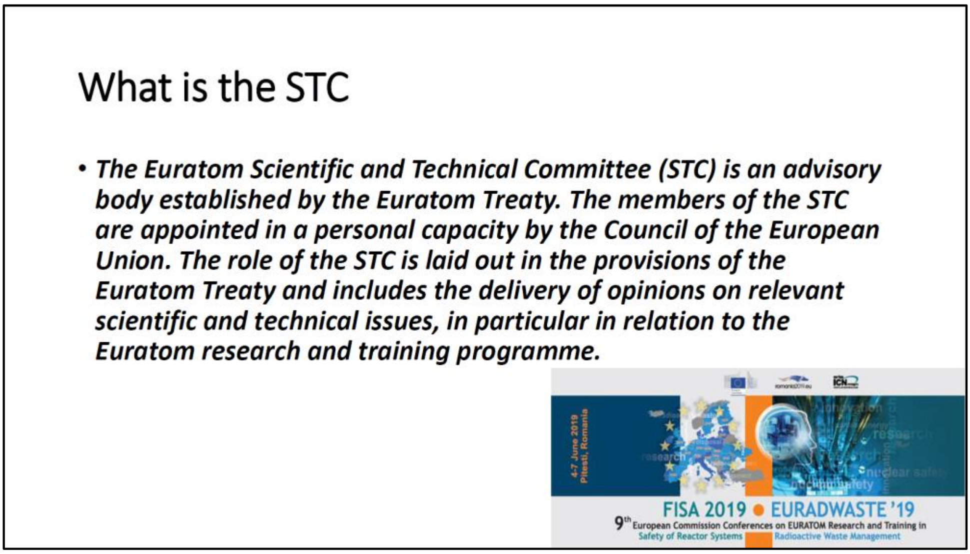
FISA 2019 – EURADWASTE '19

Presentation of Mr Martin Murray (Environment Agency, UK)

EURATOM Scientific and Technical Committee Legacy messages from the 2013-2018 Mandate



How long have we existed

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

Our Work 2013 - 2018

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

Why do we need research

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

Research Priorities

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

Future Opportunities : Limited Future Funding

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

Looking forward

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

Opening up other research fields for Euratom research

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

ROGER GARBIL

Euratom Success Stories in Facilitating Pan-European Education and Training Collaborative Efforts

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

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

1. Introduction to the European landscape

Nuclear power plants (NPP) currently provide 30 % of the overall European electricity generated and 15 % of the primary energy consumed in the European Union. In 2016, 126 NPPs are in operation in Europe, representing a total installed electrical capacity of 137 GWe and a gross electricity generation of around 850 TWh per year. Nuclear fission is a major contributor already today as a low-carbon technology in the Energy Union's strategy to reduce its fossil fuel dependency and to fulfil its 2020/2030/2050/COP21 energy and climate policy objectives [1] however the sector is currently facing several challenges: a) one concerns the plans of most EU Member States (MS) to extend the design lifetime of their nuclear power plants; b) other countries, such as France, Finland, Czech Republic, Hungary and the UK, are planning new builds; c) while others, like Germany, are either considering or have excluded nuclear energy from their energy mix for now; d) a bigger share of renewables should be fostered at European level; and e) fierce international competition is taking place on a global level. Interest in nuclear power is boosted by the need to ensure a secure and competitive supply of energy and by concern over climate change. Finally, whether or not Member States will continue to use nuclear for their electricity production, for both energy and non-energy applications, Europe will need to keep and train highly qualified staff across the whole continent and share its knowledge worldwide.

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

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

The EC promotes and facilitates through the Euratom Framework Programmes (FP) [3] nuclear research and training activities within MS and complements them through its specific Community FP. R&D activities supporting the enhancement of the highest nuclear safety standards in Europe are mainly promoted by EC DG RTD indirect actions together with JRC direct actions. JRC has also been providing for 30 years internationally recognized scientific and technical support e.g. training courses, educational modules, support to the European Safeguards R&D Association (ESARDA), and CBRN risk areas of chemical, biological, radiological and nuclear. European and International safeguards authorities such as Euratom, MS and IAEA benefitted from JRC's dedicated R&D and operational support in collaboration with other EC DGs, ENER, TRADE, DEVCO and EEAS [4]. Beyond EU borders, DEVCO manages the 'Instrument for Stability (IfS)' and the 'Instrument for Nuclear Safety Cooperation (INSC)' where among others an initiative on Training and Tutoring (T&T) provided post graduate professional education to expert staff at Nuclear Regulatory Authorities (NRA) and Technical Support Organizations (TSO), both in terms of management and of technical means in the areas of nuclear safety and radiation protection which proved to be very successful in strengthening local organizations and regional cooperation.

3. EU/Euratom initiatives are being capitalized

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

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

Successful Euratom EFTS - selected on a competitive basis and promoted through the scientific community (detailed information on all projects is available on CORDIS [10]) - covered highly relevant E&T needs for industry (energy and non-energy including medical) and associated end-users: ECNET (2011-13), EU-China nuclear cooperation; ENEN-III (2009-13), Generation III and IV engineering training schemes for nuclear systems suppliers and engineering companies; TRASNUSAFE (2010-14) nuclear safety culture in health physics (e.g. ALARA principle applied to both industrial and medical fields); CORONA-II (2015-18) on the creation of a regional center of competence for VVER technology and nuclear applications; CINCH-II (2013-16) cooperation establishing a European MSc in nuclear and radiochemistry; EUTEMPE-RX (2013-16) for Medical Physics Experts in Radiology and focusing on the implementation of the BSS Directive; GENTLE (2013-16) delivering graduate and executive nuclear training and lifelong education with a focus on synergies between industry and academia; NUSHARE (2013-16) on nuclear safety culture competences for policy makers, regulatory authorities and industry; PETRUS III (2013-15) a program for a European RadWaste MSc, E&T research on underground storage addressing mainly radiation waste management agencies; ENEN-RU-II (2014-17), ETKM MSc cooperation with Russia, ROSATOM and MEPhi and VVER technology; and ENETRAP-III (2014-18) MSc in radiological protection addressing mainly nuclear regulatory authorities and TSOs. Some of the above EFTS are developing European Passport (Europass) based on personal transcripts of records and learning outcomes modules obtained through various paths (traditional face-to-face, virtual classroom, training and tutoring, internships, workshops, webinars, on-line or blended learning tools such as e-learning or today's Massive Open Online Courses (MOOC)). IT technologies are being set to transform today the higher education system, benefitting from the huge capabilities of computer simulations and virtual reality accessible anywhere and at any time, however it will never constitute per se a license of a practice or an official authorization to operate or to supervise nuclear facilities from national nuclear regulatory authorities but complementary IT tools benefits for E&T and KSC management have to be acknowledged.

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

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

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

The OECD/NEA Generation-IV International Forum (GIF) [13] has stimulated innovation towards sustainable nuclear reactor technologies since the year 2001 such as Sodium-cooled Fast Reactor (SFR), Lead-cooled Fast Reactor (LFR), Very High-Temperature Reactor (VHTR), Gas-Cooled Fast Reactor (GFR), Supercritical Water Cooled Reactor (SCWR) and Molten Salt Reactor (MSR). On the basis of an EU Commission Decision, EU/Euratom acceded to GIF by signing in July 2003 the 'Charter of the Generation IV Forum' and the International 'Framework Agreement' existing between all Members of the Generation IV International Forum. The Joint Research Centre (JRC) of the European Commission is the Implementing Agent for EU/Euratom within GIF. In November 2016, EU Commissioner T. Navracsics has signed on behalf of EU/Euratom the agreement to extend for another ten years the Framework Agreement for an International Cooperation on Research and Development of Generation IV Nuclear Energy Systems. EU/Euratom contributions shall also be extended towards all respective six GIF Systems Arrangements as Fast Neutron Reactor systems are considered as key for the deployment of sustainable nuclear fission energy. EU/Euratom framework programmes constantly promote research and training, innovation and demonstration of nuclear fission technologies to achieve EU SET-Plan objectives being: by 2020, (1) to maintain the safety and competitiveness in fission technology, and (2) to provide long-term waste management solutions; and by 2050, (3) to complete the demonstration of a new generation (Gen-IV) of fission reactors with increased sustainability namely via the European Sustainable Nuclear Fission Industrial Initiative (ESNII), and (4) to enlarge nuclear fission applications beyond electricity production through the Nuclear Cogeneration Industrial Initiative (NC2I).

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

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

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

Some projects were 'concept-oriented' such as: CP-ESFR (2009-13) Collaborative Project on European Sodium Fast Reactor; LEADER (2010-13) Lead-cooled European Advanced Demonstration Reactor; HELIMNET (2010-12) Heavy liquid metal network; GOFASTR (2010-13) European Gas Cooled Fast Reactor; VINCO (2015-18) Visegrad Initiative for Nuclear Cooperation; ESNII+

(2013 17) Preparing ESNII for HORIZON 2020; EVOL (2010-13) Evaluation and Viability of Liquid Fuel Fast Reactor System; SAMOFAR (2015-19) A Paradigm Shift in Reactor Safety with the Molten Salt Fast Reactor, MYRTE (2015-19) MYRRHA Research and Transmutation Endeavour and ESFR-SMART (2017-21) European Sodium Fast Reactor Safety Measures Assessment and Research Tools.

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

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

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

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

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

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

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

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

5. EU/Euratom research perspectives and outreach

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

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

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

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

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

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

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

References

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

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

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

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

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

[6] Strategic Energy Technology Plan (SET-Plan)
http://ec.europa.eu/energy/technology/set_plan/set_plan_en.htm

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

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

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

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

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

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

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

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

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

SESSION 1
SAFETY OF NUCLEAR INSTALLATIONS

SUMMARY SESSION 1 - SAFETY OF NUCLEAR INSTALLATIONS

Chair: Teodor CHIRICA (FORATOM, BE), President
Co-chair: Maria BETTI (DG JRC, EC), Director of Directorate for Nuclear Safety and Security
Expert rapporteur: Abderrahim AL MAZOUZI (EDF, FR)

Attendance: 45-50 delegates

Europe produces about 25% of its electricity through the operation of 131 reactors. Maintaining a high level of safety and competitiveness is a major challenge and requires the establishment of a coordinated R & D programme at European level.

The first session of two on safety of nuclear installations is devoted to reactor performance, system reliability, advanced numerical simulation and modelling for reactor safety, as well as to long-term operation of current Generation II-III reactors. As identified within SNETP-NUGENIA Generation II-III water cooled reactor technology and technical research areas, the last topic is an important challenge since most countries 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, both nuclear operators and regulators need to have, in addition to a skilled and well-trained workforce, reliable tools to assess the ageing and degradation processes of components and structures, as well as methods and guidelines for their validation and safe management.

The Keynote speaker Michel Maschi (president of NUGENIA association and vice president of EDF R&D) has pointed out that:

To date, the NUGENIA association made up of 110 members from 25 Countries nuclear power plant operators have joined forces to build R & D programmes since 2011 with research centres, nuclear industry and technical support organizations. With the support of the European Commission, it has made possible to launch transnational programmes with major R & D advances in fields as varied as severe accidents, the estimation of the lifespan of critical components or the development of methodologies such as non-destructive control. Nevertheless, these progresses must now be part of a logic of industrial deployment that will allow Europe to have a globally competitive nuclear sector, particularly with China and Russia. The establishment of an ambitious R & D programme will also consolidate a very high-level nuclear science and technology sector where spin-offs impact the energy, construction and industrial manufacturing industries.

An analysis of recent technological innovations in the field of manufacturing, digital technology and safety approaches leads us to propose three R & D and innovation priorities for the next FP9 Horizon Europe Framework Programme (2021-2027)

The establishment of an ambitious R & D & I programme is on-going to consolidate a very high-level nuclear science and technology sector whose spin-offs impact the energy, construction and industrial manufacturing industries.

In his talk, he highlighted the historical achievement of the young association NUGENIA and address the needed innovation to strengthen the important role of nuclear in the combat against climate change as it is low CO2-emission, safe, efficient and a competitive energy source. He pointed out the following domains in which the innovation appears at hands provided a substantial support from industries, policy makers and founding organisations:

Innovations and Competitiveness of Nuclear:

In conjunction with the deployment of renewable energies, the production of nuclear electricity is one of the solutions to meet the challenges of climate change. In addition to nuclear power reactors such as the European Power Reactor (EPR), Europe needs to broaden the available offer to meet national specificities. The development of SMR (Small Modular Reactors) is a possible way for Europe. The establishment of a shared R & D programme at European level will lead to a detailed design by 2025 based on harmonised European safety standards. In order to reconcile the development of safer and more competitive European reactors, ambitious R & D programmes are also needed to optimize particularly passive systems or new nuclear fuels EATF (Enhanced Accident Tolerant Fuel) that are more resistant to accidental situations. This is to stay ahead of the US and lead to industrial deployments by the end of the next decade. The acceleration of the transfer to the nuclear industry of emerging technologies in the field of additive manufacturing or civil engineering will become effective only through the implementation of applied research programmes based on the construction of demonstration prototypes. By creating European technological competitiveness clusters, the spin-offs go beyond the nuclear sector.

Digital Transition:

The digital transformation of the industry is a reality and nuclear energy is part of this underlying trend. In order to accelerate collaborations between industrial players and European academics, it is essential to build a European digital integration bench in order to achieve a digital twin such as a Digital Reactor. Russia (Rosatom), the USA via the DOE and China are fully committed to this approach. A European federated programme around this issue will lead towards the definition of a digital integration bench comparable to that which the aeronautical industry has created. This is a major technical and organizational challenge. Concerted integration work at the European level is essential to make progress in terms of multi-physics modeling and simulation (High Performance Computing), data analysis (Data Analytics), visualization (e.g. Virtual Reality), advanced instrumentation (e.g. IOT Internet of Things) and control-command. The benefits of this ambition go beyond the scope of the nuclear sector and reinforce the programmes already undertaken by Europe on the digital field.

Safety and Environment

The existing nuclear fleet makes it possible to produce electricity without CO2 emissions and meets the challenges of energy independence in Europe. Safety is a priority for the nuclear industry and must lead to the establishment of safety standards. For power plants in operation, Europe must continue to share R & D programmes in the areas of accidents and hazards such as earthquakes, fire or severe accidents but also on methodological approaches such as Probabilistic Studies. The programme shall strengthen the construction of a pan-European network of experimental infrastructures.

Safety concerns all phases of the life of a nuclear installation. Decommissioning is an area on which Europe must make progress in terms of research and standards. A decommissioning R & D programme will enable Europe to master the end of the nuclear installations cycle and also to position the European industry in this growing sector.

Questions and Answers

Q1: *Would it be possible to make a specific passive system accepted by different countries?*

A1: R&D shall help overcoming this important issue. In fact, it is maybe the only way to demonstrate the usefulness of any type of system and therefore making it accepted by the one or the other safety authority.

Q2: *Is NUGENIA proposing also Marie-Curie Type projects?*

A2: Well NUGENIA helps addressing the main R&D topics through its roadmap and also through labellisation of projects

Complements: the Marie Curie will be open for Euratom activities starting next framework programme (Horizon Europe) and discussion are still on going on how to make use of it in an efficient way.

Q3: *When the NUGENIA roadmap will be published?*

A3: We have been busy over the last months to allow the creation of the new SNETP legal association, now that is done, we will target the publication within the next months as the work has almost been done.

Q4: Has NUGENIA included in its vision, the ECO-DESIGN directive?

A4: Not yet, but it shall be taken into account shortly.

Reactor Performance, system reliability: Long-Term Operation based on Horizon 2020 projects INCEFA-PLUS, SOTERIA, ATLAS-PLUS, MEACTOS and FP7-NUGENIA-PLUS

Being aware of the challenges of long-term operation, especially the severe safety and environmental consequences shown through historical nuclear power plant accidents (e.g. Fukushima or Chernobyl), it is imperative that European research and innovation focuses on demonstrating reliable long-term operation. This challenge is how to predict material performance over at least 60 years, when there is no experience of such long exposures. It is relevant to new build and to current operating plants. Four of the projects covered by this paper have tackled this challenge:

- **INCEFA+** focusses on improving predictability of fatigue endurance for austenitic stainless steel, in light water reactor environment, over extended operation. Tests are accelerated, compared to plant conditions, through cyclic loading that is more frequent than would occur in plant. Statistical significance for the findings is assured through a large test matrix, adherence to common test materials and finishes, commonly agreed testing methods, and consistent data recording.
- **SOTERIA** tackles long-term radiation damage to Reactor Pressure Vessel steels (which can suffer embrittlement), and Reactor Internals (which can become susceptible to Irradiation Assisted Stress Corrosion Cracking, IASCC). There is emphasis in this project on developing mechanistic understanding of the degradation processes, and using this to develop models that can be used to extrapolate to long-term operation. The understanding in this project derives from detailed examination of materials at various scales from sub-atomic to whole test specimens.
- **MEACTOS** is tackling the sensitivity of Stress Corrosion Cracking (SCC) to surface finish. The goal is creation of practical guidelines on the creation of surface finishes able to have maximum resistance to SCC over extended operation.
- Several of the pilot projects performed under **NUGENIA+** were focused on materials performance.

A recurrent requirement for being able to justify extended materials performance is the availability of statistically significant data, able to demonstrate the trends in materials behaviour necessary for extrapolation to long lives. For INCEFA+, SOTERIA and MEACTOS, the resource requirements for the testing are significant and beyond the capabilities of any single laboratory. Furthermore, there remain significant differences in opinion as to how accelerated testing should be done. The assembly of focused consortia, comprising the majority of European expertise, enables development of robust test strategies that can be better defended under scrutiny from outside Europe, and from regulatory bodies. The combining of resources also helps maximise the statistical significance of the project findings. It is notable that all three projects have developed international links beyond Europe (especially in the USA and Japan) that also help ensure best practice and provide access to additional supporting data.

The likely remaining challenges can be summarized as follows:

- How laboratory findings translate into full sacle components?
- How to overcome data accessibility barriers for the long-term operation to ensure statistical significance?
- How to validate experimentally and on-site the developed methodologies, models and understandings?

Questions and Answers

Q5: *How would you do if you discover one or the other issue in a NPP? and you do have a code or standard to deal with?*

A5: From the environmental fatigue standing point, we are in the situation that the USNRC code seems to be very conservative to assess the residual lifetime of some components, therefore we have to provide statistically relevant data of high quality in order to improve it.

<u>*Reactor Performance, system reliability: Instrumentation and control, based on Horizon-2020 projects ADVISE, NOMAD, TEAMCABLES, FP7-HARMONICS*</u>

The effective maintenance of nuclear power plants is essential for their safe operation. Maintenance ensures that the level of reliability and effectiveness of all safety-relevant components and systems remains in accordance with design assumptions, and also that it is not adversely affected during operation. Scheduling preventive and corrective maintenance operations requires an understanding of ageing mechanisms for the different components and materials used in plants, as well as a thorough and quantitative assessment of the health and reliability of safety-relevant components.

With three out of four projects running in their second year and only one terminated, it is appropriate to discuss challenges and achievements at the same time.

The principal scientific challenge faced by HARMONICS was to formally justify high to very high reliability figures for a given piece of software: It is extremely difficult to claim and formally demonstrate failure probabilities lower than 1E-4, and moreover, no universally accepted approach for the quantitative evaluation of software reliability exists. HARMONICS answered this challenge with a safety justification framework for the software of systems implementing category A nuclear safety functions.

For ADVISE, NOMAD and TeaM Cables, the main scientific challenge of all these projects is to obtain a deeper understanding of operation-induced degradation mechanisms. This will be carried out by applying innovative Non-Destructive Examination (NDE) methods in ADVISE and NOMAD, and will be used to develop NDE methods in TeaM Cables.

For the larger part of the currently operating generation 2 plants with an initial design life of 40 years, the lifetime extension to 60 years has become economically viable. For many components of these plants, NDE has often been designed as an afterthought, rather than being an integral part of the design. This lesson has been learnt, and leads to three interesting paradigm changes:

- Continuous monitoring of the structural health of components has demonstrated its added value in other industries (such as aviation/aerospace) as a complement to in-service inspections at programmed intervals, and is progressively making its way into the nuclear industry.
- Ageing models, fed with data from continuous monitoring and in service inspections, allow for predictive maintenance (as opposed to scheduled maintenance). The question of how to aggregate and use such data has led to the development of digital replica of components.
- Inspection-oriented design, already well-established in instrumentation & control, has to be considered at manufacture and for replacement components.

Questions and Answers

Q6: *About Harmonics project: Zero defect software is not achievable.You need to involve the safety authority and minimise the risk of failure otherwise it would be difficult to deal with public acceptability?*

A6: Talking about risk assessment in an inappropriate manner (even if with numbers <10-6) does not help progressing. We should come to a direct dialogue between technology provider and regulator to define the best trade-off between risks and benefits for safety.

<u>*Advanced numerical simulation and modelling for reactor safety based on Horizon 2020 projects: CORTEX, McSAFE, FP7-NURESAFE and FP7-HPMC*</u>

The safe and reliable operation of nuclear power plants relies on many intertwined aspects involving technological and human factors, as well as the relation between those. On the technological side, the pillars of reactor safety are based on the demonstration that a reactor can withstand the effect of disturbances or anomalies. Predictive simulations have always been one of the backbones of nuclear reactor safety.

Nuclear reactors are by essence multi-physics and multi-scale systems, the techniques that were then favoured relied on modelling the different fields of physics and sometimes the different scales by different codes that were only thereafter coupled between each other. In the current best-estimate approaches, the modelling of neutron transport, fluid dynamics and heat transfer is thus based on a multi-stage computational procedure involving many approximations.

Because of the progress recently made in computer architectures, high performance computing techniques can be used for modelling nuclear reactor systems, thus replacing the legacy approaches by truly high-fidelity methods.

Using the NURESIM platform, challenging Direct Numerical Simulation (DNS) & Large-Eddy Simulation (LES), simulations were performed within NURESAFE to analyse bubbly flows with and without phase change in order to understand intricate phenomena that are beyond measurements capabilities.

In the area of Monte Carlo methods, the methods for depletion and dynamic calculations are close to their culmination. The developed coupled codes based on the Interface for Code Coupling (ICoCo)-methodology are now implemented in the European simulation platform NURESIM and the testing and validation phase will soon start.

Application to LWR and SMR are foreseen to demonstrate the extended capabilities of the multi-physics codes.

Generally, it can be stated that considerable efforts are still needed for high-fidelity simulations based on Monte Carlo codes in an High Performance Computing (HPC)-environment in order to perform core analysis with acceptable statistics for the key parameters of interest.

For such a purpose, machine learning was demonstrated in CORTEX, using simulated test data, to be potentially capable of retrieving anomalies. Tests on actual plant data remain nevertheless to prove the viability of this technique.

Beyond neutronics, thermal-hydraulics, and thermo-mechanics, other as important physics might need to be included: fuel physics, structural mechanics, coolant and radiation chemistry, radionuclide transport, etc. Truly multi-physics and multi-scale modelling approaches still need to be developed at a more mature level for tackling such situations. This includes the development of new models, their coupling, as well as the use of the latest advancements in numerical analysis optimized for HPC.

This requires having different scientific communities collaborating and capitalizing on each other's strengths and expertise. With so challenging modelling targets, the use of machine learning for predictive modelling should also be considered, where machine learning could be used in place of or in addition to more traditional modelling approaches.

The enormous amount of measured data at commercial reactors, research reactors, and experimental facilities represent a definite asset, in a machine learning-based modelling strategy, that should be utilized as much as possible.

Questions and Answers

Q7: *Many software/codes/platforms have been developed over the various framework programmes, they are now either open sources or accessible via contact of the developers. Europe has done a great job but not to the same level as in the USA /CASL. Who is really using these tools (industry/regulator)?*

A7: Yes, some universities are also using them in their national research programme as well as NRG for the assessment of MTR PALLAS.

Q8: *What about cybersecurity?*

A8: Yes, it's a real issue although in NPPs, the computing is almost done off-line. However with the increase of digitalization, of the use of artificial intelligence and learning machine, attention has to be raised on this issue

The Finnish nuclear programme, including LTO and new build: see the presentation.

Q9: *Finland is one of the most active countries regarding new builds, surprisingly with different technologies which necessitates many different competencies and skills.*

A9: The choice of the technology is based on public bids and also stated as historical choices.

General Discussion and research perspectives

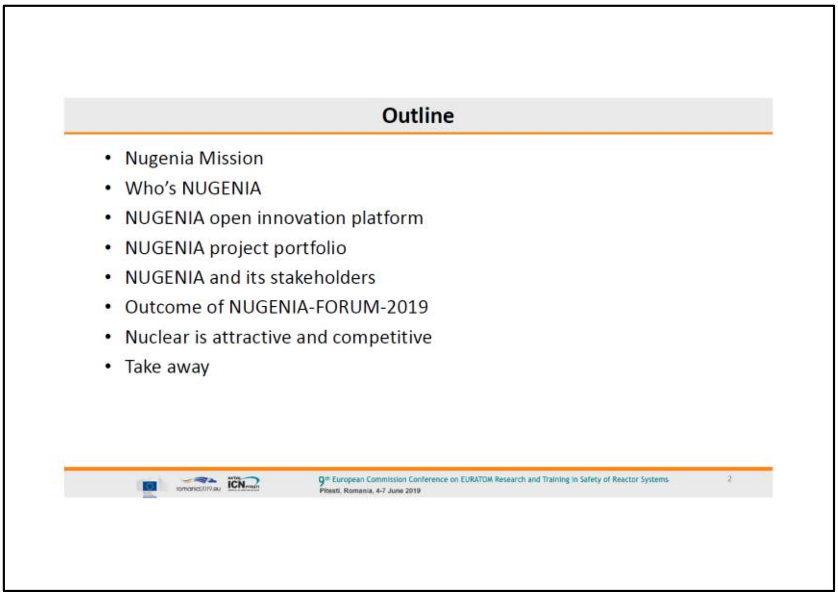
- R&D is a must to ensure a safe, efficient and competitive nuclear energy in the future European energy mix, therefore it is necessary to strengthen collaboration between public and industrial organisations: the EC shall keep up with its role providing this kind of fora and also supporting the innovation in this field
- The past and on-going projects have proved the usefulness of European collaboration in providing new knowledge and data, and it is mandatory to improve the coordination within the EU but also at the international level.
- Many effort have been devoted during last decades to develop new/advanced physical models and computer simulation codes of high fidelity but they are unfortunately hardly implemented within the European industry or even regulatory bodies.
- The use of advanced simulation tools would necessitate the introduction of new technologies such as artificial intelligence, on-line monitoring, deep-learning. It becomes therefore important that the Euratom program takes into account new threats/challenges such as cybersecurity, bigdata

MICHEL MASCHI

FISA 2019 – EURADWASTE '19

Presentation of Mr Michel Maschi (EDF, FR)

SNETP-NUGENIA Research and Innovation in Nuclear



What is NUGENIA?

Definition

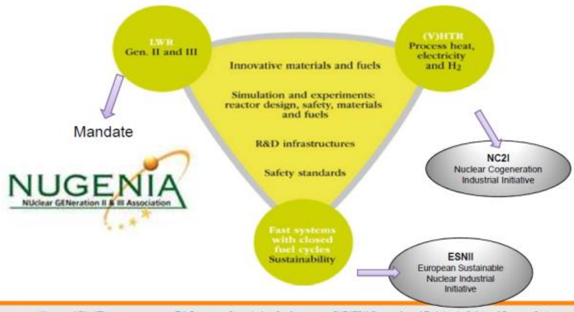
- NUGENIA is an international non-profit association founded under Belgian legislation in November 2011 and launched in March 2012

Mission

- Its mission is to be an integrated framework for safe, reliable and competitive Gen II & III fission technologies, whose objectives are to:
  - Fosters collaboration between industry, SMEs, RTOs, academia and technical safety organisations
  - Build knowledge and expertise
  - Facilitate the emergence of innovation
  - Maintain and develop the needed skills, competences to tackle the up-coming challenges (LTO, new build, dismantling, ….)

NUGENIA in the SNETP frame

The *Sustainable Nuclear Energy Technology Platform* is the European forum dedicated to nuclear fission technologies, with a focus on three strategic pillars:



Who is NUGENIA today?

- **Members: major nuclear stakeholders**
  - 103 full members and 8 honorary members from 24 countries *(as of April 2019)*: Industry, utilities, research institutions, SMEs and technical safety organisations

- **Honorary Members**

Work fields

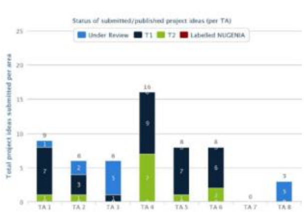
Technical Areas

1. Plant Safety and Risk
2. Severe Accidents
3. Improved Nuclear Power Plant Operation
4. Integrity of Systems, Structures and Component
5. Fuel Development, Waste & Spent Fuel Management and Decommissioning
6. Innovative LWR Design & Technology
7. Harmonisation
8. In-Service Inspection and Qualification

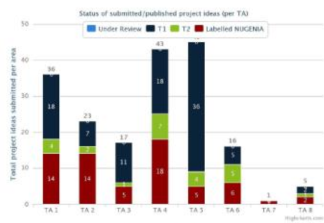
- Targets
  - Raising public awareness on nuclear R&D
  - Supporting technical excellence
  - Improve safety in operation and by design
  - Efficient integration of NPPs in the energy mix
  - High reliability of components

Project ideas: Bottom-up approach

- NUGENIA Open Innovation Platform (NOIP) allowed identification of more than 180 project ideas (more than 1000 users)
- 63 project ideas labelled since May 2014



Sept' 2014



May 2019

9th European Commission Conference on EURATOM Research and Training in Safety of Reactor Systems
Pitesti, Romania, 4-7 June 2019

NUGENIA+ project: Making NUGENIA ready for Horizon 2020 and beyond

- The ultimate goal of the N+ project is strengthening of the role of NUGENIA
  - to become the reference association able to structure the R&D at the European level integrating private and public efforts, and
  - To initiate international collaboration creating added value in its activity
- 32 new partners joined the 18 original partners as the result of the pilot research project call launched in September 2014

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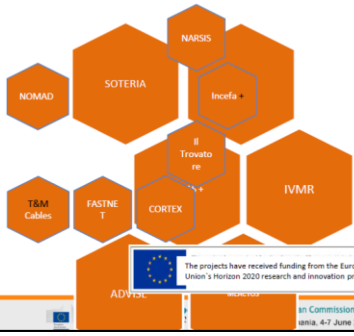
Pitesti, Romania, 4-7 June 2019

NUGENIA portfolio (1/3)

18 H2020 Euratom ongoing projects

- 13 running since 2016-2017…



The projects have received funding from the European Union's Horizon 2020 research and innovation programme

- **SOTERIA** *(CEA): Safe LTO of LWR (Degradation of RPV and RVI, follow-up project of FP7 projects PERFORM60 & LONGLIFE);*
- ***Mc Safe*** *(KIT): High-Performance Monte Carlo Methods for SAFEty Demonstration – From Proof of Concept to realistic Safety Analysis and to Industry-like Applications*
- ***INCEFA+*** *(Wood): INcreasing Safety in NPPs by Covering gaps in Environmental Fatigue Assessment*
- ***IVMR*** *(UJV): Management Strategy of In-Vessel Melt Retention in existing and future NPPs*
- ***ATLAS +*** *(VTT):* Advanced Structural Integrity Assessment Tools for Safe Long Term Operation
- **MEACTOS** (CIEMAT): Mitigating EAC Through Optimisation of Surface condition
- **ADVISE** (EDF): Advanced Inspection of Complex Structures
- **NOMAD** (IZFP): NDE System for the inspection of operation-induced material degradation
- **T&M CABLES** (EDF): European Tools and Methodologies for an efficient ageing management of nuclear power plant cables
- **Il Trovatore** (SCK-CEN): Innovative cladding materials for advanced accident-tolerant energy systems
- **CORTEX** (IRSN): Non-Intrusive Core Monitoring Techniques Relying on Inherent Reactor Dynamics
- **FASTNET** (IRSN): Fast Accident Source Term tools for Emergency Centers
- **NARSIS** (CEA): New Approach to Reactor Safety Improvements

NUGENIA portfolio (2/3)

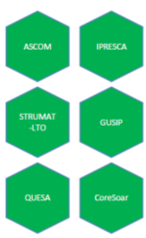
18 H2020 Euratom ongoing projects

- …And 5 started in 2019!

- ***R2CA*** *(IRSN): Reduction of Radiological Consequences in design basis Accident (R2CA)*
- ***MUSA*** *(CIEMAT): Management & uncertainties of severe accidents*
- ***SCO2-4 NPP*** *(EDF): sCO2-based heat removal technology FOR and increased level of safety of Nuclear Power Plants*
- ***SHARE*** *(CEA): StakeHolder-based Analysis of REsearch for Decommissioning*
- ***ELSMOR*** *(VTT): towards European Licensing of Small Modular Reactors*

NUGENIA portfolio (3/3)

6 in-kind on-going projects



- **Projects description**
  - **CoreSOAR** (IRSN): In-Vessel Core Degradation State-of-the-Art Report Update
  - **QUESA** (IRSN): QUENCH experiment with Steam and Air
  - **GUSIP** (EDF): Guidance on the USability of a Inspection Procedure
  - **IPRESCA** (IRSN): Integration of Pool Scrubbing Research to enhance Source-term Calculations
  - **ASCOM** (IRSN) : ASTEC Community
  - **STRUMAT-LTO** (NRG) – STRUctural MATerials research for safe Long-Term Operation of LWR NPPs

A portfolio of about 120 M€, and more than 2500 europeans experts are involved
70% of the members are contributing to at least one project

NUGENIA Interactions

- **MoU signed between NUGENIA and:**
  - IAEA
  - European Radiation Protection Research Platforms (MELODI, EURADOS, NERIS, ALLIANCE: MENA)
  - Ministry of Economic Affairs and Employment of Finland
  - .....


March 18, 2015: Third General Assembly in London ratified EPRI as Honorary member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NUGENIA Interactions

- **NUGENIA R&D Stakeholders' sessions**
  - Exchanges with the NUGENIA ExCom Members to share views on NUGENIA Activities and potential synergies
  - Several Sessions in February, May and December:
    - *Spain (Madrid – Empresarios Agrupados)*
    - *Czech Republic (Prague/Rez – UJV, CV Rez, CEZ)*
    - *UK (Manchester - Wood, NIRO)*
    - *France (Paris – CEA)*
    - *Finland (Helsinki – Fortum & VTT)*
    - *Hungary (Budapest- Bay Zoltan & MTA-EK)*


Helsinki Session

Budapest Session

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After Budapest (2012, 2013), Madrid (2014), Ljubljana (2015)
Marseille (2016), Amsterdam (2017), Prague (2018),

<u>Main Topics to be discussed:</u>
✓Improved safety: passive systems and ATF
✓Hazards and environment: severe-accidents, earthquakes, fire, etc.
✓Digital transition: multi-physics modeling and simulation, data analysis, visualisation, advanced instrumentation
✓Components manufacturing: additive manufacturing, civil engineering
✓Decommissioning and dismantling: advanced tools and methods
✓Innovation and competetiveness of Nuclear: flexibility, SMR,

260 participants representing 90 organisations

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Pitesti, Romania, 4-7 June 2019

Fostering Nuclear Industry R&D

Competitive

Attractive

Driving Research and Innovation toward existing fleet and new built

Nuclear of the Future

Competitive

Develop technological bricks

- Providing *a global and long-term vision*, with clearly identified milestones
- *Accelerating* integration of outsourced technological breakthroughs
- Identifying and tackling *technological and scientific challenges*
- Bridging academic and industrial research
- Featuring *flexibility:* new designs / existing fleet in operation

Attractive

Showcase nuclear R&D and communicate

- Rally academic partners to tackle our scientific challenges
- Enlarge collaboration to new players (start-up, SME)
- Attract new talented people

Safety

Reducing severe accident impact & improving operation margins

Enhanced Accident Tolerant Fuel

SiC/SiC concept (release of silica, manufacturability)

Seismic evaluation to address more stringent requirement

Extreme hazards, experimental data (knowledge acquisition, validation) and design of seismic-proof equipment

Passive systems to simplify new built design

Dimensions constraints limiting the ability to fulfill the function, ability of the codes to handle the phenomena

New Fabrication and Repair solutions

Identify game changing technologies

Powder metallurgy

- Additive Manufacturing (3D Printing) for spare parts or new components
- High Isostatic Pressure (HIP) manufacturing

Metallurgic and mechanical properties for nuclear use, control methods

Polymers

New technology and methods of rebar concrete and steel concrete panel

Fast and reliable welding process, control methods for concrete

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Digital Transition and Data Analytics

Keys performances enablers to simplify operation and design

Outage preparation : as built Reactor Building Mock up and deep learning tools

Adding more intelligence into digital models

Predictive maintenance with data analytics

Handle heterogeneous data

Virtual power plant, Digital Twins for operation and maintenance

Enhanced interaction by the use of virtual reality, develop the links with simulation codes

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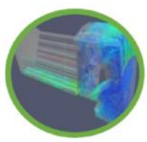
Digital Twins for Operation & Maintenance



Process/multi-Systems

System

Local/building

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Pitesti, Romania, 4-7 June 2019

Take away

NUGENIA has achieved:

- Strong **involvement** of utilities, vendors, suppliers, safety and R&D
- Annual **work plans** setting priorities, involving public authorities and private organisations
- A transparent **open-innovation process**: NUGENIA facilitates the bottom-up emergence of projects within the roadmap
- Balanced cooperation with **international counterparts on cross-cutting issues**

...still to do:

- Contribute to preparation of the **next generation** of researchers and engineers
- Future **structuring** within public-private (PPP) and/or public-public partnerships (P2P)
- Play a **driving role** in the implementation of **Horizon Europe/SET-PLAN** objectives
- Increase the **integration of innovation** (shorten the time to market through R&D)
- Development of mutual understanding through **public engagement**

Thank you for your attention

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KEVIN MOTTERSHEAD

SAFETY ASSURANCE THROUGH ADVANCES IN LONG-TERM OPERATION

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Abstract. Mindful of the challenges to long-term operation, especially the severe safety and environmental consequences shown through historical nuclear power plant accidents (e.g. Fukoshima, Chernobyl, etc), it is imperative that European research and innovation focuses on demonstrating reliable long-term operation. Five examples of European Commission supported projects meeting such objectives are INCEFA+, SOTERIA, ATLAS+, MEACTOS and NUGENIA+. There are economies of scale within, and synergies across these projects which enable further advantage to be gained. Additionally, since researchers are well engaged internationally, this brings into European Organisations latest developments in understanding from further afield (e.g. USA, Japan), further enabling safety assurance advances, and enabling work overseas to be influenced consistent with European requirements. Through examples, this paper provides evidence of the advances claimed, whilst being careful to also declare areas of interest for which further work is still a priority.

1. Introduction

This paper presents evidence of the advances gained from selected European Commission supported Horizon2020 and FP7 projects, supporting long-term operation of nuclear power plant. The paper begins by briefly introducing the projects. Nuclear industry operational issues leading to long-term operation challenges are then described. These challenges are summarised next, together with examples of how the EC supported project portfolio has combined to meet some of these. The paper concludes with a summary of the challenges remaining, and activities underway to meet them.

2. The EC supported project portfolio

The authors of this paper are coordinators of five EC supported projects, four current, and one complete. These are described briefly here, and their relevance to long-term operation challenges is summarised later.

- **INCEFA+[1] (INcreasing safety in nuclear power plants by Covering gaps in Environmental Fatigue Assessment)** began work in July 2015 (though the consortium had been together on an in-kind basis since 2013). 16 organisations participate in this project, which is funded at €2.5M over 5 years from the EC, and in excess of €3.6M from national sponsors. This project's focus is on creation of new environmental fatigue data aimed at improving understanding of fatigue sensitivity to three common parameters of interest, namely, effects of surface finish, hold time and mean stress. The objective is the creation of assessment rules that are able to predict fatigue lives which are more consistent with plant experience than is the case for present ASME/USNRC guidance. The project will reduce assessment conservatism through the creation of more reliable consistent data than has hitherto been available; this is through partners working to an agreed test protocol, and using common material specimens all made in the same facility. Detailed material and specimen characterisation data are collected to help understand data outliers.

- **SOTERIA[2] (Safe lOng TERm operation of light water reactors based on Improved understanding of rAdiation effects in nuclear structural materials)** began work in September 2015, building on many years of collaboration for consortium members within previous projects. 23 organisations work in this project, which is funded at €5M over 4 years from the EC, and in excess of €1M from national sponsors. The project is developing understanding of ageing phenomena in reactor pressure vessel steels and reactor internals. Experiments are performed to explore flux and fluence effects, effects of metallurgical heterogeneities, and environmental effects on materials ageing behaviours. Modelling tools are developed to help with assessment of structural components, based on the developed understanding.

- **MEACTOS[3] (Mitigating Environmentally Assisted Cracking (EAC) Through Optimization of Surface condition)** started in September 2017 and runs for 4 years. 16 organisations participate and the EC supports the project with €2.5M funding, with greater than €1.5M national sponsor funding. This project will quantify the effect of various surface treatment

[1] This project has received funding from the Euratom Research & Training programme 2014-2018 under grant agreement N°662320. The project website is https://incefaplus.unican.es

[2] This project has received funding from the Euratom Research & Training programme 2014-2018 under grant agreement N°661913. The project website is http://soteria-project.eu

[3] This project has received funding from the Euratom H2020 programme 2014-2018 under grant agreement No 755439. The project website is https://meactos.eu

techniques on the EAC behaviour of nuclear primary circuit structural materials, with the objective of developing practical guidelines suitable for incorporation in nuclear design and manufacturing codes. SCC testing is done using specimens with a variety of surface finishes. Significant demonstration of machining procedures, applied successfully in industries such as aeronautics or automotive to mitigate against SCC, is included in the test programme.

- **ATLAS+**[4] (**Advanced Structural Integrity Assessment Tools for Safe Long Term Operation**) began in June 2017 and runs for 4 years. 19 organizations collaborate with €4M EC funding, and more than €3.2M from national sponsors. Five different innovative large scale experiments are planned to generate data for validation of advanced modelling tools for application to nuclear piping systems and associated components. Modelling tool development is focussed on simulation and assessment of weld residual stresses and prediction of large ductile tearing. Assessment of safety margins using probabilistic methods is also being explored.

- **NUGENIA+**[5] ran from September 2013 to September 2016. The project comprised two parts. Part 1 was concerned with optimising the way NUGENIA is managed such that it could fill the role of the European Commission's chosen integrator of Research and Development focussed on safety of existing Gen II and future Gen III nuclear installations. During Part 2, there was a call for proposals for small pilot projects, and 13 projects were chosen (with 50% EC funding totalling €2.6M) and managed under NUGENIA+. The chosen pilot projects addressed subject areas encompassing materials analysis, fluid dynamics modelling, materials forming, inspection, materials degradation, soil mechanics, test optimisation, and test data management.

3. The Nuclear Industry Operational Issues

The issues leading to long-term operational challenges can be categorised as economic, engineering, legislative, and safety.

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[4] This project has received funding from the Euratom H2020 programme under grant agreement No 754589. The public website is under construction

[5] This project has received funding from the Euratom Research & Training programme 2007-2013 under grant agreement N°604965. The NUGENIA website is http://nugenia.org

3.1 Economic issues

Reference [0] provides a good general summary of the up to date position for electricity generation in Europe, and the role of nuclear power in this. Presently, the nuclear capacity being retired, through either life expiry or political pressure, significantly exceeds the capacity under construction. As a result, forecasts are for European nuclear generation capacity to reduce, at least in the period to 2030. The effects of this reducing capacity, on confidence in electrical generation capacity, are further compounded by a) retirements of fossil fuelled capacity driven by environmental concerns, b) uncertainties in security of supply for the significant remaining fossil fuels imported from outside Europe, and c) significant delays bringing new nuclear generation capacity into service throughout Europe. Thus, there are clearly strong economic drivers to keep as much as possible of the existing European Nuclear capacity running for as long as possible.

3.2 Engineering issues

The engineering issues come from exposure of power plant materials to degradation phenomena and/or environmental exposure conditions never foreseen when the plant were designed, for example:

- Increased dose leading to materials embrittlement, swelling and cracking susceptibility.
- Increased exposure of materials and structures to operation at high temperature and pressure, leading to:
    - Higher than anticipated creep damage.
    - Material embrittlement.
    - Material properties degradation due to thermal effects.
    - Increased susceptibility to Environmental Assisted Cracking.
- Increased numbers of thermal and pressure cycles leading to increased fatigue.
- A switch from traditional base-load operations to load-following operations [0] leading to increased temperature and pressure cycling.

3.3 Legislative issues

Irrespective of European country, operation of nuclear power plant is underpinned by a safety case, justifying the safety of operation, and approved by a regulatory authority. The validity of safety cases often takes advantage of assessments to available codes and standards (e.g. ASME, ISO). The attraction is the standards' internationally agreed status, underpinned by significant collaborative discussions. Generally, the requirements of standards are stable, since they require significant international consensus to revise, but occasionally significant iterations in standards can emerge which require attention in safety submissions.

Thus, creation of challenge to long-term operation can arise:

- When an assessor needs to justify operation beyond the scope of available standards.

– When a significant update to available standards necessitates safety case revision if the case is to remain compliant with the standard.

3.4 Safety issues

Public perceptions of nuclear power as an environmentally clean source of electricity are improved today, compared with a few decades ago. However, awareness of the significant consequences possible following nuclear accidents is also very strong given some high profile events such as Fukoshima, Chernobyl, Three Mile Island and the Windscale fire. Therefore, high reliability assurance of safety is rightly demanded for nuclear power plant. For this reason, assurance of safety sits behind all of the issues discussed above. It also drives the need for high confidence in predictions of material degradation or structural integrity.

4. Long-term operation challenges and the advances gained from the project portfolio

There are a number of challenges arising from the issues described above. Some are mainly relevant to new plant, others to older operating plant, and some to both situations. Each challenge is described in the following sub-sections, together with examples of how the challenge has been met by the project portfolio covered by this paper.

4.1 Materials performance over at least 60 years

This challenge is, how to predict material performance over at least 60 years, when there is no experience of such long exposures? It is relevant to new build and to current plant. Four of the projects covered by this paper have tackled this challenge:

– INCEFA+ focusses on improving predictability of fatigue endurance for austenitic stainless steel, in light water reactor environment, over extended operation. Tests are accelerated, compared to plant conditions, through cyclic loading that is more frequent than would occur in plant. However, care is taken to ensure that loading rates are not so fast as to render environmental effects irrelevant, since this would invalidate the results for supporting long-term operation. Statistical significance for the findings is assured through a large test matrix, adherence to common test materials and finishes, common agreed testing methods, and consistent data recording.

– SOTERIA tackles long-term radiation damage to Reactor Pressure Vessel steels (which can suffer embrittlement), and Reactor Internals (which can become susceptible to Irradiation Assisted Stress Corrosion Cracking, IASCC). There is emphasis in this project on developing mechanistic understanding of the degradation processes, and using this to develop models that can be used to extrapolate to long-term operation. The understanding in this project derives from detailed examination of materials at various scales from sub-atomic to whole test specimens.

– MEACTOS is tackling the sensitivity of Stress Corrosion Cracking (SCC) to surface finish. The goal is creation of practical guidelines on the creation of surface finishes able to have maximum resistance to SCC over extended operation. Whilst not specifically targeting extrapolation of susceptibility to the long-term, the programme will determine optimum surface finishes that can then be proven through accelerated testing. Optimisation of accelerated test methods is one of the objectives of this project in order to allow it to deliver its primary objective. Since surface finish is of interest to both MEACTOS and INCEFA+, there has been collaboration between these projects, particularly regarding consistent creation and measurement of surface finishes.

- Several of the pilot projects performed under NUGENIA+ were focussed on materials performance. McSCAMP, MICRIN+ and ASATAR separately looked at effects of machining on SCC, and at different types of SCC test and their suitability for accelerated testing; the larger MEACTOS project benefitted from these pilot projects. APLUS delivered standard protocols for analysis of atom probe data that were available to SOTERIA, which has used atom probe tomography to investigate microstructure evolution under irradiation of RPV steels. AGE60+ investigated use of common test databases, with particular focus on data collation relating to RPV embrittlement and SCC of reactor internals. Both these subject areas have been progressed further during SOTERIA, whilst INCEFA+'s focus on use of a common long-term test database is also consistent with the recommendations of AGE60+.
- A recurrent requirement for being able to justify extended materials performance is the availability of statistically significant data, able to demonstrate the trends in materials behaviour necessary for extrapolation to long lives. For INCEFA+, SOTERIA and MEACTOS, the resource requirements for the testing are significant and beyond the capabilities of any one laboratory. Furthermore, there remain significant differences in opinion as to how accelerated testing should be done. The assembly of focussed consortia, comprising the majority of European expertise, enables development of robust test strategies that can be better defended under scrutiny from outside Europe, and from regulatory bodies. The combining of resources also helps maximise the statistical significance of the project findings. It is notable that all three projects have developed international links beyond Europe (especially in the USA and Japan) that also help ensure best practice and provide access to additional supporting data.
- The NUGENIA+ pilot projects were small (by definition), with small consortia. Nonetheless, through exposure to peer scrutiny via NUGENIA, the ideas generated for possible extended work could be properly evaluated for maximum benefit.

4.2 Materials choice for long-term operation

This challenge is relevant to new-build plant. The work described in the preceding section is relevant. In particular, the work being done by INCEFA+ and MEACTOS will help plant designers choose surface finishes best able to mitigate either environmental fatigue or SCC. It is also notable that MEACTOS is testing both austenitic stainless steels and nickel-based alloys, and INCEFA+ is testing some stabilised materials for comparison with the standard 304 stainless steel used for most of its tests.

Other than these examples, it is true that the projects mostly concentrate on limited material selections. However, development of mechanistic understanding does offer the chance of extrapolating findings to other materials, albeit with the need to do confirmatory testing eventually. SOTERIA and MEACTOS, in particular, are both significantly increasing mechanistic understanding and so their findings are relevant to this challenge.

4.3 Design code fitness for purpose

As described above, plant safety cases, as much as possible, take advantage of codes and standards. However, circumstances do arise, for both new and operating plant, when assessors have to consider safety justification for conditions beyond the scope of such references. Challenges are as follows:

- How to extrapolate beyond the scope of codes? For example, some codes prescribe minimum allowable thicknesses (MAT). However, for localised defects, tolerable penetration can be allowed to exceed MAT. Assessments to justify such departures must obviously be robust and defendable.
- How to alleviate excessive code conservatism that is not considered relevant? For example, many codes have evolved over significant time, with factors of safety introduced over the years for a variety of reasons, often due to emerging research. Sometimes, conservatisms can compound. Whilst conservatism is retained with this approach, it can be excessively pessimistic for some circumstances. For an assessor to justify departure from accepted advice, there is (rightly) a strong requirement for reliable, statistically significant evidence.

The project portfolio has tackled these challenges as follows:

- INCEFA+ was set up in direct response to emergent United Stated Regulatory Commission (USNRC) guidance to assume an environmental penalty for assessments of endurance in light water reactor (LWR) conditions. This penalty applies to design curves for fatigue endurance in air, that already contain allowances for effects such as surface condition. There is evidence to show that some effects already allowed for in air design curves, do not have the same effect in LWR conditions; however, the quantity and statistical significance of available data was insufficient to justify departure from USNRC recommendations. INCEFA+ tackles three sensitivities, surface finish, hold time and mean stress, and determines how these vary between air and LWR environments. By combining 13 European laboratory resources, the project is creating the quantity of data needed for a robust response on these issues. Furthermore, by agreement of common test protocols, data formats, and use of common materials and specimen conditions, the project reducing scatter leading to further statistical reliability.
- Building on the NUGENIA+ pilot projects, MEACTOS tackles established practice to control surface finish of components in terms only of surface roughness. The belief is that newly available machining techniques offer the potential for SCC susceptibility mitigation. The project will produce guidelines for designers to use to specify surface finish requirements. The validity of accelerated SCC testing methods can be questioned, and furthermore resource requirements for SCC testing can be large. Bringing together leading European expertise helps, a) ensure best practice, and b)

deliver statistical significance. Inclusion of industrial machining expertise also maximises the likely relevance and usefulness of the project guidelines.

- ATLAS+ is developing improved methods for prediction of ductile tearing for large defects in components, and for undertaking leak-before-break (LBB) assessments of piping components. The project will quantify the uncertainties and confidence in these methods using probabilistic approaches. Such assessments are specialised and beyond the scope of basic design codes; thus, high confidence is a requirement for use of such techniques. The ATLAS+ strategy is an assessment programme examining residual stress effects, validated using a comprehensive multiscale testing programme. The test programme is demanding of resources, since it includes large scale testing as well as conventional lab specimen tests. Furthermore, the assessment methodologies are specialised. Thus, a major ATLAS+ advantage is the assembled consortium. This provides the test resources necessary, and also combines leading European experts for this subject. The result promises to be highly significant and likely to be positively received internationally.
- The NUGENIA+ pilot project DEFI-PROSAFE explored potential benefits of a probabilistic integrity assessment approach for Reactor Pressure Vessel assessment. Results suggested possible significant positive impact potential for margin to long-term operation. These findings are available for building on at some stage.

4.4 Justification for operation of structures

This applies to operational and new-build plant. Obviously, materials understanding, combined with code familiarity are both important to meet this challenge. However, structural response must also be tackled, in particular there must be confidence in the possible failure mode. Assessors must demonstrate that failure would be benign rather than catastrophic (e.g LBB).

ATLAS+ and the earlier NUGENIA+ pilot project DEFI-PROSAFE are both clearly focussed on this challenge, one for pipes, and one for RPV’s.

4.5 Threat mitigation through inspection

This applies to all stages of plant life. Once degradation is credible, the next challenges are how quickly cracks may propagate, and how reliably propagation could be detected prior to it becoming problematic? Each of the four full projects, plus several NUGENIA+ pilot projects, deliver useful advances in understanding of degradation timescales.

For flaw detection, the NUGENIA+ pilot projects REDUCE and MAPAID are relevant. MAPAID considered the reliability of Phased Array ultrasonic inspection of dissimilar metal welds. REDUCE evaluated the reduced risk possible through use of in-service inspection. These projects were pre-cursors to the projects NOMAD[6] and ADVISE[7]. These projects are not within the scope of this paper.

4.6 Expertise availability

Many European organisations have skewed staff demographics resulting from limited recruitment during the 1990's in particular. The result is a pool of expertise at, or already beyond, retirement age, with limited expertise in the successor staff. Development of the next generation of experts is important to maintain capability to meet the challenges to long-term operation. Expertise availability challenge also arises from reduced interest of the new generations in nuclear energy. Some analysts suggest the cause is competition from renewable energy sources. However, although nuclear accidents have created negative reaction, growing energy demand and non-generation of greenhouse gases also keeps nuclear energy as a "green" option, which should help public perception. Perhaps, the problem comes from nuclear sector conservatism, from which overprotection has slowed technological innovation.

The most attractive professional careers are those with highest technological content. Many technologies and innovative approaches for fabrication, repair and joining are currently available in non-nuclear industries, but are not addressed in nuclear codes and standards or endorsed by regulatory bodies. This difficulty about the adoption of technologies threatens the nuclear industry with technological obsolescence. Restoring the nuclear industry's lead in technology development is important to recover attractiveness for working in this sector.

Fortunately, dissemination and sponsoring of students is encouraged in EC supported projects. Furthermore, the projects in this paper will significantly advance understanding in some technologically advanced subjects. Examples of this are as follows:

- INCEFA+
  - A public website is maintained, along with a ResearchGate presence and a Twitter account. Significant traffic demonstrates interest in INCEFA+.
  - The project is presented at international conferences (e.g., ASME Code Week 2017, NPFA 2017, ASME PVP2017 and 2018, PLiM2017, annual NUGENIA Forums, Fracture Fatigue and Wear 2018, 22nd European Conference on Fracture). Project presentations are committed for 2019 and 2020.
  - Project special sessions have taken place at the XVIII International Colloquium on Mechanical Fatigue of Metals (ICMFM XVIII, September 2016, Gijón, Spain), and at the ASME PVP2018 conference in July 2018 in Prague, Czech Republic.
  - The dissemination activity has led to nine international scientific papers indexed in Scopus; the events expected for 2019 and 2020

[6] This project has received funding from the Euratom H2020 programme under grant agreement No 755330.

[7] This project has received funding from the Euratom H2020 programme under grant agreement No 755500.

will increase this number. Also, a third project session is agreed to take place at ASME PVP2020.

  - The first Seminar and Workshop Dissemination event was in June 2018 in Santander, Spain. This provided an introduction to fatigue and environmental fatigue phenomena, and to the treatment of them for different industries, through presentations by experts from industrial and research organisations. The seminar was designed for PhD and Masters students, professional engineers and researchers new to the field, or experienced researchers and engineers wishing to update their knowledge and share experiences. The event was attended by about 70 people and feedback was excellent.
  - A second dissemination workshop, designed to appeal to established researchers, is planned for June 2020 in Aix-en-Provence, France.
- SOTERIA
  - The demographic challenge in SOTERIA is mainly addressed through the dissemination activities (training school and workshops).
  - The SOTERIA Training School was held in September 2018 in Valencia (Spain), with the aim of transferring and preserving the knowledge about nuclear reactor pressure vessel and internals materials degradation mechanisms to students, post-docs and early career professionals, as well as to scientists and engineers working on these areas. The school hosted 60 participants, including students, lecturers and organisers, with a share of 20% women and 80% men. While most students were in their early career, many 'advanced' students also attended. The participants came from 29 different organisations, distributed in 13 different countries. About 80% of the organisations represented at the school were European, but there was also presence from Argentina, Rep. of Armenia, Mexico, Ukraine and Switzerland. Most participants came from research and development (R&D) organisations although utilities, safety authorities and technical safety organisations were also represented. The programme, focused on the effects of irradiation on RPV and internals materials, with emphasis on a long-term operation approach, comprised three days of lectures and two days of interactive sessions, with hands-on demonstrations, working with the new version of the SOTERIA platform. From analysis of the questionnaire filled in by school attendees, it is clear that the training school was positively appreciated.
  - The SOTERIA Mid-term Workshop was in April 2018 in Prague. The workshop was a great opportunity for dissemination of important results achieved in SOTERIA. It was also useful to facilitate interchange of ideas and experiences with the full Nuclear Research Community, especially with NUGENIA members. On the last day, a Joint Technical Session, with other related NUGENIA projects (NOMAD, ADVISE, INCEFA+, ATLAS+ and MEACTOS), was held to exchange information and available results.
  - The SOTERIA Final Workshop is in June 2019 in Miraflores de la Sierra (Madrid). The objective is to disseminate project final results among nuclear research and industrial communities, and particularly end-users, as well as identifying future research needs. The workshop will be a forum for regulators, user groups, experts and industry, to

exchange information and experiences on radiation effects on nuclear power plant components.

- MEACTOS
  - An objective of MEACTOS is to reduce technological obsolescence associated with the nuclear industry, evaluating the applicability of procedures for machining/surface modification of materials that have shown their effectiveness in other industrial sectors.
  - MEACTOS is committed to dissemination and exploitation of results, and has created the role of Exploitation Manager to further this. This Manager has responsibility for finding the best ways to exploit project results, for coordinating exploitation-related issues within the Consortium, such as patents, licenses, diffusions activities, and for coordinating possible negotiations concerning exploitation issues between the Consortium and external partners.
  - Actions to introduce nuclear technology to a new generation of professional are:
    - Presentation of project contents in different nuclear forums of participating countries.
    - Co-organize a summer school in cooperation with European corrosion federation NuCoss, to be in Slovenia in 2019 with expected attendance of 40 participants.
    - Create a web page to inform about the project, activities and events.
    - Formation of at least two new PhDs.
    - Maximize the interest and impact in the stakeholders, creating an End User Group (EUG), to which three new organizations have joined.
- ATLAS+
  - The knowledge transfer seminar with the title "Seminar on Piping Issues in ATLAS+ (SEPIA)" was organized in October 2018 in Ljubljana. 37 people attended. The aim was to introduce and educate colleagues new in the field in the ATLAS+ technical topics. The discussions, and questions and answers, after the presentations demonstrated great interest. Feedback from attendees after the seminar was positive and they expressed the wish to repeat this type of activity. Abstracts and presentations were provided to all participants.
  - ATLAS+ members disseminated first results at the ASME PVP2018 conference, in July 2018 in Prague. One session with four presentations was organised under the topic of European programs in structural integrity. Papers are planned for PVP2019. PVP papers appear in conference proceedings.
  - The ATLAS+ disseminations will be able to be followed on a website.
  - ATLAS+ has nine training missions, where new researchers can visit another organisation. The goal is learning and sharing knowledge in ATLAS+ topics.
  - A training book on the lessons learnt in ATLAS+ and summary of the final seminar is published at the end of the project.
- NUGENIA+
  - NUGENIA+ pilot projects were small, and so major dissemination activities within each project were limited. However, through

NUGENIA, there has been significant dissemination of NUGENIA+ results. The pilot projects were presented and discussed at a final workshop in 2016 in Helsinki, Finland. This was open to all NUGENIA members. Ever since, it is still possible to learn about NUGENIA+ projects through the NUGENIA website; where the details provide contacts if more details are sought.

- o A major objective for NUGENIA is the building of knowledge and expertise in Europe. Recent examples of success in this include, a) provision of grants to facilitate short secondments of young researchers to other organisations, and b) organising a paper competition for PhD students at the NUGENIA 2019 Forum, through which the students gained exposure to industry experts.

5. Remaining challenges

The NUGENIA+ pilot projects were small, and intended to demonstrate the benefits possible through more work. Thus, remaining challenge from these projects was inevitable and varied.

For the four full projects, the likely remaining challenge varies as follows:

- By its end, INCEFA+ will have delivered advances in understanding of the sensitivities of fatigue endurance to surface finish, hold time and mean stress in both air and LWR environments. This will be mainly for a single heat of 304 stainless steel; thus, understanding of the effects of material variability will remain a challenge, albeit not a serious one given low variability evident in literature for austenitic stainless steels. Regarding test condition sensitivities, the project has focussed on four, and so others will remain. Of these, the dominant remaining challenge will be how laboratory findings translate to full component scale; in fact, plans are developing for the consortium to possibly continue by addressing this knowledge gap next.
- SOTERIA's multi-scale approach to developing understanding of irradiation effects on degradation of RPV and Internals materials will deliver advances mechanistically. However, largely due to the high cost of the tests being done, the actual number of data points generated will be limited. Hence, statistical significance will remain a challenge. Furthermore, data accessibility for the long-term from this and predecessor projects is a challenge affecting usefulness of project findings for plant assessors. Building on INCEFA+ experiences, the SOTERIA consortium proposes to focus on this challenge after the project ends. Meanwhile, accumulation of IASCC test evidence and understanding is also proposed to continue in a parallel possible project.
- The main MEACTOS focus is determination of optimum machining methods for SCC mitigation. As noted, the collection of a powerful consortium comprising experts in understanding and testing, and machining, promises impressive advances. However, once an optimum machining method is determined, it is likely that focussed testing to parameterise sensitivity to SCC for that method, for a variety of candidate materials, will be needed. This will support statistical substantiation sufficient for the guidance to become definitive.

– The position for ATLAS+ is different to the other projects, since the objective for the project is to deliver assessment methodologies validated using a multiscale test programme. At this stage it is not so straightforward to define the remaining challenges. Clearly, data availability into the future must be a concern, as it is for SOTERIA. Also, there will remain knowledge gaps to be pursued.

The ongoing nature of these research streams could perhaps indicate problems realising the project benefits. However, the projects' influence on international research and development has been demonstrated through interest in engaging with the projects from the USA and Far East in particular. Two examples of this are, a) data sharing agreements being set up by INCEFA+ with USNRC, EPRI and JNRA, and b) user groups set up for SOTERIA and MEACTOS, showing active industrial engagement and interest.

6. Conclusions

Safety assurance through advances in long-term operation requires research and development activities that tackle, extended period materials performance, selection of materials for new plant, improvements to design and assessment codes, structural performance, mitigation of risk through inspection, and expertise availability. Since activities to gain advances in these areas are demanding in terms of resource needed, either because of the cost of testing, or because of the volume of data required for statistical significance, it follows that the best advances are when expert organisations combine forces. The EC support for research and development activities provides funding to enable coordinated activities to be performed by expert consortia. The advantages this enables are demonstrated by reference to developments arising from the FP7 NUGENIA+ pilot projects, and from the running Horizon2020, INCEFA+, SOTERIA, MEACTOS and ATLAS+ projects. This paper also postulates the challenges likely to remain when these projects have ended.

References

[1] World Nuclear Association, Nuclear Power in the European Union, July 2018 http://www.world-nuclear.org/information-library/country-profiles/others/european-union.aspx

[2] Lokhov A, OECD. Load-following with nuclear power plants. NEA updates, NEW News 2011 – No. 29.2 https://www.oecd-nea.org/nea-news/2011/29-2/nea-news-29-2-load-following-e.pdf

ANDREAS SCHUMM

REACTOR PERFORMANCE, SYSTEM RELIABILITY, INSTRUMENTATION AND CONTROL

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Abstract. We present a cross-cutting review of three on-going Horizon 2020 projects (ADVISE, NOMAD, Team CABLES) and one already finished FP7 project (HARMONICS), which address the reliability of safety-relevant components and systems in nuclear power plants, with a scope ranging from the pressure vessel and primary loop to safety-critical software systems and electrical cables. The paper discusses scientific challenges faced in the beginning and achievements made throughout the projects, including the industrial impact and lessons learned. Two particular 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 nuclear power plants.

1. Introduction

The effective maintenance of nuclear power plants is essential for their safe operation. Maintenance ensures that the level of reliability and effectiveness of all safety-relevant components and systems remains in accordance with design assumptions, and also that it is not adversely affected during operation [1].

Scheduling preventive and corrective maintenance operations requires an understanding of ageing mechanisms for the 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 to this challenge, and cover a wide range of "safety relevant components and systems". ADVISE [2] and NOMAD [3] aim to improve quantitative Non-destructive Evaluation Techniques (NDE) to components in the primary loop (restricted to cladded components in NOMAD and to materials with complex microstructure in ADVISE) to obtain a quantitative assessment of the structural integrity of the components at hand. TEAM Cables [4] aims to improve the understanding of ageing mechanisms on cables used in plants (specifically to the polymers used in the insulation), to model this ageing, and to devise NDE and monitoring techniques for the health assessment. HARMONICS [5], the only project of the four already terminated, extends this approach to the software of computer-based I&C safety systems.

This review is intended to be voluntarily cross-cutting, focusing on achievements, challenges and impacts of these projects rather than giving exhaustive descriptions, with an 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.

Table 1. *Key figures for concerned projects.*

Project	Duration	Funding	Lead	Partners	Framework
ADVISE	09/17-09/21	4,2ME	EDF	11	H2020
NOMAD	06/17-12/21	4,9ME	Fraunhofer	10	H2020
TEAM CABLES	09/17-12/21	4,2ME	EDF	13	H2020
HARMONICS	01/11-01/15	1,0 ME	VTT	5	FP7

1.1. ADVISE

ADVISE is an acronym for "advanced inspection of complex structured materials" and aims to advance the ultrasonic inspection of complex structured materials, for which conventional ultrasonic techniques suffer from severe performance limitations due to the micro and/or macro-structure. The most prominent examples of materials concerned are welds and cast austenitic stainless steel.

The key idea of the project is to use a-priori, model-predicted and in-situ obtained information about the structure to be inspected in computer modelling in all stages of the inspection to obtain a step change improvement in terms of inspectable depth, defect detection and characterisation accuracy:

- During the inspection design, model-assisted optimisation of customised transducers and delay laws aims to specify the most appropriate inspection approach
- During the acquisition, in-situ characterisation techniques aim to acquire specific information about the structure to be inspected;
- After the acquisition, model-assisted diagnostic tools exploit the entire available information in adaptive imaging and inversion techniques.

The project admits that no single magic bullet exists, and that a number of incremental improvements need to be combined. The consortium includes industrial stake-holder, academics with specific background for the R&D tasks, and an equipment manufacturer, as well as a distributor for rapid dissemination.

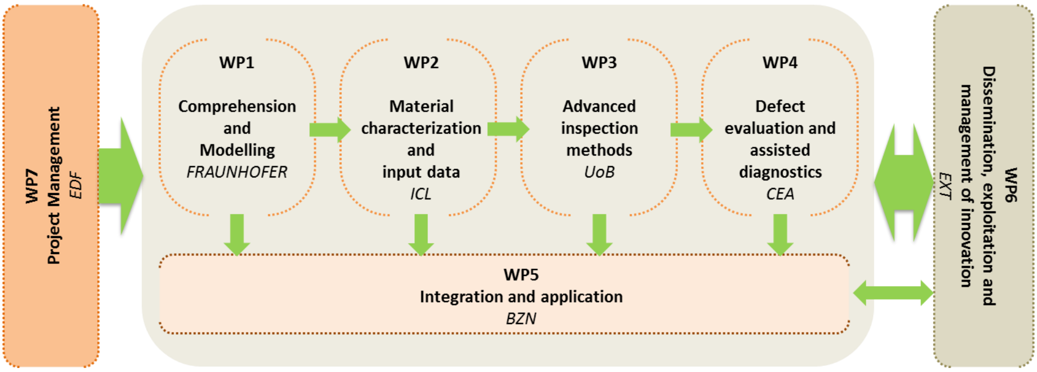

FIG. 1. ADVISE work plan.

1.2. NOMAD

NOMAD means "Nondestructive Evaluation (NDE) System for the Inspection of Operation-Induced Material Degradation in Nuclear Power Plants" and aims to develop and demonstrate an NDE approach for the quantification of neutron radiation-induced embrittlement in cladded reactor pressure vessel materials. Additionally, NOMAD focuses on the validation of the existing surveillance programs with respect to the actual vessel under LTO conditions, in terms of equivalence of radiation damage accumulation. These topics are of particular importance in terms of lifetime extension of existing operating reactors, the reactor pressure vessel (RPV) being considered the only part of the primary loop, which cannot be replaced [8,9].

A multiple scale of samples from Charpy samples, over non-cladded blocks to realistic cladded blocks, made from representative steels of eastern and western RPV design are made available in various irradiated conditions representing different realistic degradation levels. Multiple NDE technologies including micromagnetic, electrical and ultrasound-based methods are developed and applied to these multiple scales of samples in neutron-irradiated condition. The results are to be compared and combined across methods, samples and degradation parameters in order to define a hybrid approach and finally demonstrate it in a modular way.

For the first time, a systematic study in terms of correlation of microstructure, mechanical properties, neutron irradiation conditions and non-destructive properties is carried out on a well-characterized set of samples. The aim is not only to extend the existing database, but also to include issues such as reliability and uncertainties of the techniques as well as effects caused by material heterogeneity. Furthermore, the capabilities of the individual NDE techniques and, as result, the performance of the NDE tool regarding the future application in the field will be determined. The NOMAD consortium consists of partners with complementary expertise having common interest in the project goals: academic partners for identifying the problems in details and developing the suitable measurement methods, industrial partners guiding the developments by representing the market-needs and also industrial partners, end-user-group or external scientific advisory board for the validation of the needs but the solutions as well.

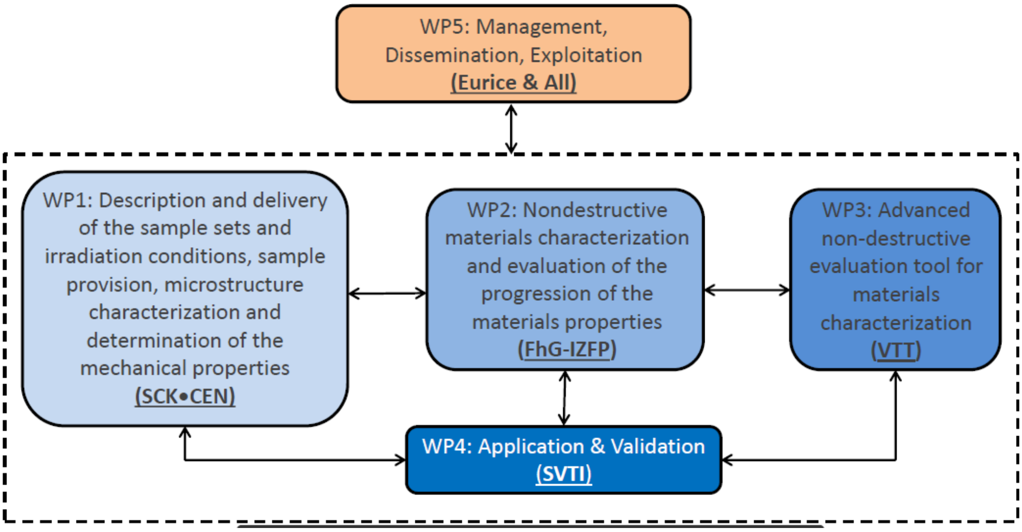

FIG. 2. NOMAD work plan.

1.3. TEAM CABLES

TeaM Cables focuses on European tools and methodologies for an efficient ageing management of nuclear power plant cables and addresses the challenge of long term operation for cables – more precisely, their polymer insulation, which is subjected to aging. The sheer amount of cables in a NPP (about 1500 km for one nuclear unit, or twice as much for a typical 2 reactor plant) makes the replacement of cables economically unfeasible, which requires for accurate predictive models for their safe lifetime, as well as for generic tools and methods for on-site monitoring.

TeaM Cables will develop a novel multiscale approach for more precise estimation of the cable lifetime. Cable lifetime is governed by polymer layers lifetime. A large part of the project is so dedicated to polymer science. The project will analyse the effects of irradiation and temperatures on polymers from micro- to macroscale level, in order to develop multiscale models of ageing. Ageing in normal operation conditions and accidental conditions will be addressed. The unique multi-scale and kinetic models will be 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 will be proposed for on-site use of non-destructive testing techniques.

The program combines highly scientific work packages for the actual polymer ageing kinetics models with experimental work packages to obtain data throughout accelerated ageing. The consortium is comprised of stake-holders, cable manufacturers, academic partners with specific experience in polymer aging kinetics modelling, as well as applied institutes for the experimental and NDE aspects.

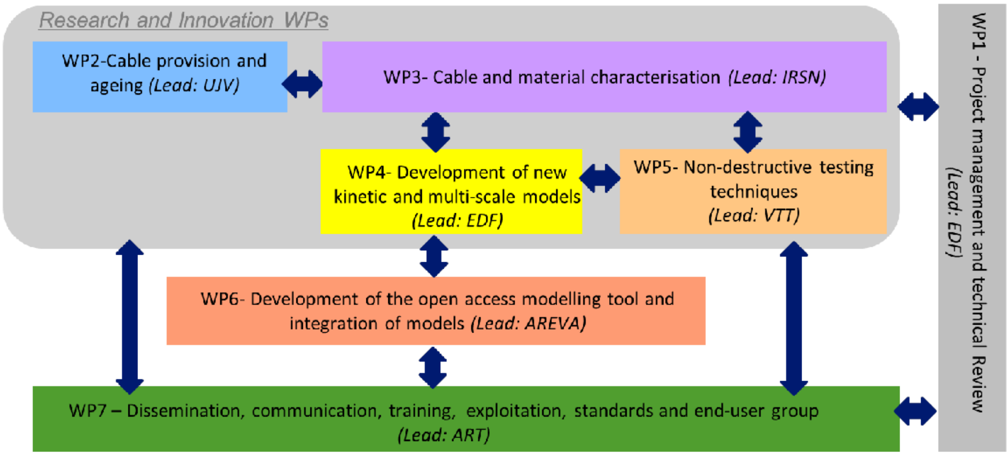

FIG. 3. TeaM Cables work plan.

1.4. HARMONICS

HARMONICS (abbreviation for Harmonised Assessment of Reliability of MOdern Nuclear I&C Software) recognized that software can in general not be proven to be completely defect-free, and addressed the issue of reliability and safety of the computer-based systems that implement safety functions in nuclear power plants. HARMONICS had the objective to ensure well founded and up-to-date methods and data for assessing software of computer-based safety systems in Gen-II and Gen-III NPPs throughout the entire system lifecycle. It has taken advantage of the aforementioned advances to propose systematic and consistent, yet realistic and practical approaches for software assessment.

The project addressed three key issues: software verification & validation (V&V), software safety justification, and quantitative evaluation of software reliability. The term "software reliability" is used as a shortcut for "software-related aspects of system reliability". The focus was mainly on I&C systems performing category A functions (as defined by IEC 61226) which is the highest safety category in NPP. To support research activities on these three main issues, the project investigated and developed theories, techniques and tools as necessary. In addition, the feasibility of the developed approaches was experimented and demonstrated with selected case examples provided by the project participants and the end user group.

Related to the IAEA Report on Dependability Assessment of Software for Safety I&C Systems at NPPs started in May 2014, major results from the HARMONICS project were proposed (approaches to improve confidence in functional requirements, role of formal software verification, safety justification framework).

The consortium regrouped utilities and safety authorities and consultants, led by a multidisciplinary research organisation. As a particularity, HARMONICS had a parallel project on reliability and V&V of nuclear safety I&C software in China.

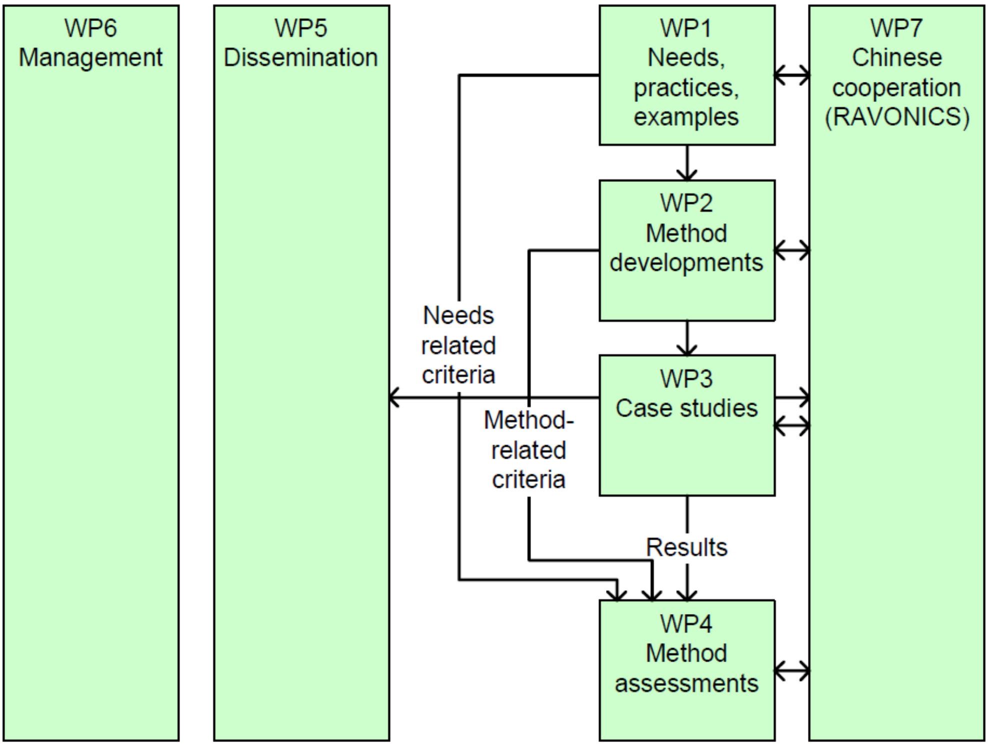

FIG. 4. Harmonics work plan.

2. Challenges, Achievements, Impact

2.1. Scientific Challenges and Achievements

With three out of four projects running in their second year and only one terminated, it is sensible to discuss challenges and achievements at the same time.

The principal scientific challenge faced by HARMONICS was to formally justify high to very high reliability figures for a given piece of software: It is extremely difficult to claim and formally demonstrate failure probabilities lower than 1E-4, and moreover, no universally accepted approach for the quantitative evaluation of software reliability exists. HARMONICS answered this challenge with a safety justification framework for the software of systems implementing category A nuclear safety functions. HARMONICS created scientific deliverables covering formal verification methods, a safety justification framework, a proposed approach to quantify software reliability, and a method on complexity analysis. An comprehensive list of publications with summaries can be found on the project's website

ADVISE, NOMAD and TeaM Cables are funded in the frame of the section "Continually improving safety and reliability of Generation II and III reactors" of the Euratom Program 2016. The main scientific challenge of all these projects is to obtain a deeper understanding of operation-induced degradation mechanisms. This will be carried out by applying innovative NDE methods in ADVISE and NOMAD, and will be used to develop NDE methods in TeaM Cables.

ADVISE established the scientific challenges early on in the project in the first technical delivery in the form of a state of the art report. The project considers this as a good means to take a snap-shot at the start of the project, which shall be used at the end of the project to measure the achievements. A major challenge for the project concerns the experimental non-destructive (as opposed to destructive laboratory analysis) characterization of material microstructure in situ, the prediction of micro- and macrostructures in weld models, and the ability of fast ultrasound simulation models to take material microstructure into account.

NOMAD's main scientific challenge is the quantification of neutron irradiation-induced embrittlement of RPV steels independent on the austenitic cladding, combining information from multiple non-destructive evaluation techniques. To this, signals originated from the cladding must be separated from the signals obtained from the base material. Another challenge is to produce irradiated cladded blocks similar to the real operating RPV and afterthat to compare the non-destructively detected material properties with those detected on irradiated Charpy samples. To this, NDE methods based on different physical principles have been developed and successfully tested on neutron-irradiated Charpy samples and thermally aged cladded blocks.

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 analysing the data based on multi-scale studies of the materials.

2.2. Industrial Impact

Shortly before the end of the HARMONICS project, the IAEA had started the development of a technical report on the Dependability Assessment of Software for Safety I&C Systems at NPPs. Several members of the HARMONICS project were part of the expert team that drafted the report, and some major results from the project were ultimately integrated into this report (approaches to improve confidence in functional requirements, role of formal software verification, safety justification framework). The research problems and the results were also disseminated in the end-user workshops during the project.

In the short term, TEAM CABLES and NOMAD intend to achieve industrial impact through a series of 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 LTO, non-destructively, fast and reducing the consumed surveillance material. TEAM CABLES will organize a training workshop for NPP operators and researchers on the developed tool. ADVISE takes a different approach, relying on the acquisition system manufacturer and the distributor of the CIVA software package to achieve rapid industrial impact. NOMAD and ADVISE realize that any novel NDE procedure will ultimately go through qualification, which is difficult to anticipate at this early stage.

In the medium term, these projects shall provide the background for robust national and EU strategies in the field of nuclear reactor safety in order to further improve the safety of RPVs in Europe and worldwide through increased resistance of safety relevant equipment. 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 where relevant, by delivering such innovations to the markets.

2.3. End user implication

Horizon 2020 focuses on dissemination, which clearly emerges in all ongoing projects. All three projects have designated dissemination work packages. TEAM Cables pushes this idea particularly far, with a summer school, two end user workshops, a training workshop for NPP operators and researchers as well as a final symposium. ADVISE and NOMAD will hold at least one joint public symposium. To ensure the industrial applicability of models and tools developed in all those projects, end-user groups composed of external advisors have been set up, with the main goal to assess the developed models and tools during and by the end of the project.

HARMONICS, which was funded by FP7, held two end user workshops in order to establish and maintain a link with stakeholders. All projects set up public web sites with detailed descriptions of the projects and their publications [2,3,4,5].

2.4. Academic involvement

TEAM Cables collaborates with the University of Bologna and ENSAM Paris, with a total of three PhDs. They will work on the development and validation of a kinetics model for polymer aging, and the use of the output of the kinetics models in multiscale models to predict mechanical, physical and electrical parameters. ADVISE and NOMAD employ several young researchers with first time contact to the nuclear industry. Four researchers with a PhD degree and two PhD students worked in HARMONICS.

3. Lessons learnt

A common challenge shared by all projects concerns the capitalization of achievements made. TEAM CABLES realized this already at the proposal stage and centers its capitalization effort around a software tool as a federating item. For ADVISE, the situation is more challenging, as a commercial software platform has been chosen to become the target of the various work-packages, which is inherently more complex and needs to comply with more requirements and restrictions. The consortium held a dedicated two day training session to address this difficulty. During the development stage, a simpler rapid prototyping tool is thus used before integration into the commercial software. Due to the nature of the HARMONICS project, a natural way to capitalize achievements was via an IAEA Safety Series publication [6].

For an experiment-centric project such as NOMAD, which deals with the characterisation of changes of the materials properties due to neutron irradiation, the characterisation of same samples before and after irradiation connected with samples irradiation beyond periodical safety reviews revealed to be a challenging issue. Such a procedure has never been performed before and turned out to require an extremely extensive preparation.

All projects were confronted with the issue of how to extend the scope of their work beyond western nuclear technology. NOMAD was able to secure a comprehensive range of neutron irradiated samples for eastern and western base and weld material, as well as non-irradiated samples from different RPV steels. ADVISE has access to Russian VVER type reactor samples through its partner UJV, who is also member of the TEAM CABLES project. HARMONICS made an attempt to enlarge its scope by teaming up with a parallel Chinese project, although the added value of this collaboration turned out to be disappointing.

4. Conclusions and Follow-up issues

For the larger part of the currently operating generation 2 plants with an initial design life of 40 years, the lifetime extension to 60 years has become economically viable and is partly due to the increased capital cost of generation 3+ reactors. The long term operation of these plants has raised issues, which are at the origin of the three ongoing H2020 projects discussed in this paper. For many components of these plants, NDE has often been designed as an afterthought, rather than being an integral part of the design. This lesson has been learnt, and leads to three interesting paradigm changes:

- Continuous monitoring of the structural health of components has demonstrated its added value in other industries (such as aviation/aerospace) as a complement to in-service inspections at programmed intervals and is progressively making its way into the nuclear industry.
- Ageing models, fed with data from continuous monitoring and in service inspections, allow for predictive maintenance (as opposed to scheduled maintenance). The question of how to aggregate and use such data has led to the development of digital replica of components.
- Inspection-oriented design, already well-established in instrumentation & control, has to be considered at manufacture and for replacement components.

References

[1] „Maintenance of Nuclear Power Plants", IAEA Safety Series No. 50-OG-07, 1990
[2] ADVISE public website https://www.advise-h2020.eu/
[3] NOMAD public website https://nomad-horizon2020.eu/
[4] Team CABLES public website https://www.team-cables.eu/
[5] HARMONICS public website http://harmonics.vtt.fi/ (see D5.6 for publications and D5.5 for end user workshop proceedings)
[6] "Instrumentation and Control Systems and Software Important to Safety for Research Reactors", IAEA Safety Guide SSG-38, 2015
[7] "Crystallization of cross-linked polyethylene by molecular dynamics simulation", Antti Paajanen, JukkaVaari and Tuukka Verho, Polymer, Vol. 171, pp. 80-86, 2019
[8] The Economics of Long-term Operation of Nuclear Power Plants, Nuclear Development 2012, Nuclear Energy Agency and Organisation for Economic co-operation and development, ISBN 978-92-64-99205-4.
[9] A. Ballesteros, R. Ahlstrand, C. Bruynooghe, U. von Estorff, L. Debarberis: The role of pressure vessel embrittlement in the long term operation of nuclear power plants, Nuclear Engineering and Design 243 (2012) 63-68.

CHRISTOPH DEMAZIÈRE

ADVANCED NUMERICAL SIMULATION AND MODELLING FOR REACTOR SAFETY – CONTRIBUTIONS FROM THE CORTEX, HPMC, MCSAFE AND NURESAFE PROJECTS

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Abstract. Predictive modelling capabilities have long represented one of the pillars of reactor safety. In this paper, an account of some projects funded by the European Commission within the seventh Framework Program (HPMC and NURESAFE projects) and Horizon2020 Program (CORTEX and McSAFE) is given. Such projects aim at, among others, developing improved solution strategies for the modelling of neutronics, thermal-hydraulics, and/or thermo-mechanics during normal operation, reactor transients and/or situations involving stationary perturbations. Although the different projects have different focus areas, they all capitalize on the most recent advancements in deterministic and probabilistic neutron transport, as well as in DNS, LES, CFD and macroscopic thermal-hydraulics modelling. The goal of the simulation strategies is to model complex multi-physics and multi-scale phenomena specific to nuclear reactors. The use of machine learning combined with such advanced simulation tools is also demonstrated to be capable of providing useful information for the detection of anomalies during operation.

1. Introduction

The safe and reliable operation of nuclear power plants relies on many intertwined aspects involving technological and human factors, as well as the relation between those. On the technological side, the pillars of reactor safety are based on the demonstration that a reactor can withstand the effect of disturbances or anomalies. This includes the prevention of incidents and should an accident occur, its mitigation.

Predictive simulations have always been one of the backbones of nuclear reactor safety. Due to the extensive efforts the Verification and Validation (V&V) of the corresponding modelling software these represent, most of the tools used by the industry are based on coarse mesh in space and low order in time approaches developed when computing resources and capabilities were limited. Because of the progress recently made in computer architectures, high performance computing techniques can be used for modelling nuclear reactor systems, thus replacing the legacy approaches by truly high-fidelity methods.

In parallel with the more faithful modelling of such systems, the monitoring of their instantaneous state is becoming increasingly important, so that possible anomalies can be detected early on and proper actions can be promptly taken. On the one hand, over 60% of the current fleet of nuclear reactors is composed of units more than 30 years old, therefore operational problems are expected to be more frequent. On the other hand, the conservatism in design previously applied to the evaluation of safety parameters has been greatly reduced, thanks to the increased level of fidelity achieved by the current modelling tools. As a result, nuclear reactors are now operating more closely to their safety limits. Operational problems may be also accentuated by other factors (e.g. use of advanced high-burnup fuel designs and heterogeneous core loadings).

In this paper, a brief account of four projects previously or currently funded by the European Commission in the area of the simulation and the monitoring of nuclear reactor systems is given. Despite the differences in nature between those projects, the key objectives and achievements with respect to advanced numerical simulation and modelling for reactor safety will be given particular emphasis. The paper will conclude with some recommendations for the future.

A glossary defining all the used abbreviations can be found at the end of the paper.

2. Short description of the respective projects

2.1. CORTEX

The CORTEX project (with CORTEX standing for CORe monitoring Techniques and EXperimental validation and demonstration) is a Research and Innovation Action financed by the European Commission. The project formally started on September 1st, 2017 for a duration of four years. The overall objective of CORTEX is to develop a core monitoring technique allowing the early detection, localization and characterization of anomalies in nuclear reactors while operating.

Being able to monitor the state of reactors while they are running at nominal conditions is extremely advantageous. The early detection of anomalies gives the possibility for the utilities to take proper actions before such problems lead to safety concerns or impact plant availability. The analysis of measured fluctuations of process parameters (primarily the neutron flux) around their mean values has the potential to provide non-intrusive on-line core monitoring capabilities. These fluctuations, often referred to as noise, primarily arise either from the turbulent character of the flow in the core, from coolant boiling (in the case of two-phase systems), or from mechanical vibrations of reactor internals. Because such fluctuations carry valuable information concerning the dynamics of the reactor core, one can infer some information about the system state under certain conditions.

A promising but challenging application of core diagnostics thus consists in using the readings of the (usually very few) detectors (out-of-core neutron counters, in-core power/flux monitors, thermocouples, pressure transducers, etc.), located inside the core and/or at its periphery, to backtrack the nature and spatial distribution of the anomaly that gives rise to the recorded fluctuations.

Although intelligent signal processing techniques could also be of help for such a purpose, they would generally not be sufficient by themselves. Therefore, a more comprehensive solution strategy is adopted in CORTEX and relies on the determination of the reactor transfer function or Green's function, and on its subsequent inversion.

The Green's function establishes a relationship between any local perturbation to the corresponding space-dependent response of the neutron flux throughout the core. In CORTEX, state-of-the-art modelling techniques relying on both deterministic and probabilistic methods are being developed for estimating the reactor transfer function. Such techniques are also being validated in specifically-designed experiments carried out in two research reactors.

Once the reactor transfer is known, artificial intelligence methods relying on machine learning techniques are used to recover from the measured detector signals the driving anomaly, its characteristic features and location.

More information about the CORTEX project can be found in [1].

2.2. HPMC and McSAFE

The projects HPMC (High Performance Monte Carlo Methods for Core Analysis) and McSAFE (High Performance Monte Carlo Methods for SAFEty Analysis) are two collaborative research projects funded by the European Commission in the seventh Framework Program (2011 to 2013) and Horizon 2020 Program (2017 to 2020) with the main goal of developing high fidelity multi-physics simulation tools for the improved design and safety evaluation of reactor cores. The peculiarity of HPMC and McSAFE is the focus on Monte Carlo neutronics solvers instead of deterministic ones, in order to take profit of the huge and cheap available computer power currently available.

The scientific goal of the HPMC was the "proof of concept" of newly developed multi-physics codes for depletion analysis taking into account thermal hydraulic feedbacks, static pin-by-pin full LWR core analysis considering local feedback, and the development of time-dependent Monte Carlo codes including the behaviour of prompt and delayed neutrons for accident analysis.

Based on the success and promising results of the HPMC project, the goal of the McSAFE project that started in September 2017 is to become a powerful numerical tool for realistic core design, safety analysis and industry-like applications of LWRs of generation II and III [2], [3]. For this purpose, the envisaged developments will permit to predict important core safety parameters with less conservatism than current state-of-the-art methods and they will make it possible to increase the performance and operational flexibility of nuclear reactors. Moreover, the multi-physics coupling developments are carried out within the European Simulation platform NURESIM developed during different projects in the seventh Framework Program such as NURESIM, NURISP and NURESAFE [4], heavily relying on the open-source SALOME-software platform. In this context, the European Monte Carlo solvers MONK, SERPENT, and TRIPOLI are coupled with the subchannel thermal-hydraulic code SUBCHANFLOW and with the thermo-mechanic solvers TRANSURANUS using the ICoCo-methodology [5].

At present, the application and demonstration are done for LWRs and SMRs. However, the peculiarity of the codes and methods make their application possible to the Gen- III and Gen-IV reactors as well as to research reactors, for which the complicated geometry and physics of the core can only be adequately simulated by Monte Carlo codes.

Finally, all developed methods and codes are validated against plant data of European VVER and PWR plants as well as using test data of the SPERT Series IV E REA.

2.3. NURESAFE

NURESAFE (NUclear REactor SAFEty simulation platform) is a collaborative research project funded by the European Commission in the seventh Framework Program [5], [6]. The project started early 2013 for a duration of three years. The main objective of NURESAFE was to develop a European reference tool for higher fidelity simulation of LWR cores for design and safety assessment.

The simulation tool developed by the NURESAFE project includes deterministic core physics codes, thermal-hydraulics and fuel thermo-mechanics codes, all integrated in a software platform whose name is NURESIM. This platform provides a capability for code coupling, capability of paramount importance as the main phenomena occurring in reactors involve an interaction between the above-mentioned physics. The NURESIM platform also offers an uncertainty quantification, which is necessary for validation and safety evaluation.

The scope of the NURESIM platform includes the simulation of steady states of LWRs and design basis accidents of LWRs. This platform was initially created in the framework of former collaborative projects within the sixth and seventh Framework Programs (NURESIM and NURISP), during which core physics and thermal-hydraulics codes were first integrated. In NURESAFE, the platform was extended to more codes, particularly fuel thermo-mechanics codes. An important part of the NURESAFE work was also dedicated to:

- The demonstration of the multi-physics capability of the platform.
- Advanced CFD modelling.
- Uncertainty quantification and validation.

3. Key objectives with respect to advanced numerical simulation and modelling for reactor safety

3.1. Introduction

As earlier mentioned, most of the modelling tools used by the nuclear industry were developed when computing resources and capabilities were limited. Although nuclear reactors are by essence multi-physics and multi-scale systems, the techniques that were then favoured relied on modelling the different fields of physics and sometimes the different scales by different codes that were only thereafter coupled between each other. In the current best-estimate approaches, the modelling of neutron transport, fluid dynamics and heat transfer is thus based on a multi-stage computational procedure involving many approximations.

On the neutronic side, deterministic approaches have been used primarily, due to their lower computational cost compared to probabilistic methods (i.e. Monte Carlo). Deterministic tools nevertheless rely on many approximations, with the neutron transport equation solved explicitly after reducing the complexity of the task at hand (typically using space-homogenization, energy-condensation, and angular approximation techniques) [7]. The problem is first solved over a small region of the computational domain using approximate boundary conditions, and the "fine-grid" solution then computed is used for producing equivalent average properties locally. In a second step, a global "coarse-grid" solution is found for the full computational domain, in which only average local properties are considered, i.e., in which the true complexity of the system is not represented explicitly. Typically, three to four of such "bottom-up" simplifications are used to model a full reactor core. Although used on a routine basis for reactor calculations, the approximations used in each of the computational steps are almost never corrected by the results of the calculations performed in the following steps when a "better" (i.e. taking a larger computational domain into account) solution has been computed.

In the probabilistic approach on the other hand, no equation as such is solved. Rather, the probability of occurrence of a nuclear reaction/process of a given type on a given nuclide at a given energy for a given incoming particle (which can still exist after the nuclear interaction) is used to sample neutron life histories throughout the system [8]. Using a very large number of such histories, actual neutron transport in the system can be simulated without requiring any simplification, and statistically meaningful results can be derived by appropriately averaging neutron tallies. However, due to the size and complexity of the systems usually modelled, Monte Carlo techniques are extremely expensive computing techniques, which limited their use for routine applications in the past.

With the advent of cheap computing resources, both the deterministic approach and the probabilistic approach are now being used on massively parallel clusters to circumvent the limitations mentioned above. In the deterministic case, the process of averaging ("bottom-up") is now being complemented by a de-averaging process ("top-down") in an iterative manner, so that a better modelling of the boundary conditions can be achieved using the information available from the coarser mesh. The modelling of full cores in a single computational step is also being contemplated. In the probabilistic case, the use of large clusters allows modelling full reactor cores, and efforts are being pursued to include the feedback effects induced by changes in the composition and/or density of the materials [9], [10]. Due to the complexity and level of details in the deterministic approach based on the averaging/de-averaging process, there are situations where the deterministic route can become quite expensive, being almost on par with the probabilistic route for high-fidelity simulations.

On the thermal-hydraulic side, the strategy is to average in time and in space the local conservation equations expressing the conservation of mass, momentum and energy. The double averaging results in a set of macroscopic conservation equations that are tractable for a large system as a nuclear reactor, unfortunately at the expense of filtering the high-frequency and small-scale phenomena [7]. In addition, the averaging process introduces new unknown quantities (expressing for instance the wall transfer and possible interfacial transfer between the phases) that are usually determined using empirical or semi-empirical correlations. These correlations are heavily dependent on the flow regimes. Such a modelling strategy is often referred to as a system code approach. With the advent of cheap computing power, current efforts focus on modelling much finer scale using CFD tools instead.

3.2. CORTEX

For the CORTEX project, since a majority of the diagnostic tasks are based on the inversion of the Green's function, the key objectives in the area of advanced numerical simulation and modelling can be summarized as follows: (a) the development of modelling capabilities for estimating the transfer function, (b) the validation of such tools against experiments specifically designed for that purpose, and (c) the inversion of the reactor transfer function using machine learning.

Concerning (a), one of the strategic objectives of the project is to determine the area of applicability of existing tools for noise analysis and to develop new simulation tools that are specifically dedicated to the modelling of the effect of stationary fluctuations in power reactors with a high level of fidelity. The ultimate goal is to develop modelling capabilities allowing the determination, for any reactor core, of the fluctuations in neutron flux resulting from known perturbations applied to the system. Two tracks are followed. Existing low-order computational capabilities are consolidated and extended. Simultaneously, advanced methods based on deterministic neutron transport and on probabilistic (i.e. Monte Carlo) methods are developed so that the transfer function of a reactor core can be estimated with a high resolution in space, angle and energy. Since the modelling of the response of the system to a perturbation expressed in terms of macroscopic cross-sections is equally important as the modelling of the actual perturbation, large efforts are spent on converting actual noise sources into perturbations of cross-sections. For that purpose, emphasis is put on developing models for reproducing vibrations of reactor vessel internals due to FSI. Finally, the evaluation of the uncertainties associated to the estimation of the reactor transfer function is given particular attention, together with the sensitivity of the simulations to input parameters and models.

Concerning (b), although the tools allowing estimating the reactor transfer function can be verified against analytical or semi-analytical solutions for simple systems and configurations, the validation using reactor experiments specifically designed for noise analysis applications is essential. Two types of neutron noise measurements are considered: a so-called absorber of variable strength and a so-called vibrating absorber.

Finally, concerning (c), the backtracking of the driving perturbation (not measurable) from the induced neutron noise (measurable at some discrete locations throughout the core) is performed using machine learning. With the tools referred to above, the induced neutron noise for many possible scenarios of considered perturbations is estimated. The results of such simulations are then provided as training data sets to machine learning techniques. Based on such training sets, the machine learning algorithms have for primary objective to identify the scenario existing in a nuclear core from the neutron noise recorded by the in- and ex-core neutron detectors and, when relevant, retrieve the actual perturbation (and its location).

3.3. HPMC and McSAFE

The major objectives of the HPMC project were the following:

- Optimal Monte Carlo-thermal-hydraulics coupling: the objective was to realise efficient coupling of the Monte Carlo codes SERPENT and MCNP with the thermal-hydraulic subchannel codes SUBCHANFLOW and FLICA4, suitable for full core applications.
- Optimal Monte Carlo burn-up integration: the objective was to realise an efficient integration of burnup calculations in the Monte Carlo codes SERPENT and MCNP, suitable for full core applications.
- Time-dependence capabilities in Monte Carlo methods: the objective was to develop an efficient algorithm for modelling time-dependence in the Monte Carlo codes SERPENT and MCNP, applicable to safety analysis and full core calculations.

Based on the promising results of the HPMC project, the McSAFE project started in September 2017 with the goal to move the Monte Carlo-based multiphysics codes towards industrial applications, e.g. simulation of depletion of commercial LWR cores taking thermal-hydraulic feedback into account, analysis of transients such as REA. For this purpose, a generic and optimal coupling approach based on ICoCo and the open-source NURESIM platform is followed for the coupling of the European Monte Carlo solvers such as MONK, SERPENT and TRIPOLI with subchannel codes e.g. SUBCHANFLOW and fuel thermo-mechanics solvers e.g. TRANSURANUS. Moreover, dynamic versions of TRIPOLI, SERPENT and MCNP6 coupled with SUBCHANFLOW are developed for analysing transients. Especially, SERPENT/SUBCHANFLOW is being coupled with TRANSURANUS for the depletion analysis of commercial western PWR and VVER cores while considering thermal-hydraulic feedback. Emphasis is put on the extensive validation of the tools being developed within McSAFE. For the validation of the depletion capabilities, plant data are used, whereas for the validation of the dynamic capability of the coupled Monte Carlo – thermal-hydraulics codes under development, experimental data of unique tests e.g. the SPERT REA IV E are used. Finally, high fidelity tools based on Monte Carlo requires a massive use of HPC in order to solve full cores at the pin level. Methods for optimal parallelization strategy, scalability of Monte Carlo-based simulations of depletion problems and time-dependent simulations, are also scrutinized in the McSAFE project. Since memory requirements for such problems may represent a limiting factor, methods for the optimal use of memory during depletion simulations of large problems needs to be further developed.

3.4. NURESAFE

The main objectives of NURESAFE were:

- To enhance the prediction capability of the computations used for safety demonstration of the current LWR nuclear power plants through the dynamic 3D coupling of the codes, simulating the different physics of the problem into a common multi-physics simulation scheme.
- To advance the fundamental knowledge in two-phase thermal-hydraulics and develop new multi-scale thermal-hydraulics models. Emphasis was put on coupling interface tracking models with phase-averaged models. Moreover, pool and convective boiling were given special attention, together with the physics of bubbly flow.
- To develop multi-scale and multi-physics simulation capabilities for LOCA, PTS and BWR thermal-hydraulics, thus allowing more accurate and more reliable safety analyses. The aim was to develop a European reference tool for higher fidelity simulation of LWR cores for design and safety assessments. The delivery of safety-relevant industry-like applications was also one of the primary objectives of the project, so that the various applications could be used by the industry at the completion of the project.
- To develop generic software tools within the NURESIM software platform and to provide a support to developers for integration of the codes into this platform.

4. Key achievements with respect to advanced numerical simulation and modelling for reactor safety

4.1. CORTEX

Since the start of the project, the key achievements in the area of advanced numerical simulation and modelling along the three objectives identified in Section 0 can be summarized as follows.

Development of modelling capabilities for estimating the transfer function

The work carried out so far is performed along several lines.

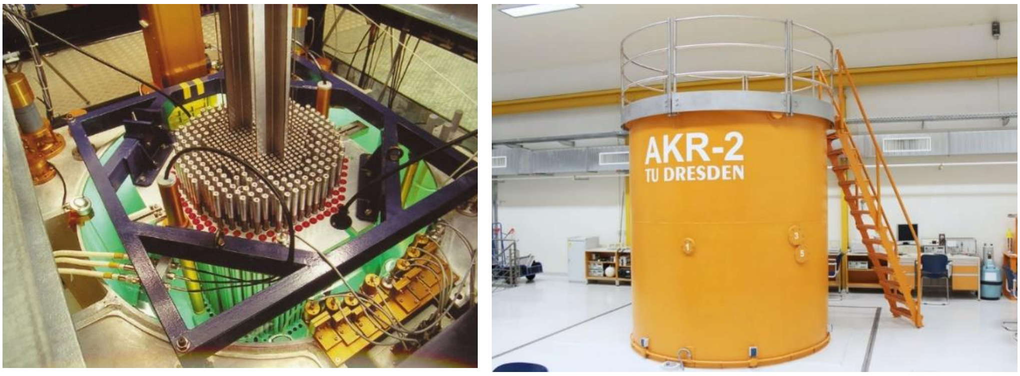
In the area of mechanical vibrations, an extensive review of the past work on vibration of reactor internals was carried out. The focus was on both obtaining a coverage of all possible sources of neutron noise, a phenomenological description of each corresponding scenario, and of the observed neutron noise patterns when actual plant measurements were available. First simulations using thermal-hydraulic perturbations generated by a system code were later fed into a FEM code modelling mechanical structures.

In parallel to those activities, neutronic capabilities are being developed. For coarse mesh approaches, three parallel tracks are pursued. Nodal codes used for the simulation of other core transients in the time-domain are used. To use some of these codes, the first step is to generate a set of time-dependent macroscopic cross-sections that simulate the movement of the fuel assemblies on a fixed computational coarse grid, based on the results of the FSI simulations. Procedure are being implemented to generate the whole set of cross-sections. In addition to the use of existing time-dependent tools with a set of time-dependent cross-sections, another approach is pursued based on the development of an ad-hoc software relying on FEM. The FEM method has a large versatility for solving balance equation using different spatial meshes and a code is being developed along those lines. It will offer the possibility in the future to have a moving mesh following the vibration characteristics determined from the FSI calculations. The main advantage of the FEM route lies with the fact that only static macroscopic cross sections for the initial configuration of the core are necessary. Finally, a third and complementary approach based on a mesh refinement technique in the frequency domain is being developed. The modelling of vibrating reactor internals requires the definition of perturbations on very small spatial domains compared to the size of the node size used in coarse mesh modelling tools. This makes it necessary to development mesh refinement techniques around the region where the perturbation exists. This mesh refinement technique is currently implemented in a frequency-domain core simulator earlier developed. For fine mesh approaches, deterministic methods relying on the method of discrete ordinates (Sn) are being developed. Moreover, a neutron noise solver relying on the method of characteristics is being implemented. In probabilistic methods, an equivalence procedure between neutron noise problems in the frequency-domain and static subcritical systems is being developed. A method using complex statistical weights and a modified collision kernel for the neutron transport equations in the frequency domain have been implemented in a Monte-Carlo code. Likewise, another method using complex-valued weights in the frequency domain has been implemented.

As can be seen above, several complementary approaches are being developed. They either rely on existing codes or codes specifically developed for noise analysis. Moreover, these codes work either in the time- or in the frequency-domain. These tools use either a coarse-mesh approach (possibly with a moving mesh) or a fine-mesh approach regarding the spatial discretization. Finally, both deterministic and probabilistic methods are considered.

Validation of the modelling capabilities against experiments

Concerning the validation of such tools against experiments specifically designed for neutron noise, two research facilities are used: the AKR-2 facility at TUD, Dresden, Germany, and the CROCUS facility at EPFL, Lausanne, Switzerland. Pictures of those two facilities are given in FIG. 1.



(a) CROCUS (courtesy of EPFL) (b) AKR-2 (courtesy of TUD)

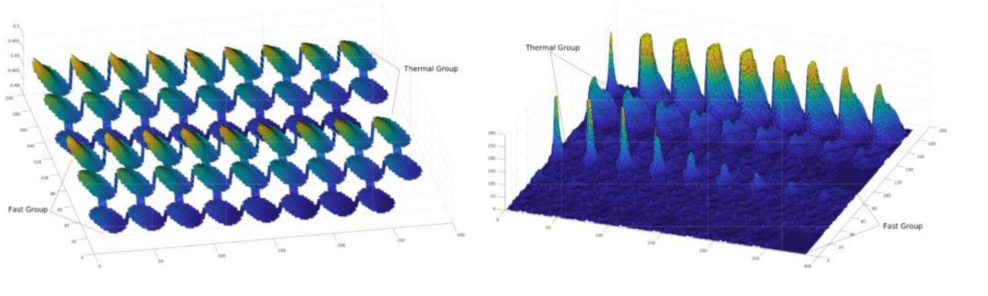
FIG. 1. Overview of the CROCUS and AKR-2 facilities.

The perturbation was simultaneously recorded by seven and 11 neutron detectors, for the first AKR-2 and CROCUS campaigns, respectively, located throughout the respective cores, together with the recording of the actual perturbation introduced. The data acquisition systems were successfully benchmarked against an industry-grade data acquisition system from TUV Rheinland ISTec GmbH. In terms of perturbations, AKR-2 has the ability to perturb the system in two ways: either by rotating a neutron absorbing foil (thickness of 0.02 cm x length of 25 cm x width of 2 cm) along a horizontal axis or by moving a neutron absorbing disc (thickness of 1.0 mm x diameter of 12.7 mm) along a horizontal axis. In the former case, the foil rotates at a distance of 2.98 cm from its axis at a frequency of up to 2.0 Hz, whereas in the latter case, the disc is moving horizontally with a maximum displacement amplitude of 20 cm at a frequency up to 2.0 Hz. At CROCUS, up to 18 fuel rods located at the periphery of the core can be displaced laterally with a maximum displacement up to ±2.5 mm from their equilibrium positions at a frequency up to 2 Hz. The first noise measurements for the three types of noise sources (rotating absorber and vibrating absorber at AKR-2; vibrating fuel rods at CROCUS) have been performed as part of the validation of the data acquisition systems.

Since both the perturbations and the corresponding induced neutron noise are recorded in the experiments described above, such experiments can be used to validate the neutronic tools aimed at estimating the Green's function of the reactor and being developed within CORTEX. Such noise measurements, where both the perturbations and the corresponding neutron noise are recorded, represent a world premiere.

Inversion of the reactor transfer function using machine learning

Preliminary tests were performed using simulated signals, either in the time-domain or in the frequency-domain. Several scenarios corresponding to different types of noise sources were considered: localized absorbers of variable strength in the frequency-domain, travelling perturbations along fuel channels in the frequency domain, fuel assembly vibrations in the time-domain, and inlet coolant perturbations in the time-domain. First successful machine learning tests on the absorbers of variable strength were based on "unrolling" the three-dimensional induced neutron noise into the juxtaposition of two-dimensional images, each corresponding to the plane-wise response of the reactor core to the perturbation [11]. FIG. 2 represents such two-dimensional information that was then fed to a Deep CNN to retrieve the actual location of the perturbation. The recovery of the exact spatial location of the noise source was thereafter improved by using instead a three-dimensional CNN, so that the axial coupling information could be fully exploited in the unfolding [12]. In addition, both the absorber of variable strength data and the travelling perturbation data were used. The network could both recognize the type of perturbation applied and recover the actual location of the perturbation being applied. For the time-domain data, the different scenarios could be successfully identified using a LSTM network.



(a) Phase information (b) Amplitude information

FIG. 2. Example of the reactor response to a localized absorber of variable strength unrolled as two-dimensional images (courtesy of University of Lincoln) [11].

4.2. HPMC and McSAFE

Optimal Monte Carlo-thermal-hydraulics coupling

The HPMC project demonstrated the potentials and capabilities of Monte Carlo based multi-physics coupled codes for improved static core analysis taking local interdependencies between neutronics and thermal-hydraulics into account. At the completion of the project, two coupled codes, SERPENT/SUBCHANFLOW and MCNP/SUBCHANFLOW, had been developed for static full core simulations at the pin level. Those codes were successfully applied to the analysis of a PWR core with UOX and MOX fuel assemblies, while taking local thermal-hydraulic feedback into account and using HPC clusters [9], [10]. As an illustrative example, the capability of the coupled code SERPENT/SUBCHANFLOW to perform a pin-level analysis of a full PWR core with local thermal-hydraulic feedback is shown in

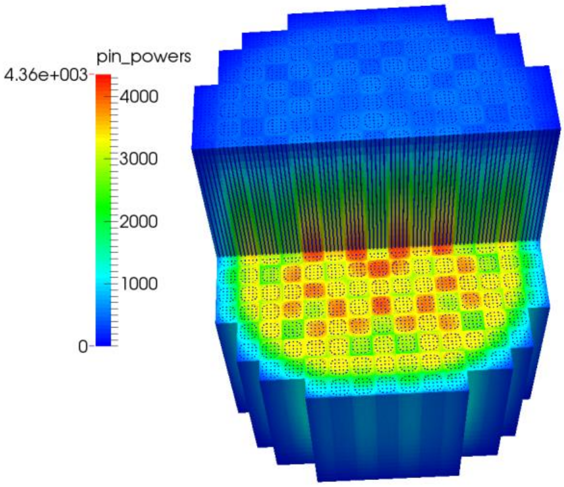


FIG. ***3***. The problem consists of 55777 neutronic nodes (pins and guide tubes), 2.2 million fluid cells, as well as 23.4 million solid cells (thermal-hydraulic solver). A total of 4x106 neutrons per cycle and 650 inactive and 2500 active cycles were used in the SERPENT calculations. The simulation was performed at the KIT IC2 HPC cluster using 2048 cores. A converged solution was achieved after 5.8 CPU-year (1.03 days).

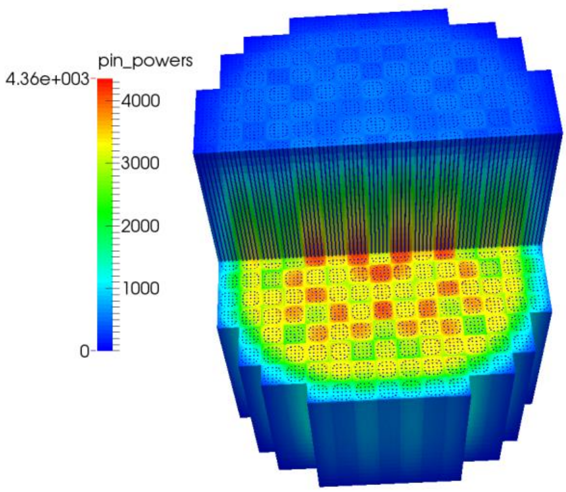


FIG. 3. 3-D pin power predicted by SERPENT/SUBCHANFLOW for the PWR UOX/MOX core [10].

Optimum Monte Carlo burn-up integration

Another important outcome was the exploration and development of various schemes for stable depletion calculation using Monte Carlo codes such as the SIE method [13] for stable steady state coupled Monte Carlo-thermal-hydraulics calculations.

Time-dependence capabilities in Monte Carlo methods

A highlight of the project was the implementation of a time-dependence option in MCNP5 (dynMCNP) that required source code modifications [14]. This option includes the generation and decay of delayed neutron precursors, possible control rods movement, etc. To reduce the statistical error in the generated reactor power in successive time intervals, a method of forced decay of precursors in each time interval was implemented. Moreover, variance reduction methods (like the branchless collision method) were introduced. Thermal-hydraulic feedback was also implemented. To let the time-dependent thermal-hydraulic calculations take the heating history into account, further extensions of the codes were necessary.

Finally, various ways for parallel execution of a Monte Carlo calculation using the MPI and OpenMP application programming interfaces were investigated and their efficiency measured in terms of the speedup factor. For application on large computer clusters with different computer nodes and multiple processors per node, the optimum combination of MPI and OpenMP was determined. Application of OpenMP was introduced in the SERPENT2 code. The MCNP code was modified to use all available processor cores for neutron history simulation [15].

The main achievements close to the midterm of the McSAFE-project are described hereafter.

Full core multiphysics depletion

Methods for depletion of full core using Monte Carlo codes are being developed. First of all, the efficiency and stability of Monte Carlo burnup simulations were studied by optimal combination of free parameters that allow to solve full core problems [16]. In addition, a collision-based domain decomposition scheme for SERPENT2 is being developed to solve large-scale high-fidelity problems with large memory demands (e.g. full core pin-by-pin depletion). For this purpose, memory-intensive materials are split among MPI tasks, enabling the memory demand to be divided among nodes in a high-performance computer [17]. Investigations were also performed to identify the computational requirements for depletion calculations taking thermal-hydraulic feedback into account for 3-D problems (e.g. 5x5 fuel assemblies mini-core) [18]. Potential bottlenecks and limitations, e.g. huge RAM-requirements which increase linearly with the number of fuel assemblies – 40 GB for eight fuel assemblies, could be identified. Alternatives were also proposed to overcome the challenges, such as a collision-based domain decomposition.

Code integration

The European Monte Carlo codes TRIPOLI, SERPENT, and MONK as well as the fuel thermo-mechanics code TRANSURANUS were fully integrated into the

European NURESIM simulation platform (SUBCHANFLOW – SCF was already part of the platform). Each solver owns a specific meshing. New flexible and object-oriented coupling schemes based on the ICoCo-methodology are being developed for each of the codes integrated into the NURESIM platform. The following coupled code versions are available: MONK/SCF, SERPENT/SCF, TRIPOLI/SCF.

Dynamical multiphysics calculations

Another important task in the McSAFE project is to extend general-purpose Monte Carlo codes (SERPENT2, TRIPOLI-4 and MCNP6) to dynamic version that can accurately calculate transient behaviour in nuclear reactors considering local thermal-hydraulic feedback. New versions of Monte Carlo codes with time-dependent capabilities (called dynamicMC) are at the end of the development phase for the analysis of transients. These Monte Carlo codes are coupled with the SCF thermal-hydraulic solver, thus leading to the coupled codes: dynMCNP/SCF, dynTRIPOLI/SCF, dynSERPENT/SCF. The code extensions and modifications are described in more detail in [14], [19] and [20]. The coupling schemes must be appropriate for massive HPC-simulations. The peculiarity of time-dependent Monte Carlo is to describe the behaviour of delayed neutrons, which have a significant influence on the statistical uncertainty (standard deviation) of the power prediction. An additional challenge is the short lifetime of prompt neutrons (roughly 100 µs in an LWR) compared to the large decay time of precursors of delayed neutrons for the method development. To test the dynamic capability of the Monte Carlo codes, different REA scenarios are being developed within McSAFE.

4.3. NURESAFE

Simulation platform

One of the main outcomes of the NURESIM and NURISP projects was the release of the NURESIM platform that is heavily used in NURESAFE. The NURESIM platform is based upon the software simulation platform SALOME. SALOME is an open-source project, (http://salome-platform.org), which implements the interoperability between a CAD modeller, meshing algorithms, visualisation modules and computing codes and solvers, as represented in FIG. 4. It mutualises a pool of generic tools for pre-processing, post-processing and code coupling. Its supervision module provides functionalities for code integration, dynamic loading and execution of components on remote distributed computing systems, and supervision of the calculation. Support is provided to developers for integration of the codes into the SALOME software and for producing and managing the successive versions of the NURESIM platform on a dedicated repository. Innovative deterministic and statistical methods and tools for quantification of the uncertainties developed within NURESAFE give a better knowledge of conservatisms and margins.

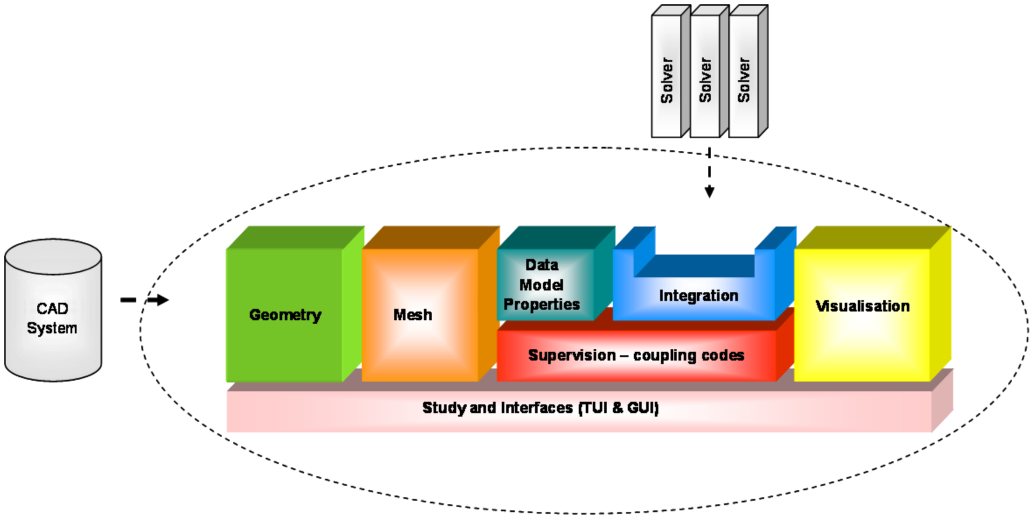


FIG. 4. SALOME global view.

The NURESIM platform provides a set of state-of-the-art software devoted to the simulation of normal operation and design basis accidents of LWR (i.e. BWR, PWR, and VVER). The platform includes 14 codes covering different physics: neutronics, thermal-hydraulics, fuel thermo-mechanics at different scales, 2 thermal-hydraulics system codes, 2 single-phase CFD codes, 2 two-phase CFD codes, 3 sub-channel thermal-hydraulic analysis codes, 2 advanced fuel thermo-mechanics codes, 2 DNS codes, 3 neutron-kinetics codes. All these codes were extensively benchmarked and validated against experiments during the course of the NURESAFE project.

SALOME is connected to URANIE, an open-source platform aimed at providing methods and algorithms about uncertainty and sensitivity, and verification and validation analyses in the same framework

(https://sourceforge.net/projects/uranie/).

The URANIE and SALOME platforms work nicely together. Any calculation scheme developed in SALOME can be used within URANIE.

Through the link with URANIE, users of the NURESIM platform successfully performed in the NURESAFE project sensitivity analyses and model calibration studies.

3D dynamic coupling of codes

Individual models, solvers, codes and coupled applications, were run and validated through modelling "situation targets" corresponding to given nuclear reactor situations and including reference calculations, experiments, and plant data. As safety analysis was the main issue within the project, all these situation targets consisted in some accidental scenarios. The challenging "situation targets" were selected according to the required coupling between two different disciplines. Industry-like applications were released at the end of the project for the following "situation targets":

- Square lattice PWR MSLB.
- One selected BWR ATWS.
- VVER MSLB.

The analysis also included uncertainty quantification using the URANIE open-source software.

The BWR ATWS analysis framework featured coupled simulations combining system thermo-hydraulics, 3-D neutronics, thermo-mechanical evaluation of fuel safety parameters, and uncertainty evaluation. The MSLB transient analysis provided more accurate assessment of margins between predicted key parameters and safety criteria. The outcome of the transient simulation was evaluated with respect to local re-criticality and maximum reactor power level. As an illustrative example, the results of the PWR MSLB are presented hereafter.

A two-step modelling approach was applied. In the first step, reference results were produced using the platform codes with higher resolutions of coupling between core nodal and sub-channel scale. In the second step, CFD evaluations were included into the solution. In that way, an improvement in the prediction of the target safety parameters could be achieved. In order to increase the confidence of the CFD results, a validation was also performed by comparing the calculation results with experimental data from the HZDR test facility on coolant mixing ROCOM. The cross-section libraries were created using new methods of grid point selection [21]. Various combinations of system codes, core thermal-hydraulic codes and neutronic codes were used. FIG. 5 highlights the 3-D distributions at time t=86s after the initiation of the MSLB.

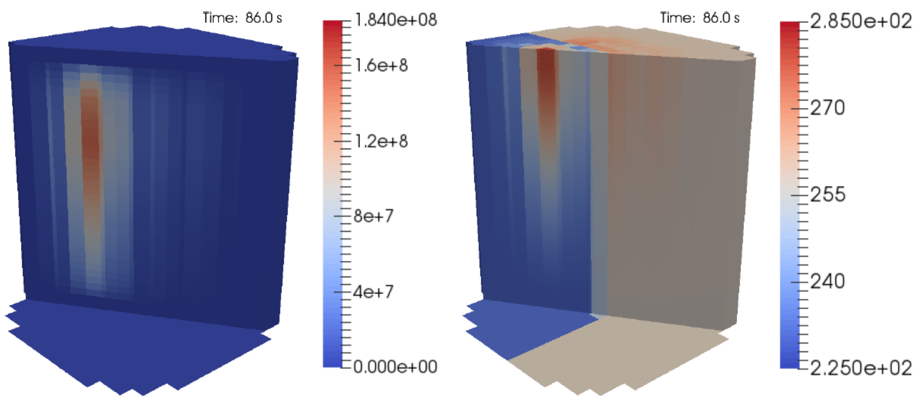


FIG. 5. Distribution of power density (MW/m3, left) and coolant temperature (°C, right) at 86 s after the initiation of the MSLB event.

The obtained results confirmed that the NURESIM platform is applicable for challenging coupled transients in PWRs. Furthermore, by accomplishing the coupling of reactor dynamics codes and CFD codes, the superiority of the NURESIM platform was demonstrated. The conducted advanced calculations demonstrated the excellent status and the readiness for industrial applications of the NURESIM platform and the integrated codes.

Advanced CFD modelling

Advancement in the fundamental knowledge of CFD modelling was pursued and new models based on detailed DNS for momentum exchange and boiling heat transfer situations typical of LWR thermal-hydraulics were developed. New benchmark data bases for fundamental and applied problems were developed. The existing computational multiphase flow strategies were first extended in order to cope with a wider range of practical applications. Novel methods for pool and convective boiling in a channel were also developed. Advanced strategies for modelling turbulent bubbly flow in a channel and in a rod bundle were analysed. Finally, the novel models and simulation techniques were implemented in codes, validated and applied in this context. New versions of the CFD platform codes NEPTUNE_CFD, TransAT and TRIO_U were delivered to end-users, including the most advanced numerical simulation features and the associated modelling approaches for the physics pertinent to both PWRs and BWRs.

Three specific issues were addressed within NURESAFE:

- All-topology flow modelling by coupling interface tracking models with phase-averaged models.
- DNS and LES of pool and convective boiling [22].
- DNS and LES of bubbly flows [23], [24].

Multi-scale and multiphysics simulations

In the area of multi-scale and multiphysics simulations of LOCA, PTS and BWR thermal-hydraulics, multi-scale and multiphysics simulation capabilities for more accurate and more reliable safety analyses were developed.

LOCA is usually simulated with industrial versions of thermal-hydraulic system codes. Although system codes are able to address most safety needs, the status and limits of the current methods and tools for plant analysis were reviewed during the NURISP project and areas for improvements were pointed out. Advanced tools and methods for multi-scale and multi-physics analyses and simulations of LOCA, including situations with deformed or ballooned rods and possible fuel relocation, were developed. The addition to system thermal-hydraulic codes of two-phase CFD tools and of advanced fuel models allowed revisiting these transients for more accurate and reliable predictions. This required improving and coupling CFD to system codes or improving system codes and system codes coupled with fuel thermo-mechanics codes. Furthermore, methods for uncertainty and sensitivity analysis applied to system codes were improved. In this framework, a special focus was put on the issue of the quantification of the uncertainties of the closure laws. This work was based on a benchmarking of the possible methods using reflooding experimental data (FEBA and PERICLES).

Concerning PTS, better simulation capabilities were achieved by improving the CFD modelling thanks to the analysis of new experimental data (including TOPFLOW steam-water tests and KAERI CCSF test). In addition, sensitivity and uncertainty methods were applied to CFD codes and state-of-the-art methods on validation, uncertainty and uncertainty of CFD applications to reactor issues were reviewed.

In the field of BWR thermal-hydraulics, progress in the simulation of two-phase thermal-hydraulics phenomena specific to BWR was achieved. This includes dry-out prediction, transient core thermal-hydraulics and steam injection in pressure suppression pool. CFD codes and sub-channel codes were used, improved and validated during the project.

5. Training, education and dissemination activities

5.1. CORTEX

The dissemination of the project results is carried out along five parallel lines of actions: involvement of end-users into the project, organization of workshops, organization of short-courses, peer-reviewed publications, and presentations at conferences and meetings.

Concerning the involvement of end-users, the project involves, beyond academic partners, research institutes, TSOs, utilities, fuel and reactor manufacturers, as well as services companies. Those organizations are either directly contributing to the project as project partners or participating to the project via the Advisory End-User Group, having a consultative role to the consortium.

Three workshops will be organized:

- Two workshops on the experiments performed at the research reactors and on the validation of the neutronic models based on such experiments, where experimentalists and modellers will present, describe and discuss their results.
- One (final) workshop on the demonstration of the methods developed within the project on actual plant data. During this workshop, the entire consortium will: (a) summarize the findings and the lessons learnt throughout the project, (b) give recommendations on techniques and instrumentations for core monitoring and surveillance (in order to improve the reliability and safety of the nuclear units); and (c) provide an outlook for the future in this area.

Eight short courses were/will be developed:

- Two courses on reactor dynamics and neutron noise. Both courses were already given and had 47 registered participants in total. The first course covered the fundamentals of reactor kinetics and the theory of small space-time dependent fluctuations. The second course dealt with additional aspects, such as core thermal-hydraulics, its coupling to neutron kinetics and reactor stability, and included hands-on training on the AKR-2 reactor at TUD.
- Two courses/workshops on signal processing methods and their applications. Both courses/workshops were already arranged and attracted 64 attendees. The first course was an introduction to basic techniques for signal analysis and their possible applications. The second course dealt with advanced signal processing methods and statistical characterization of plant measurements, which can be applied to reactor core monitoring and dynamic sensor surveillance.
- One hands-on training session on the simulation of reactor neutron noise in power reactors using a time-domain neutron kinetics code. The students will have the opportunity to model different types of disturbances, such as fuel assembly vibrations, inlet disturbances, flow fluctuations, etc. and study their effect on the neutron flux throughout the entire system.
- One course on uncertainty and sensitivity analysis. Emphasis will be put on the application of such methods to the estimation of the reactor transfer function and the corresponding neutron noise.
- Two hands-on training sessions on the two research facilities used in the project. The sessions will consist of the following exercises: reactor start-up procedures, control rod and critical experiments, and a set of neutron noise experiments.

In the area of publications, after 18 months as a running project, the following has been achieved:

- One journal publication (two more under review).
- Eight conference publications (ten more under review).
- Seven conference presentations.

In addition, most of the deliverables (26 in total – ten were already delivered) are/will be publicly available.

All the publicly available resources are directly accessible on the project website http://cortex-h2020.eu. In addition to the publications and deliverables listed above, newsletters are distributed once a year. The consortium is also heavily using LinkedIn http://linkedin.com/company/cortex-h2020 to inform about the project. Promotional materials (video, leaflet, poster) are also available.

5.2. HPMC and McSAFE

The dissemination, education and training activities of both projects rely on the following pillars:

- Dissemination plan for the identification of end users and stakeholders (industry, academia, regulators, TSO).
- Creation of a public website http://www.mcsafe-h2020.eu.

- Organisation of a dedicated training course to be held in April 2020 where the main tools of McSAFE will be presented and demos of selected applications will be shown to the community.
- Presentation of the main results at international conferences, e.g. PHYSOR, M&C, etc., publication of the main results in scientific journals, presentation at the NUGENIA Forum, the FISA Conference, etc.
- Establishment of a Users' Group consisting of institutions which will get access to the use of the codes being developed and extended within McSAFE, for performing simulations of own problems. Important feedback from the Users' Group is expected regarding the capabilities and user-friendliness of the codes.
- Creation of a Technical Advisory Board consisting of selected experts of the community of stakeholders and aimed at reviewing the McSAFE developments and at providing advice and comments on the main developments.
- Delivery of 57 deliverables in total, from which around 30 are already finalized. Some of them are publicly available on the project website.
- Education and training of young scientists through doctoral programs and through the involvement of master and bachelor students in the project at the different partner institutions.

5.3. NURESAFE

In order to foster the dissemination and facilitate the use of the platform codes, 15 training sessions of a few days each were given to the staff of the NURESAFE partners and to external users' organisations during the course of the project. The end-users of the NURESIM platform and of the individual codes could thereafter efficiently use the tools and methods.

Two public NURESAFE general workshops were held in Budapest on June 16-17, 2014 and in Brussels on November 4-5, 2015, respectively, in order to present the new methods, models and functionalities that were developed. About 50 people attended each of the workshops.

Many publications were made:

- 12 articles were published in peer-reviewed journals (Annals of Nuclear Energy, International Journal of Heat and Fluid Flow, Multiphase Science and Technology, Nuclear Engineering and Design).
- 28 presentations were delivered at international conferences (NURETH, ICONE, CFD4NRS, SNA-M&C, ….).

An active Users' Group was set up when starting the project. The objective was to give the opportunity to organizations which were not members of the NURESAFE consortium to use and test the new methods and tools. Five universities and companies were members of the NURESAFE Users' Group: 3 non-European and 2 European. They provided fruitful feedback on the use of the codes in some challenging situations, especially in thermal-hydraulics.

6. Utilization and cross-fertilization

CORTEX is by essence an international project, since one of the partners is from USA and another one is from Japan. Moreover, the project gathers academic partners, research institutes, TSOs, utilities, fuel and reactor manufacturers, as well as services companies in order to develop a core monitoring technique in close dialogue with all relevant stakeholders. This will result in a method directly applicable for the industry. Finally, additional interest was received from the USA for developing a similar method as the one being developed in CORTEX.

Although neutron noise core monitoring has been used in a "rudimentary" manner in some plants worldwide, the methodology proposed in CORTEX and relying on machine learning techniques combined with dedicated neutron noise simulations has never been attempted. Moreover, the development of neutron noise simulation capabilities at an industrial level also represents a novelty in CORTEX. Being able to infer from the detector readings the existence, location and features of possible anomalies would represent a world-premiere.

If successful, the project will also be able to identify the root-cause of some operational problems during exploitation. CORTEX will for instance investigate the increase of the neutron noise levels observed in some Pre-KONVOI PWRs, events remaining unexplained and which, in some cases, led to reduced power operation or reactor scrams [25]-[28].

In the area of Monte Carlo simulations, the main tools being developed within HPMC and McSAFE are high-fidelity tools, which can also provide reference solutions to any low-order solution (e.g. nodal diffusion solvers) used by regulators and the industry in real life situations and for licensing purposes. Since the tools are able to provide unique full core solutions at the pin level taking into account local thermal hydraulic feedback, such tools substantially improve the modelling accuracy when predicting depletion and simulating static core configurations. In addition, the dynamic capability added to the Monte Carlo codes coupled with thermal hydraulic subchannel codes pave the way for the analysis of transients (e.g. REA, MSLB) with an unequalled accuracy as of today. Hence, these tools are very well suited for being used by the industry as a complement to low-order solutions. Finally, for all cases where no experimental data are available at a fine resolution, these tools can predict local safety-relevant parameters. With the maturity of the being developed Monte Carlo solutions, the project will allow industry-like problems to be modelled. This will provide a possibility to assess the adequacy of deterministic based solution methods that are routinely used by the industry and that rely on many approximations and limitations, as highlighted in Section 0.

The end-users of the NURESIM software platform also benefit since the end of the project from the improvements made within the NURESAFE project in simulation capabilities, more precisely when e.g. they perform industrial studies, safety analyses, optimisation of reactor operation and reactor design. The end-users are the members of the NURESAFE consortium (22 organisations) and the members of the NURESAFE Users' Group (five organisations). They can be categorized into 1) utilities (three utilities operating the majority of the European fleet of nuclear reactors), 2) one reactor and fuel manufacturer and vendor (Framatome), 3) three TSOs to safety authorities and 4) universities and research institutes. The standardised environment offered by the platform and the interoperability of codes facilitate collaborative work between all partners. Collaborative work contributes to the increase of the leadership of European science for nuclear reactor simulation.

Since the end of the NURESAFE project, further use and development of the software platform are pursued thanks to:

- A continuous maintenance by CEA of the software repository dedicated to the NURESIM platform.
- Further development and maintenance of the general-purpose software SALOME and URANIE (two open-source software supporting the entire platform).
- Further development and maintenance of each individual software by code owners.

This above resulted in long-term frameworks that have already been used for many years.

7. Conclusions and future recommendations

Using the NURESIM platform, challenging DNS & LES simulations were performed within NURESAFE to analyse bubbly flow with and without phase change in order to understand intricate phenomena that are beyond measurements capabilities. New modelling routes were proposed based on these results and were documented and implemented in the platform available to all stakeholders. Novel ideas were explored, and some others were further refined, such as combining large-scale and small-scale prediction techniques. Such techniques should in the medium term replace state-of-the-art methods that are limited to one flow regime. These novel techniques are applicable to more complex core-level thermal-hydraulic situations involving boiling. Solution procedures taking advantage of the coupling between various codes tackling different physics and scales were successfully developed.

In the area of Monte Carlo methods, the methods for depletion and dynamic calculations are close to their culmination. The developed coupled codes based on the ICoCo-methodology are now implemented in the European simulation platform NURESIM and the testing and validation phase will soon start. For this purpose, different benchmark problems of different size are being developed so that all partners will apply the developed tools for the analysis of those problems. Moreover, the validation of the codes under development using plant /experimental data is of paramount importance for McSAFE. Therefore, plant data of two European reactors (PWR-KONVOI, VVER-1000) are being prepared and documented for the validation of the advanced depletion capability of the tools. On the other hand, selected SPERT III REA E test data will be used for the validation of the dynamic versions of the Monte Carlo codes. Finally, application to LWR and SMR are foreseen to demonstrate the extended capabilities of the multi-physics codes. Generally, it can be stated that considerable efforts are still needed for high-fidelity simulations based on Monte Carlo codes in an HPC-environment in order to perform core analysis with acceptable statistics for the key parameters of interest.

Beyond the major developments in computing capabilities for normal operation and design basis accidents, the monitoring of reactors and the early detection of anomalies will become increasingly important, due to the ageing fleet of reactors in Europe. By extending the current simulation platforms to the modelling of stationary fluctuations and their effect, such simulation tools can be used for creating large data sets that can thereafter be used to detect, from given measured reactor parameters, possible anomalies. For such a purpose, machine learning was demonstrated in CORTEX, using simulated test data, to be potentially capable of retrieving anomalies. Tests on actual plant data remain nevertheless to prove the viability of this technique. In addition, although the phenomena considered so far in CORTEX do not require taking the thermal-hydraulic feedback into account, the estimation of the coupled neutronics/thermal-hydraulics reactor transfer function might be necessary for other scenarios.

In the area of neutron transport, it should also be noted that the methods being developed would allow modelling full core in pure transport. The limitations and approximations otherwise introduced when pre-generating assembly-wise macroscopic cross-sections would then be eliminated, thus greatly enhancing the level of faithfulness of neutron transport simulations for strongly heterogeneous cores (such as when using new fuel assembly designs, MOX fuel, etc.).

In essence, the different situations needing accurate modelling require the inclusion of more and more physics. Beyond neutronics, thermal-hydraulics, and thermo-mechanics, other as important physics might need to be included: fuel physics, structural mechanics, coolant and radiation chemistry, radionuclide transport, etc. Truly multi-physics and multi-scale modelling approaches still need to be developed at a more mature level for tackling such situations. This includes the development of new models, their coupling, as well as the use of the latest advancements in numerical analysis optimized for HPC. In this respect, the development of hybrid methods, such as deterministic and probabilistic methods in neutron transport, or DNS, LES, CFD, and macroscopic approaches in fluid dynamics and heat transfer, should be favoured and optimized. This requires having different scientific communities collaborating and capitalizing on each other's strengths and expertise. With so challenging modelling targets, the use of machine learning for predictive modelling should also be considered, where machine learning could be used in place of or in addition to more traditional modelling approaches. The enormous amount of measured data at commercial reactors, research reactors, and experimental facilities represent a definite asset, in a machine learning-based modelling strategy, that should be utilized as much as possible.

References

A complete list of the papers published within the projects can be found on the project respective websites: http://cortex-h2020.eu (for CORTEX), http://www.fp7-hpmc.eu (for HPMC), http://www.mcsafe-h2020.eu (McSAFE), http://www.nuresafe.eu (for NURESAFE).

[1] C. Demazière et al., Overview of the CORTEX project, Proc. Int. Conf. Physics of Reactors – Reactor Physics paving the way towards more efficient systems (PHYSOR2018), Cancun, Mexico, April 22-26, 2018 (2018).
[2] V. Sanchez et al., High Performance Monte Carlo Computing Projects: from HPCM to McSAFE, NUGENIA Forum, Ljubljana, Slovenia, April 14, 2015.
[3] L. Mercatali et al., McSAFE projects highlights, International Multi Physics Validation Workshop, North Carolina State University, USA, June 2017.
[4] E. Deville and F. Perdu, Documentation of the Interface for Code Coupling: ICOCO, CEA, Paris (2012).
[5] B. Chanaron et al., Advanced multi-physics simulation for reactor safety in the framework of the NURESAFE Project, Ann. Nucl. Energy, 84, 166–177 (2015).
[6] B. Chanaron, The European NURESAFE simulation project for reactor safety, Proc. Int. Conf. Nuclear Engineering (ICONE22), Prague, Czech Republic, July 7-11, 2014 (2014).
[7] C. Demazière, Multi-physics modelling of nuclear reactors: current practices in a nutshell, Int. J. Nucl. Energy Sci. Technol., 7 (4), 288–318 (2013).
[8] I. Lux and L. Koblinger, Monte Carlo particle transport methods: neutron and photons calculations, CRC Press, Boca Raton, FL, USA (1991).
[9] A. Ivanov et al., Internal multi-scale multi-physics coupled system for high fidelity simulation of light water reactors, Ann. Nucl. Energy, 66, pp. 104–112 (2014).
[10] M. Däubler et al., High-fidelity coupled Monte Carlo neutron transport and thermal-hydraulic simulations using Serpent 2/SUBCHANFLOW – Part I: Implementation and solution verification, Ann. Nucl. Energy, 83, pp. 352–375 (2015).
[11] F. Calivà F et al., A deep learning approach to anomaly detection in nuclear reactors. Proc. 2018 Int. Joint Conf. Neural Networks (IJCNN2018), Rio de Janeiro, Brazil, July 8-13, 2018 (2018).
[12] F. De Sousa Ribeiro et al., Towards a deep unified framework for nuclear reactor perturbation analy-sis. Proc. IEEE Symposium Series on Computational Intelligence (SSCI 2018), Bengaluru, India, November 18-21, 2018 (2018).
[13] J. Dufek and J. E. Hoogenboom, Description of a stable scheme for steady-state coupled Monte Carlo-thermal-hydraulic calculations, Ann. Nucl. Energy, 68, pp. 1–3 (2014).
[14] J. E. Hoogenboom, Demonstration of the time-dependence after a control rod movement, HPCM Deliverable D3.10 (2013).
[15] J. E. Hoogenboom et al., Maximum efficiency in massively parallel execution of Monte Carlo criticality calculations, Proc. Joint Int. Conf. Mathematics and Computation (M&C), Supercomputing in Nuclear Applications (SNA) and the Monte Carlo (MC) Method (MC2015), Nashville, USA, April 19–23, 2015 (2015).
[16] I. Mickus and J. Dufek, Optimal neutron population growth in accelerated Monte Carlo criticality calculations, Ann. Nucl. Energy, 117, pp. 297–304 (2018).
[17] M. Garcia et al., Development of a spatial domain decomposition scheme for Monte Carlo neutron transport, Proc. Int. Conf. Nuclear Engineering (ICONE26), London, United Kindgom, July 22-26, 2018 (2018).
[18] D. Ferraro et al., Foreseen capabilities, bottlenecks identification and potential limitations of Serpent MC transport code in large-scale full 3-D burnup calculations, Proc. Int. Conf. Nuclear Engineering (ICONE26), London, United Kindgom, July 22-26, 2018 (2018).
[19] M. Faucher et al., New kinetic simulation capabilities for TRIPOLI-4®: Methods and applications, Ann. Nucl. Energy, 120, pp 74–88 (2018).
[20] A. Livensky et al., Modeling the SPERT transients using Serpent2 with time-dependent capabilities, Ann. Nucl. Energy, 125, pp. 80–98 (2019).
[21] S. Sanchez-Cervera et al., Optimization of multidimensional cross-section tables for few-group core calculations, Ann. Nucl. Energy, 73, pp. 387–391 (2014).
[22] S. Lal et al., Direct Numerical Simulation of bubble dynamics in subcooled and near-saturated convective nucleate boiling. Int. J. Heat Fluid Flow, 51, pp. 16–28 (2015).
[23] Y. Sato et al., Computational fluid dynamics simulation of single bubble dynamics in convective boiling flows. Multiph. Sci. Technol., 25 (2-4), pp. 287–309 (2013).

[24] H. Li and H. Anglart, CFD model of diabatic annular two-phase flow using the Eulerian- Lagrangian approach. Ann. Nucl. Energy, 77, pp. 415–424 (2015).
[25] Bundesamt für Strahlenschutz, Kurzbeschreibung und Bewertung der meldepflichtigen Ereignisse in Kernkraftwerken und Forschungsreaktoren der Bundesrepublik Deutschland im Zeitraum Januar 2011, Stand 14.12.2012 (2012) (in German).
[26] Almaraz Trillo Report, Neutron noise status in Trillo NPP, technical report CO-12/043, Spain (2012).
[27] CSN/PDT/NCTRI/TRI/1503/203, Proposal of technical decision on the revision of the Technical Operational Specifications relative to the dead band of the filter in Trillo NPP, technical report (in Spanish).
[28] M. Seidl et al., Review of the historic neutron noise behaviour in German KWU built PWRs, Prog. Nucl. Energy, 85, pp. 668–675 (2015).

Glossary

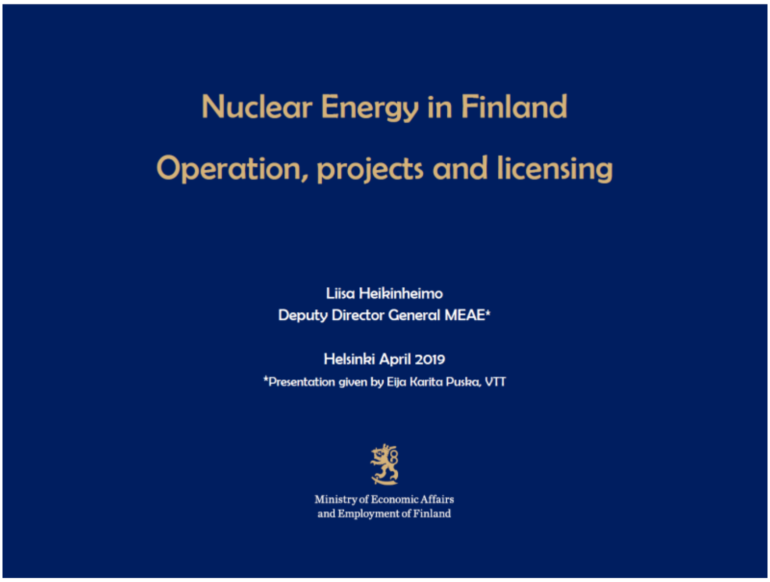
ATWS	Anticipated Transient Without Scram
BWR	Boiling Water Reactor
CAD	Computer-Aided Design
CFD	Computational Fluid Dynamics
CNN	Convolutional Neural Network
CORTEX	CORe monitoring Techniques and EXperimental validation and demonstration
DNS	Direct Numerical Simulation
EPFL	Ecole Polytechnique Fédérale de Lausanne
FEM	Finite Element Method
FSI	Fluid-Structures Interaction
HPC	High Performance Computing
HPMC	High Performance Monte Carlo Methods for Core Analysis
HZDR	Helmholtz-Zentrum Dresden-Rossendorf
LES	Large Eddy Simulation
LSTM	Long Short-Term Memory
LWR	Light Water Reactor
LOCA	Loss-Of-Coolant Accident
McSAFE	High Performance Monte Carlo Methods for SAFEty Analysis
MOX	Mixed Oxide
MPI	Message Passing Interface
MSLB	Main Steam Line Break
NURESAFE	NUclear REactor SAFEty simulation platform
NURESIM	European Platform for Nuclear Reactor Simulations
NURISP	NUclear Reactor Integrated Simulation Project
OpenMP	Open Multi-Processing
PTS	Pressurized Thermal Shock
PWR	Pressurized Water Reactor
RAM	Random Access Memory
REA	Rod Ejection Accident
SIE	Stochastic Implicit Euler
SMR	Small Modular Reactor
SPERT	Special Power Excursion Reactor Test Program
TSO	Technical Support Organization
TUD	Technical University of Dresden
UOX	Uranium Oxide
VVER	Vodo-Vodyanoi Energetichesky Reactor

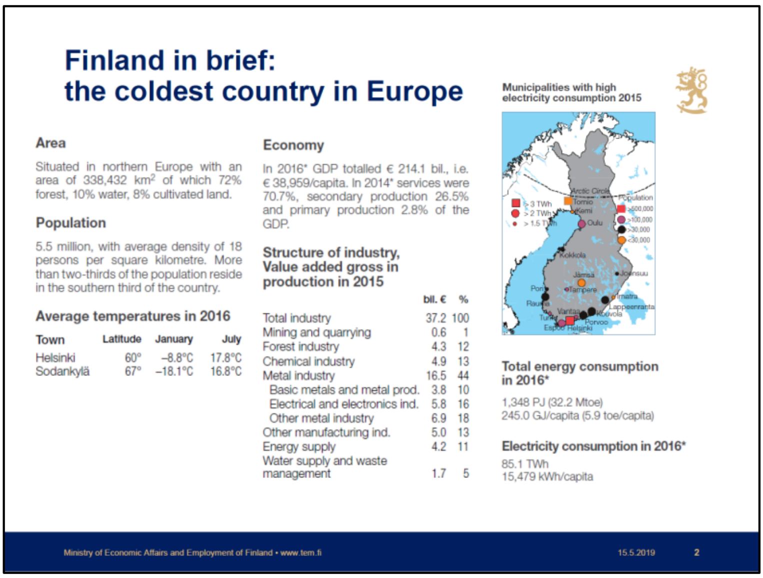
EIJA-KARITA PUSKA

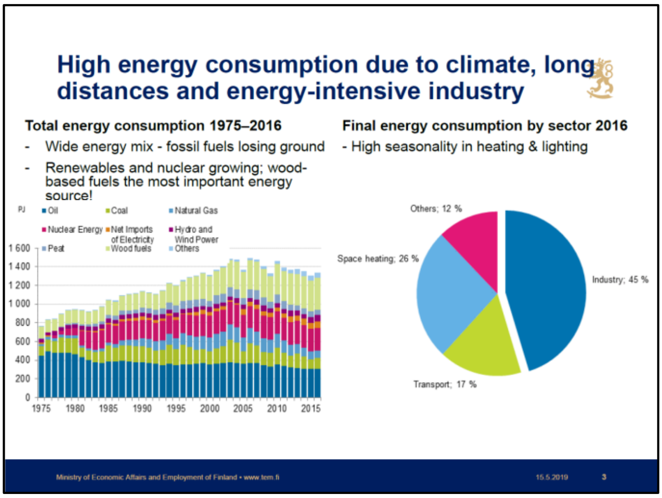
FISA 2019 – EURADWASTE '19

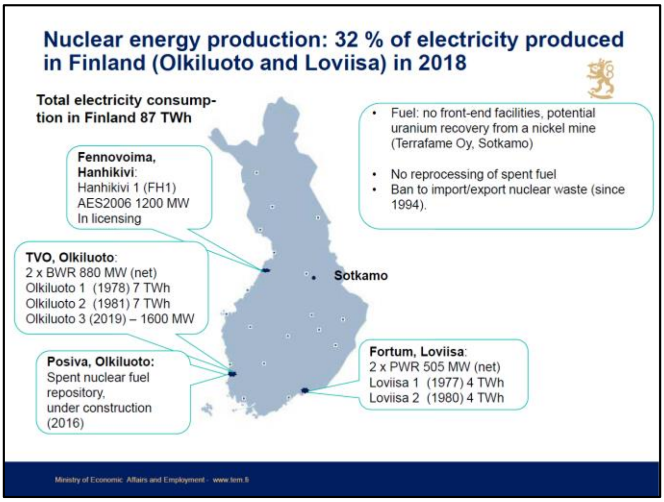
Presentation of Ms Eija-Karita Puska (VTT, FI)

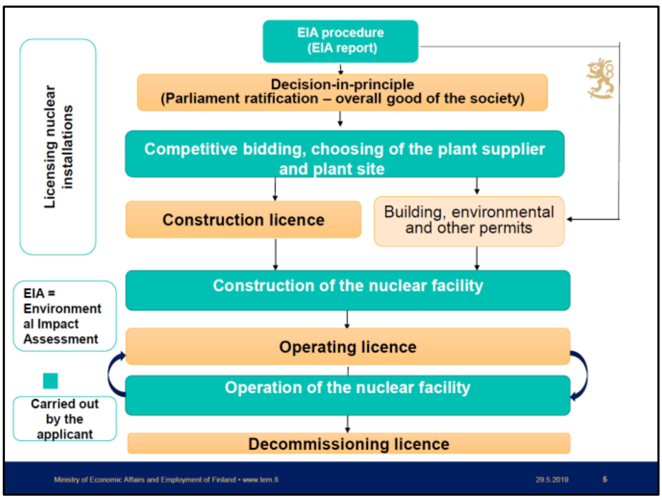
THE FINNISH NUCLEAR PROGRAMME, INCLUDING LTO AND NEW BUILD





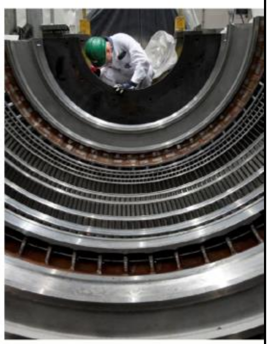

High energy consumption due to climate, long distances and energy-intensive industry
Total energy consumption 1975–2016
- Wide energy mix - fossil fuels losing ground
- Renewables and nuclear growing; wood-based fuels the most important energy source!
PJ
Oil
Coal
Natural Gas
Nuclear Energy
Net Imports of Electricity
Hydro and Wind Power
Peat
Wood fuels
Others
1 600
1 400
1 200
1 000
800
600
400
200
0
1975
1980
1985
1990
1995
2000
2005
2010
2015
Final energy consumption by sector 2016
- High seasonality in heating & lighting
Others; 12 %
Space heating; 26 %
Industry; 45 %
Transport; 17 %
Ministry of Economic Affairs and Employment of Finland • www.tem.fi
15.5.2019
3


Nuclear energy production: 32 % of electricity produced in Finland (Olkiluoto and Loviisa) in 2018
Total electricity consumption in Finland 87 TWh
Fennovoima, Hanhikivi: Hanhikivi 1 (FH1) AES2006 1200 MW In licensing
TVO, Olkiluoto: 2 x BWR 880 MW (net) Olkiluoto 1 (1978) 7 TWh Olkiluoto 2 (1981) 7 TWh Olkiluoto 3 (2019) – 1600 MW
Posiva, Olkiluoto: Spent nuclear fuel repository, under construction (2016)
Sotkamo
Fuel: no front-end facilities, potential uranium recovery from a nickel mine (Terrafame Oy, Sotkamo)
No reprocessing of spent fuel
Ban to import/export nuclear waste (since 1994).
Fortum, Loviisa: 2 x PWR 505 MW (net) Loviisa 1 (1977) 4 TWh Loviisa 2 (1980) 4 TWh
Ministry of Economic Affairs and Employment · www.tem.fi


Licensing nuclear installations
EIA procedure (EIA report)
Decision-in-principle (Parliament ratification – overall good of the society)
Competitive bidding, choosing of the plant supplier and plant site
Construction licence
Building, environmental and other permits
Construction of the nuclear facility
Operating licence
Operation of the nuclear facility
Decommissioning licence
EIA = Environmental Impact Assessment
Carried out by the applicant
Ministry of Economic Affairs and Employment of Finland • www.tem.fi
29.5.2019
5

TVO - OLKILUOTO site – OL1, OL2 and OL3

- **OL1 and OL2 - continuous improvement through modernization projects**
  - 2018 renewal of operating license till 2038.
  - Submission of the license application in January 2017, license in October 2018.
- **OL3 - toward commissioning**
  - Operating license application in 2016. License in 2019 > fuel loading expected in August/September 2019 > start of operating tests with fuel.
  - Electricity generation starts in 2019/20.
- **All nuclear waste management on one island**
  - Operating waste repository (VLJ repository at the site)
  - Interim storage for spent nuclear fuel (Renewal and extension 2015).
  - Final disposal facility for spent nuclear fuel, Posiva / ONKALO in Olkiluoto under construction.



 7

Hanhikivi 1 to be built in Pyhäjoki

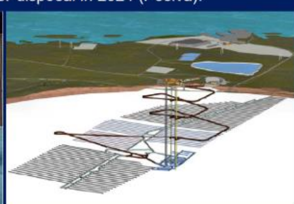
Fennovoima Hanhikivi1

- ROSATOM VVER / AES2006, 1200 MW(e) reactor
- Owners – Voimaosakeyhtiö Suomi 66 % & ROSATOM 34 %
- Site in Pyhäjoki, Hanhikivenniemi
- Construction license application submitted in 2015
- License handling ongoing (Safety assessment delayed due to the submission of documents), present schedule in 2021.
- Start of operation based on ROSATOM information in 2027/8, based on MEAE estimation around 2030.
- Currently contract with Posiva Solutions for development of spent nuclear fuel waste management solution.
- Automation contract bidding process by ROSATOM ongoing.
- Fennovoima staff about 350 in 2018, project staff from ROSATOM.
- Fennovoima participates to the national research programmes since 2010.
- Fennovoima participates MEAE working groups for national waste management and waste management funding.

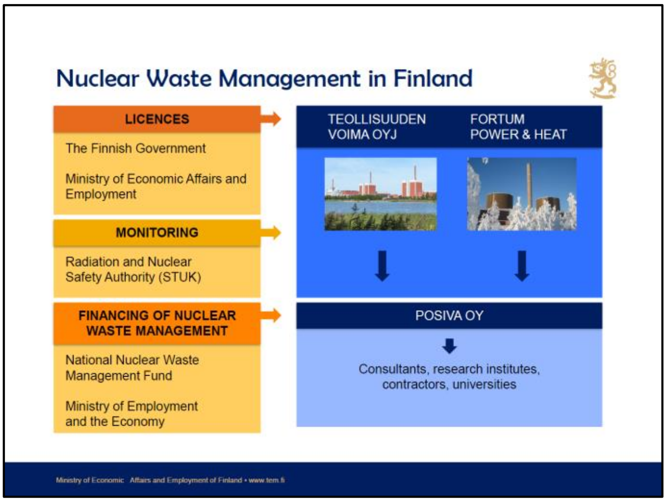
Existing functions for spent fuel

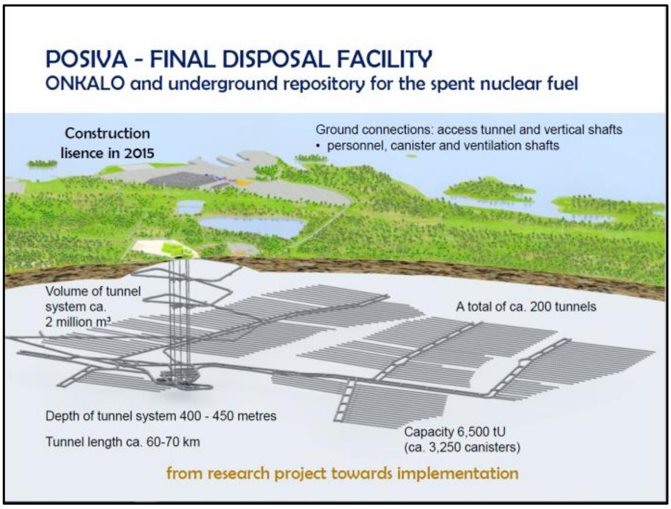
- Storage, transport activities and the research tunnel ONKALO in operation.
- ONKALO final depth of 420 metres and length more than 4000 meters.
- First in the world Construction license in 2015 for the final disposal facility, start of construction in 2016.
- Readiness to start the operation for disposal in 2024 (Posiva).

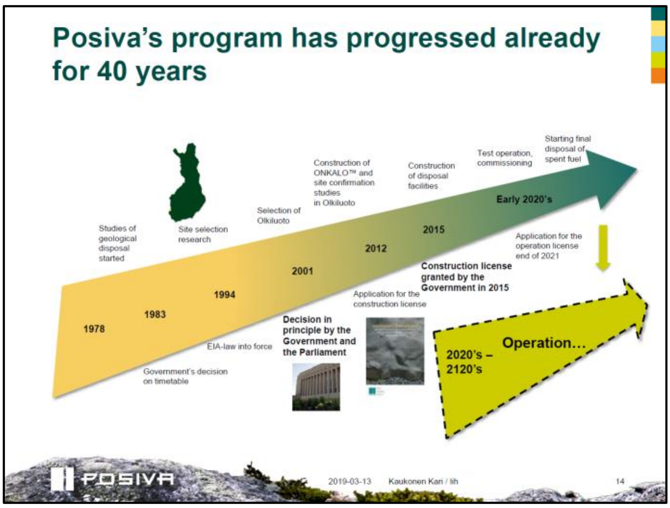
Olkiluoto spent fuel transport



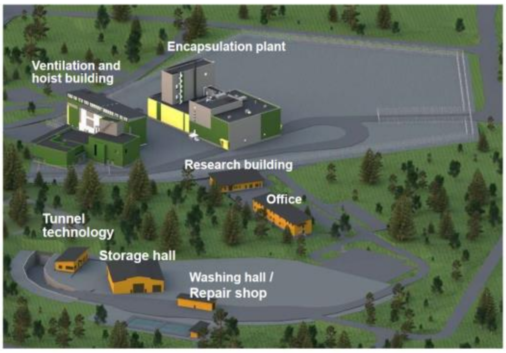
ONKALO, excavation started in 2004


Nuclear Waste Management in Finland
LICENCES
The Finnish Government
Ministry of Economic Affairs and Employment
MONITORING
Radiation and Nuclear Safety Authority (STUK)
FINANCING OF NUCLEAR WASTE MANAGEMENT
National Nuclear Waste Management Fund
Ministry of Employment and the Economy
TEOLLISUUDEN VOIMA OYJ
FORTUM POWER & HEAT
POSIVA OY
Consultants, research institutes, contractors, universities
Ministry of Economic Affairs and Employment of Finland • www.tem.fi


POSIVA - FINAL DISPOSAL FACILITY
ONKALO and underground repository for the spent nuclear fuel
Construction lisence in 2015
Ground connections: access tunnel and vertical shafts
• personnel, canister and ventilation shafts
Volume of tunnel system ca. 2 million m³
A total of ca. 200 tunnels
Depth of tunnel system 400 - 450 metres
Tunnel length ca. 60-70 km
Capacity 6,500 tU
(ca. 3,250 canisters)
from research project towards implementation


Posiva's program has progressed already for 40 years
Studies of geological disposal started
Site selection research
Selection of Olkiluoto
Construction of ONKALO™ and site confirmation studies in Olkiluoto
Construction of disposal facilities
Test operation, commissioning
Starting final disposal of spent fuel
Early 2020's
1978
1983
1994
2001
2012
2015
Application for the operation license end of 2021
Construction license granted by the Government in 2015
Application for the construction license
Decision in principle by the Government and the Parliament
EIA-law into force
Government's decision on timetable
Operation…
2020's – 2120's
POSIVA
2019-03-13
Kaukonen Kari / lih
14

ONKALO site in 2020's



Final disposal facility project proceeds

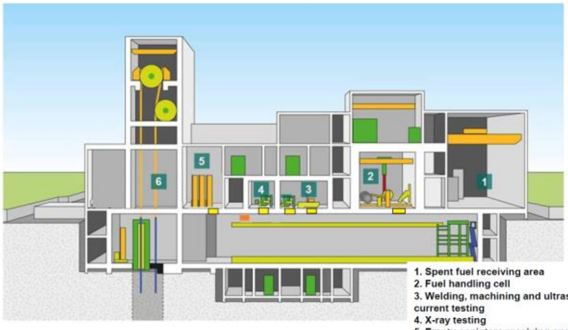
- Canister hoist raise boring about to finish
- Full-scale In Situ System Test (FISST) proceeds
    - Copper canister with heating and instrumentation installed in June 2018
    - Buffer installed in July 2018
    - Backfilling is about to finish
    - Plug installation early 2019
- Encapsulation plant main equipment suppliers have been selected and engineering/licensing is ongoing
- Production planning for the first production phase (45 years) is ongoing
- Start of encapsulation plant construction in summer 2019.

FISST-installations, canister and bentonite buffer components

Buffer installed July 23rd 2018

Canister installed June 29th 2018

Encapsulation plant – decision to start the construction works in 2019



1. Spent fuel receiving area
2. Fuel handling cell
3. Welding, machining and ultrasonic/eddy current testing
4. X-ray testing
5. Empty canisters receiving and storage
6. Canister hoist

SAFIR2022

Overall safety and systemic approach to safety: Overall safety and systemic approach to safety includes a wide range of overarching nuclear safety research topics, as well as topics affecting the nuclear power plant as a whole.

Reactor safety: Reactor safety research focuses on the development of experimental and computational analysis methods aimed to ensure that a nuclear facility and its systems are able to implement the safety requirements set for them.

Structural safety and materials: The aim of the research on structural safety and materials is to increase knowledge that supports long-term and reliable use of the nuclear power plants, particularly with respect to matters involving the integrity of barriers and material issues that affect the reliability of the safety functions.

Research infrastructure development: Domestic infrastructure and experimental research are vital for the maintenance and enhancement of national competences, as well as for leveraging international experimental capabilities for national needs.

SAFIR2018 in 2015-2018

- The total volume of research was 29,6 M€, 209 person years
- The funding organisations: the Finnish State Nuclear Waste Management Fund (VYR) with 17,7 M€, VTT with 6,4 M€, LUT University , Aalto University, NKS, SSM, Halden Reactor Project, TVO, Fennovoima, Fortum, others.
- In addition, VTT Centre for Nuclear Safety equipment and laboratory projects were funded by jointly SAFIR2018 and KYT2018, which increases the total funding to 46,4 M€.
- 1095 publications and other reports including 166 scientific journal articles and 236 conference articles
- 44 higher academic degrees, 18 doctors.

SAFIR2022 in 2019

- The total volume of research is 6,7 M€: 32 research projects and 42 person years.
- In addition, funding for the VTT Centre for Nuclear Safety projects jointly by SAFIR2022 and KYT2022 is 6,2 M€.
- Research: overall safety and organisation, plant level analysis, reactor and fuel, thermal hydraulics, mechanical integrity, structures and materials, severe accidents, research infrastructure.

The new VTT Centre for Nuclear Safety has hot cells for research and testing of radioactive structural materials from nuclear power plants.

CFD model of VVER-440 pressurizer.

For details, see SAFIR2022 and SAFIR2018 websites http://safir2022.vtt.fi and http://safir2018.vtt.fi (the final report of SAFIR2018 available).

Finnish Research Programmes on Nuclear Waste Management KYT2018 and KYT2022

- Research is divided into interacting main topics: (1) safety, (2) feasibility, and (3) acceptability of nuclear waste management with safety as the most central
- Research infrastructure development since 2016
- Funding from State Nuclear Waste Management Fund and research organisations
- Coordination at VTT

KYT2018 in 2015-2018

- 4-year budget 11,6 M€, 32 research and infra projects, 100 person-years
- 13 public seminars
- 71 peer-reviewed articles, 215 conference papers, 36 academic degrees (12 doctors)
- International review 2017
- Research organisations: VTT, Aalto University, Geological Survey of Finland, Universities of Helsinki, Jyväskylä, Eastern Finland, Tampere, Tampere University of Technology, Numerola Oy

KYT2022 in 2019

- Annual budget 2,1 M€, 30 research and infra projects, 24 person-years
- Safety on nuclear waste most central research topic
- As new topics, for instance decommissioning, and overall safety in nuclear waste management
- Research organisations: see KYT2018

Further information:

- KYT2018: http://kyt2018.vtt.fi/en/
- KYT2022: http://kyt2022.vtt.fi/en/, under completion

SESSION 2
SAFETY OF NUCLEAR INSTALLATIONS

SUMMARY SESSION 2 - SAFETY OF NUCLEAR INSTALLATIONS

Chair: Guido BRACKE (GRS, DE) Waste Management Safety
Co-chair: Massimo GARRIBBA (DG ENER, EC) Director Nuclear Energy,
Expert rapporteur: Giovanni BRUNA (FR)

Attendance: 50-60 delegates

The second session on "Safety of Nuclear Installations" was mainly devoted to the initiatives widely supported within Europe and internationally to enhance reactor safety: on one side, through the development of innovative fuels and materials - also in the objective of guaranteeing a safe and non-proliferating supply for both industrial and research facilities and, on the other side, by conveniently and extensively translating into practice - through R&D and innovation - the outcomes of the post-Fukushima-Daiichi lessons learned, studies and investigations. Overall this has contributed to a significant improvement in the severe accidents (SA) assessment methodology and in the ability of their prevention and mitigation.

These achievements have been widely supported by the development of suitable extended Probabilistic Safety Assessment (PSA) - able to address the external hazards as well as the site and environmental conditions - a deeper understanding of the transient initiation and physics - that allows filling the gap of knowledge and reducing the uncertainties in phenomena such as the core degradation, the core melt down and the hydrogen deflagration - the expansion of the computation and validation capacity, the improvement of existing mitigation systems and strategies, and the development of new ones to reduce the source term as well as the likelihood of contaminants release to the environment.

However, even if the nuclear radiological emergency management recently benefitted of a renewed interest as well as of an harmonized, shared and more coordinated approach, it is recommended devoting a specific care to the strategies adopted to inform the general public, increase its awareness and capture its confidence on the ability of the nuclear sector to prevent and conveniently handle emergency situations. This is considered mandatory for the acceptance of the nuclear power in the short / mid-term.

In the meantime, joint experimental research activities have improved and strengthened the use of shared resources, methodologies, tools, in a renewed condition of confidence and collaboration both at the European and international level. It is recommended to strengthen the effort to gather high level expertise and skills to guarantee that nuclear energy will continue contributing to the sharing of electricity production in the world while achieving a decarbonized energy future.

Stefano MONTI (IAEA, AT)

Keynote: Global trends in nuclear power: advanced reactors including SMR integrated in hybrid energy systems

Nuclear power has an important role to play to achieve UN Sustainable Development Goals as well as Paris Agreement targets on GHG emissions. Innovation applied to the current NPP fleet and R&TD supporting advanced Nuclear Energy Systems are key for an expanded role of nuclear power, in particular in combatting climate change.

Stefano Monti presented in some detail the current situation of nuclear energy deployment in the world, how nuclear power already contributes to the sustainability and decarbonization of the energy sector, and the expected further contributions from advanced reactors including Small Modular reactors (SMRs). Recent IAEA forecasts show that nuclear energy will continue to significantly contribute to the sharing of clean electricity production, even in the less optimistic scenarios which postulate a stagnant number of new nuclear built in the near future, just enough to compensate the expected shut-down of NPPs as a consequence of ageing and / or political decisions.

The today ownership of the new built (47 by state owned companies, only 6+1 by private operators) also suggests that nuclear power economic and financial sustainability calls for a clear state commitment and support. Uncertainties remain high due to fuzzy current situation in several regions of the world; this justifies three very different scenarios for the 2050 perspectives: a sharp increase of new constructions, a slow increase and even a stagnation / reduction of the installed nuclear capacity. Despite the newcomer countries which have decided to adopt nuclear power for the first time (such as - only accounting for countries in which new constructions have already started - UAE - United Arab Emirates - Bangladesh, Belarus, Turkey), the nuclear sector remains fragile. The improvement of its sustainability crucially needs and relies upon innovation both on current fleet and advanced reactors, fuels and fuel cycles.

Stefano Monti informed that the IAEA is addressing growing interest of Member States regarding advanced/innovative reactors, non-electric applications as well as loosely and tightly coupled hybrid energy systems. The IAEA Advanced Reactors Information System (ARIS) provides a comprehensive overview of the current reactor technologies being developed and deployed, by giving free access to detailed technical information provided by designers and vendors. The new edition of the supplement to ARIS on Small Modular Reactors demonstrates that there is an increasing interest worldwide on this advanced reactor technology, with great expectations in terms of technological and non-technological performances and advantages.

Monti concluded that the broad variety of advanced reactors (in particular SMR) requires an integrated holistic approach to develop guidance regarding RWM, SNF and decommissioning considerations during the design phase of new reactors, fuel types and advanced fuel cycles.

Presentation of Konstantina LAMBRINOU (SCK-CEN, BE), presented by Pietro AGOSTINI (ENEA)

The presentation on *Innovative Gen-II-III Reactors Fuels and Materials* addressed 4 projects on European studies aimed at preventing structural material failures in reactors in operation: IL TROVATORE, MULTIMETAL, MATTER, SCWR-FQT.

IL TROVATORE

IL TROVATORE, "Innovative cladding materials for advanced accident-tolerant energy systems", is an ongoing H2020 European project, coordinated by the SCK•CEN, scheduled to run from 01/10/17 to 31/03/22, with a EU contribution of about 5 M€. The project is an international collaboration that combines academic excellence with strong industrial support, boasting 30 beneficiaries across 3 continents (28 beneficiaries from Europe, 1 from the USA, and 1 from Japan). It focuses on new fuel cladding materials, able to resist the very high temperatures such as those achieved during the LOCA in PWRs. The 2011 Fukushima Daiichi event drives the development of accident-tolerant fuels (ATFs), expected to overcome the inherent technical shortcomings of the standard zircaloy/UO2 fuels, IL TROVATORE is to optimise promising ATF cladding material concepts for Gen-II/III light water reactors (LWRs) and validate them in an industrially-relevant environment via a dedicated neutron irradiation in PWR-like water.

MULTIMETAL

MULTIMETAL, "Structural performance of multi-metal component", was a FP7 project active in the period 01/02/12 to 31/01/15 under the coordination of was VTT, with a EU contribution of a little bit more than 1,5M€. It involved 8 beneficiaries, aimed at collecting and analysing relevant information from the field experience and tests on dissimilar metal welds as location of brittle fracture. Modelling of ductile failure processes was used as an innovative technique considering ageing-related phenomena and realistic stress distributions in the weld area. Modelling was supported by a comprehensive material test program. One of its objectives was to develop a procedure to measure the fracture toughness of DMWs. The underlying aim of the project was to provide recommendations for a best-practice approach to assess the integrity of DMWs, as a part of overall integrity analyses and Leak-Before-Break (LBB) procedures.

MATTER

MATTER, "MATerials TEsting and Rules", was an FP7 project coordinated by ENEA, active from 01/01/11 to 31/12/14 with a EU contribution of about 6 M€. It involved 27 beneficiaries from 13 countries. Its main objective was to support ESNII reactor design research in the field of materials, focusing on the accelerator-driven systems (ADS), ASTRID and MYRRHA. It was aimed at addressing the problems of high temperature, the brittle rupture and corrosion in the liquid metal cooled fast reactors. To this purpose, specific material testing procedures were developed and innovative design rules were proposed with particular attention to the Grade 91 (T91) ferritic/martensitic (f/m) tempered steel.

SCWR-FQT

SCWR-FQT, the FP7 "Supercritical Water Reactor - Fuel Qualification Test" was active in the period 01/01/11 to 31/12/14, with a EU contribution of 1.5 M€, under the coordination of the Centrum Výzkumu Řež (CVR). It involved 7 European partners as well as 9 from China. The Chinese partners did not care of administrative aspects, but the project was coordinated on an international collaborative basis. The European SCWR concept, a High-Performance Light Water Reactor (HPLWR), has been developed since 2006. In the "HPLWR-Phase 2" project (period 2006–2010), neutronic, mechanical, thermal-hydraulic, and safety analyses have been performed to assess the feasibility of this innovative core design. Corrosion and high temperature are considered as the most relevant failure causes for the SCWR. In the project the materials for fuel clads and core structures have been investigated and the best performing ones selected.

Questions. Questions addressed various aspects of the clad material properties. A specific one concerned the peak value of 550 °C considered in the MATTER project investigations. It was answered that, the operation pick temperature of the reactors under consideration and the value for testing has been set at the maximum peak temperature defined by the reactor designer.

Presentation of Stéphane VALANCE (CEA, FR)

The presentation of the *Innovative and safe supply of Fuels for Reactors on European studies* aimed at developing innovative reactor fuels and materials - also in the objective of guaranteeing a safe and non-proliferating supply for both industrial and research facilities. It addressed 3 projects: LEU-FOREVER, HERACLES-CP, ESSANUF.

ESSANUF

ESSANUF (European Supply of Safe NUclear Fuel) was a Euratom project funded from 2016 to 2017 in the overall objective to create greater security of fuel supply to countries operating VVER-440 nuclear power plants in Czech Republic, Finland, Hungary, Slovakia and Ukraine. The project, led by Westinghouse Sweden, gathered eight consortium partners covering - by their geographical distribution - the countries operating VVER-440 nuclear power plants. Within the project, an improved VVER-440 fuel design has been developed and its manufacturing capabilities assessed. Furthermore, the project contributed to the generation of a generic licensing methodology for VVER-440 fuel and the set-up of tools for the required analyses for licensing.

HERACLES-CP

HERACLES-CP, an ongoing Euratom project, funded from 2015 to 2019, is a pillar of the overall fuel development program of the HERACLES group, "CP" standing for "Comprehension Phase". The general objective of the project is the provision of the technical and scientific foundations for the successful qualification of the Uranium-Molybdenum fuel (UMo), both in the dispersed and monolithic phase, relying upon the SEMPER-FIDELIS irradiation campaign, for which suitable technology necessary has been developed, as well tools for analysis and the tools need for the Post Irradiation Examinations (PIE).

LEU-FOREvER

LEU-FOREvER, an on-going HERACLES Euratom funded 8-partners project, enabling the continuation of the HERACLES-CP project over the period 2017 - 2021 to secure fuel supply to the European Research Reactors. It was conducted by CEA to optimize the manufacturing process up to the construction of a pilot equipment, modelling the in-pile SEMPER-FIDELIS behaviour and the post-irradiation examination results.

A multi-disciplinary consortium composed of fuel and core designers, nuclear research centre(s) operating research reactor and fuel manufacturers has been set up to tackle both issues.

Questions. Questions addressed the transition from historical fuel to the new one, in respect to both technical and regulatory aspects and the potential improvement of life cycle cost coupled with extended operating cycle and the conditions of the VVER fuel throughout Europe. Moreover, it was stated that the projects have got commercial objectives. It has been proved that it is possible to manufacture such fuel and go through validation.

Presentation of Ahmed BENTAIB (IRSN, FR)

The presentation of "*Safety assessments and severe accidents, impact of external events on nuclear power plants and on mitigation strategies*" addressed several projects launched under the auspices of EURATOM, aimed at: filling the gap of knowledge and reduce the uncertainties on phenomena participating in SA such as the core degradation, the core melt and the hydrogen deflagration, increasing the ASTEC code suitability to address SA phenomena and management for a large number of designs including PWR, BWR, VVER and CANDU, developing new mitigation systems and strategies to reduce the source term release as well as a system for heat removal, improving the mitigation strategies in support to the in-vessel retention,

PASSAM

PASSAM, "Passive and Active Systems on Severe Accident source term Mitigation", project was launched within the FP7 in 2013. A four-year project (2013 – 2016), it was coordinated by IRSN and involved nine partners from six countries. It was aimed at exploring potential enhancements of existing source term mitigation devices (both of active and passive nature) and checking the capacity of innovative systems to achieve even larger source term attenuation. Mainly of R&D experimental nature, the program addressed phenomena able to reduce the radioactive releases to the environment in case of a severe accident.

ALISA

ALISA "Access to Large Infrastructure for Severe Accidents", an ongoing European FP7 project gathers European and Chinese research Institutions operating in the area of severe accident research for Light Water Reactors. The project provides the European and Chinese organizations with a shared access to large research infrastructures to study SA phenomena. It is intended to address the main topics in SA, such as the coolability of a degraded core, the corium coolability in the RPV, the possible melt dispersion to the reactor cavity, the molten corium-concrete interaction and the hydrogen mixing and combustion in the containment. The main objective of the program is to understand how these events affect the safety of reactors and to define suitable soundly-based accident management procedures.

SAFEST

SAFEST "Severe Accident Facilities for European Safety Targets" is a European project networking the European corium experimental laboratories and the CLADS/JAEA, Japan, the duration of which was originally set at 4.5 years with a programmed end in December 2018. The project objective was to address the variety of the still pending severe accident issues related to accident analysis and corium behaviour in Light Water Reactors. Due to the links to other European projects or platforms (e.g. CESAM, IVMR, NUGENIA/SARNET, etc.), it did offer a unique opportunity to parties to get involved in the networks and activities supporting safety of reactors and to have access to large-scale experimental facilities in Europe to enhance understanding of reactor core behaviour under severe accident conditions. Its experimental results are to be used for the development and validation of models and their implementation in the severe accident codes such as ASTEC, MELCOR, ATHLET-CD. That should enable capitalizing in the codes and in the scientific databases the outcomes of severe accident research, thus allowing to preserve and divulgate the knowledge to a large number of current and future end-users in Europe.

CESAM

CESAM, "Code for European Severe Accident Management" project was aimed at improving and extending the capacity of the ASTEC software system, the European reference for the study and the management of core melt accidents for Gen.II and Gen.III NPPs. It was launched in April 2013 under FP7 and concluded in March 2017. Coordinated by GRS with a major contribution from IRSN, the project brought together 18 European and one Indian partners. The main objectives of CESAM were: achieving a better understanding of all relevant phenomena of the Fukushima accident and of their importance for SAM (Severe Accident Management) measures, as well as improving the ASTEC computer code to simulate plant behavior throughout the accidental sequences. In parallel, significant progress has been made in the numerical performance, that allows reducing the computation time.

IVMR

IVMR, "In Vessel Molten core Retention", a H2020 project coordinated by IRSN, spans over the period 2015 – 2019, and is still ongoing. It aims at providing new experimental data and a harmonized methodology for the In-Vessel melt Retention (IVR) strategy for LWR, which intends to stabilize and isolate the corium and the fission products inside the reactor pressure vessel and in the primary circuit.

The main objectives of the project are: for small size reactors, the screening of the methodologies adopted by the partners (quite consistent results have been obtained in an extended benchmark exercise), for larger systems, the investigation of the discrepancies experienced, which can be - at least partially - explained by the use of different methodologies / approximations / simplifications in the computation chains.

The results allow concluding that the majority of current SA codes can be adopted for deterministic and probabilistic IVR studies for large systems, only if are used with care referring to the up-to-date knowledge and the SAMG logic for different reactor designs, using the material properties at extreme conditions, checking and respecting the code limitations and referring to appropriate user specific options.

sCO2-HeRo

sCO2-HeRo project (2015-2018), led by the University of Duisburg-Essen with 6 partners, was aimed at developing and proving the concept of a new self-launching, self-propelling, and self-sustaining, safety system for nuclear power plants, based on supercritical CO2 heat removal system based on Brayton cycle.

The main goal of the project is to investigate the technical potential of this system and to build up a small-scale demonstrator (technology readiness level (TRL) 3) at the PWR glass model at Gesellschaft für Simulatorschulung (GfS), Germany.

Questions. Questions addressed the progress in computation capacity to reduce uncertainty, the criteria adopted for critical heat flux, the number of nodes used to perform the calculations in ASTEC.

A comprehensive discussion was also engaged on problem of corium stratification. Actually, the stratification of melted core (corium) is a main issue in the SA management because it can engender situations challenging the integrity of the vessel, which is mandatory to all effective in-vessel retention strategy. The IVMR project outcomes indicate that the most advanced models for stratified pools can simulate transient evolution with a possible inversion of stratification (heavy metal becoming light). This situation is identified as possibly critical as it drives highly superheated metal to the top of the pool. In the current state of knowledge, it is difficult to conclude about the exact risk associated with this situation because models for the kinetics of inversion of stratification and for the heat transfers under transient conditions are not accurate enough. Nevertheless, sensitivity studies on model parameters indicate that transient effects could reduce the ablated vessel thickness by half (for the case of a 1000

MWe reactor, LBLOCA scenario). So, it would decrease the safety margin but would not increase too significantly the residual risk. In order to make some progress in understanding those processes, experiments have started in two large scale experiments with simulants: SIMECO-2 at KTH, and LIVE at KIT. LIVE has already provided data on the heat transfers in a stratified molten pool under transient conditions and variable top layer height. SIMECO-2 is still under construction and will provide similar data but the conductivity of the top layer will be higher than the conductivity of bottom layer, leading to focusing effect. In parallel, CORDEB experiments, with real materials, have provided data to quantify the kinetics of mass transfer through the crust located between the top metal layer and the bottom oxide pool. For sure, complimentary investigation will necessary to provide a complete answer to this issue. To summarize, with additional effort in both experimental and modelling sides, we will be able in relatively short term to address the issue related to stratified conditions.

Presentation of Evelyne FOERSTER (CEA, FR)

The presentation of the Probabilistic Safety Assessment for internal and external events addressed two projects concerning the methodology for Probabilistic Safety Assessment (PSA) of Nuclear Power Plants (NPPs), which has been adopted for decades by practitioners to better understand the most probable initiators of nuclear accidents by identifying potential accident scenarios, their consequences, and their probabilities, through the two projects ASAMPSA-E and NARSIS.

Following the Fukushima accident, several initiatives have been launched at the international level, in order to review current practices and identify shortcomings in scientific and technical approaches for the characterization of external natural extreme events and the evaluation of their consequences on the safety of nuclear facilities, including the ASAMPSA-E and its follower the NARSIS, projects.

ASAMPSA-E, "Advanced Safety Assessment Methodologies: extended PSA", a FP7 project, was aimed at promoting good practices to extend the scope of existing PSAs and the application of such "extended PSA" in decision-making in the European context. This project led to a collection of guidance reports that describe existing practices and identify their limits. Moreover, it allowed identifying some idea for further research in the framework of collaborative activities.

NARSIS, "New Approach to Reactor Safety ImprovementS", a H2020 pending project, aims at proposing some improvements to be integrated in existing PSA procedures for NPPs, considering single, cascade and combined external natural hazards (earthquakes, flooding, extreme weather, tsunamis). The project is aimed at releasing various tools, together with recommendations and guidelines for use in nuclear safety assessment, including a Bayesian-based multi-risk framework able to account for causes and consequences of technical, social/organizational and human aspects and a supporting Severe Accident Management decision-making tools for demonstration purposes, as well. NARSIS will test the proposed improvements of the safety assessment procedures on virtual and actual PWR plants, postulating some hazard-induced damage states representing the variety of their initial conditions in terms of relevant parameters and availability of relevant systems, functions and equipment.

Questions. The discussions engendered open exchanges on the capacity of the methodology proposed in NARSIS (dynamic Bayesian Network (BN), based on Bayesian approach) to conveniently and extensively address the multi-risk modelling approach derived for the safety assessment purposes of NPPs, integrating plant complexity and multi-hazards scenarios. The BN approach is efficient in integrating the plant complexity and in accounting for multi-aggression (internal & external) scenarios. It has already been successfully applied in other high-risk industries (e.g. Air Transport Safety). The dynamic BN is proposed to include the plant living nature. However, research is on-going as BN results may be highly sensitive to the conditional probability values entered at the nodes. Moreover, BN usually cannot account for 2nd order uncertainties. Hence, in NARSIS, dedicated works are on-going to propose solutions to handle such issues (e.g. using Global Sensitivity Analysis, …), in order to highlight high risk situations (high probabilities) with high confidence levels (low variance).

Presentation of Federico ROCCHI (ENEA, IT)

The presentation Nuclear and radiological emergency management and preparedness described recent EURATOM research efforts on Emergency Preparedness and Response (EP&R), which have been conducted via the PREPARE and FASTNET programs addressing the main knowledge gaps identified in the outcomes of investigations carried-out in Europe in response to the Fukushima accident. It was based on the solution of similar problems, among which the fast estimation of time-dependent, long-lasting Source Terms, adopting very complementary and synergic approaches, a challenge depending on the experience and skill of the users. As the EP&R is playing an increasing role in Europe, it is mandatory to create a common and shared understanding of emergencies. Both PREPARE and FASTNET recognized the fundamental role of exercises to increase the experience of emergency responders in Europe. A general recommendation can then be formulated, in that more efforts should be dedicated in the future to the realization of such important exercises.

PREPARE

This PREPARE FP7 project gathered 45 partners from Europe and the Fukushima University from Japan, under the coordination of KIT, over the period February 1 2013 - January 31 2016.

The Fukushima accident demonstrated the likelihood of long-lasting releases of radionuclides from NPPs over several weeks. That made it necessary to check the current off-site nuclear emergency plans in European countries against accident scenarios based on lessons learned from the Fukushima accident, and to edit recommendations on the ways to improve them. The project has addressed the following topics through separate and complementary work-packages: operational procedures for long lasting releases, platform for information collection and exchange, management of contaminated goods, improvement of decision support systems relying upon the atmospheric dispersion models implemented in the two Decision Support Systems (DSS) ARGOS and RODOS, communication with the public, training, exercises and dissemination.

FASTNET

The **FASTNET "Fast Nuclear Emergency Tools"**, a 4.7 M€ H2020 still ongoing project, started in October 2015 with a European contribution of 2.8 M€ and is expected to end in September 2019. It gathers 20 partners, coordinated by IRSN, together with IAEA.

The aim of FASTNET is focused on three major pillars: the development of a reference SA scenarios database inclusive of time-dependent, isotopic STs (Source Terms); the extension of existing methods (3D3P) and fast-running codes (PERSAN and RASTEP) to predict STs of all current nuclear power plant technologies deployed in Europe and their further developments; the dissemination of best-practices on the use of the methods and tools developed within the project to estimate STs in real-time and during conditions representative of real emergencies.

Questions. The presentation has been followed and complemented by a very large and enriching exchange, addressing, among others, the crucial problem of the coherence among the states and their reactivity in the actuation of emergency measures; the influence of the socio-political context, including legislation aspects and public confidence and acceptance issues, also in connection with an increasing capacity to realise ex-post measurements of the radioactivity, which can turn-out significantly lower than the values used to actuate the emergency actions (sheltering, evacuation)...

The problem of the support to states unable to develop and actuate emergency plans was also addressed. It was indicated that, in case of such inability, these states can claim for support of International Organisations, such as the JRC and the IAEA.

The security issues have been evocated too, as penalizing conditions for emergency.

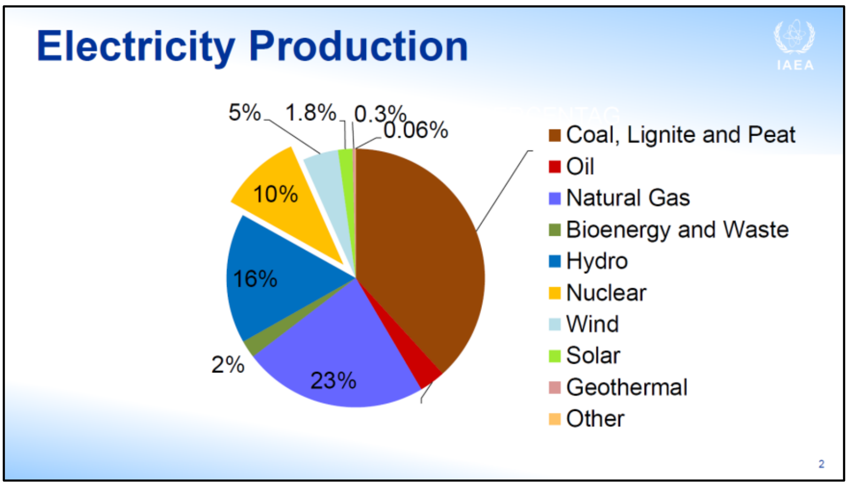
Eventually, the problem of the coherence in the emergency plans application among neighbouring states has been addressed in relationship with the interaction with legislation and responsibility sharing. The HERCA-WENRA approach requires mutual confidence between neighbouring countries in case of transboundary accidents; that can be achieved only through sharing common approaches, if not methods. It is true that national legislations differ to some extent, but if we can achieve a common understanding of an accidental situation, then implementation of countermeasures can become more and more coherent. That's why joint trainings, joint exercises and joint drills at the European scale and level are so important in this field and should be more and more encouraged and fostered.

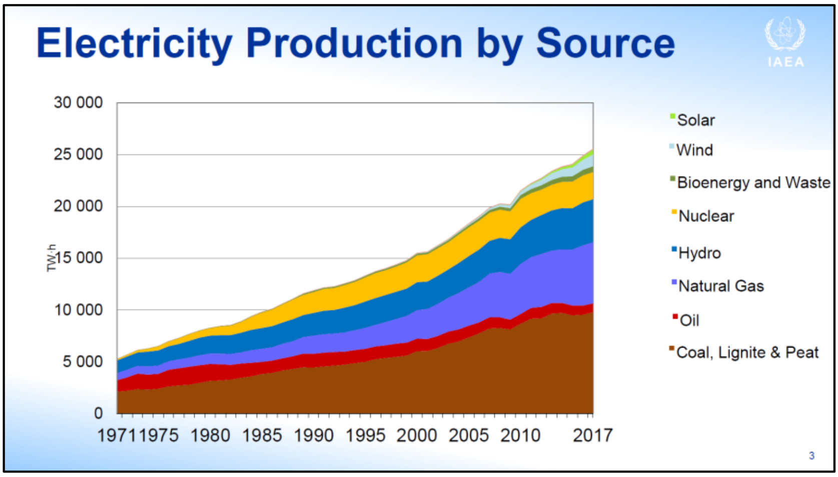
STEFANO MONTI

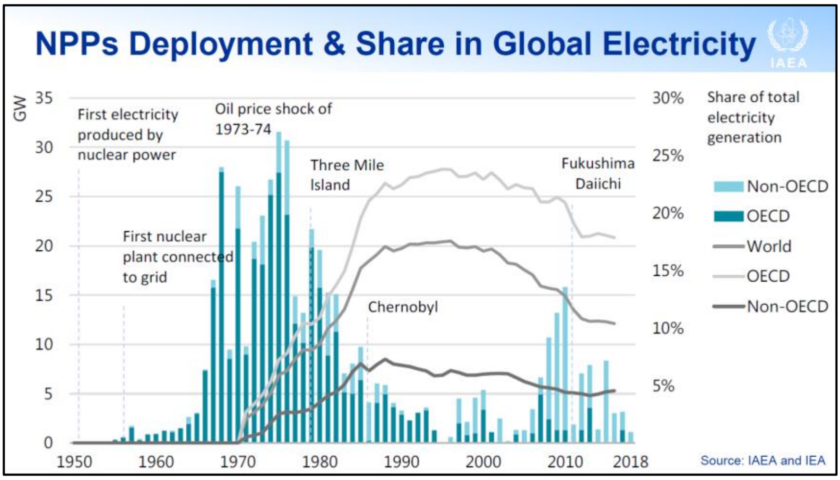
FISA 2019 – EURADWASTE '19

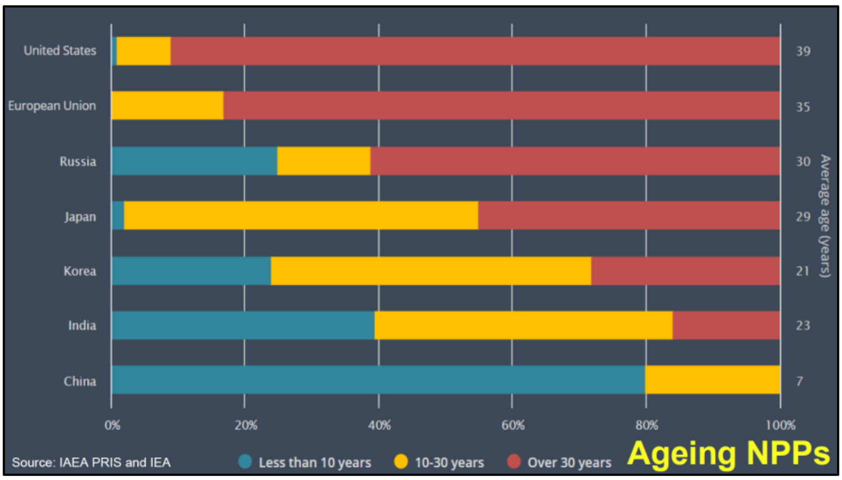
Presentation of Mr Stefano Monti (IAEA), Section Head, Nuclear Power Technology Development section, Division of Nuclear Power, Department of Nuclear Energy:

Global trends in nuclear power: Advanced reactors including SMR integrated in hybrid energy systems




Electricity Production by Source
IAEA
30 000
25 000
20 000
TWh
15 000
10 000
5 000
0
1971 1975 1980 1985 1990 1995 2000 2005 2010 2017
Solar
Wind
Bioenergy and Waste
Nuclear
Hydro
Natural Gas
Oil
Coal, Lignite & Peat
3


NPPs Deployment & Share in Global Electricity
IAEA
GW
35
30
25
20
15
10
5
0
1950 1960 1970 1980 1990 2000 2010 2018
First electricity produced by nuclear power
Oil price shock of 1973-74
First nuclear plant connected to grid
Three Mile Island
Chernobyl
Fukushima Daiichi
30%
25%
20%
15%
10%
5%
Share of total electricity generation
Non-OECD
OECD
World
OECD
Non-OECD
Source: IAEA and IEA

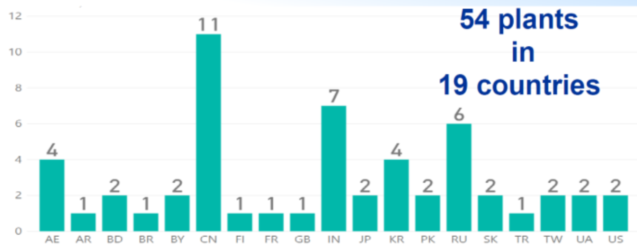

United States
European Union
Russia
Japan
Korea
India
China
0%
20%
40%
60%
80%
100%
39
35
30
29
21
23
7
Average age (years)
Source: IAEA PRIS and IEA
Less than 10 years
10-30 years
Over 30 years
Ageing NPPs

Nuclear Power

6

6

NPPs Under Construction



Economy type	Number of plants	State-owned operator	Private operator – regulated environment*	Private operator – wholesale market
Advanced economies	14	7	6	1
Developing economies	40	40	0	0
World	**54**	**47**	**6**	**1**

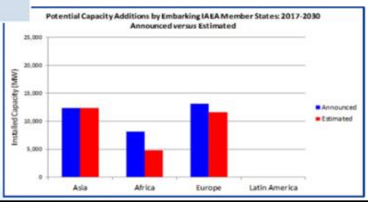
Source: IAEA and IEA

7

Newcomers in numbers

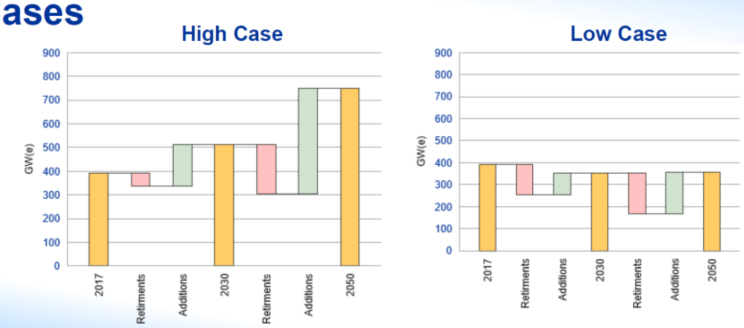
Country Status (according to the Milestones)	Countries
First NPP construction started	4
First NPP contract under negotiation or signed	1
Decision made, preparing infrastructure	4
Active preparation for final decision	9
Considering nuclear power programme	9

Construction: UAE, Bangladesh, Belarus, Turkey



8

World Nuclear Capacity: Actual, Retirements and Additions, High and Low Cases



Source: Energy, Electricity and Nuclear Power Estimates for the Period up to 2050 – RDS 1, 2018

9

Improving sustainability of the existing fleet of NPPs through innovation

- Ensure the key contribution of NP to decarbonization of the energy sector
- Ensure their availability to bridge the nuclear industry to a future that includes the routine deployment of:
  - SMRs & microreactors
  - Innovative reactor technologies (GIF technologies)
  - Tightly coupled hybrid energy systems
  - Non-electric applications of NP

10

ARIS

enables users to easily get an overview of the current reactor technologies being developed and deployed by giving access to the designers' reactor descriptions

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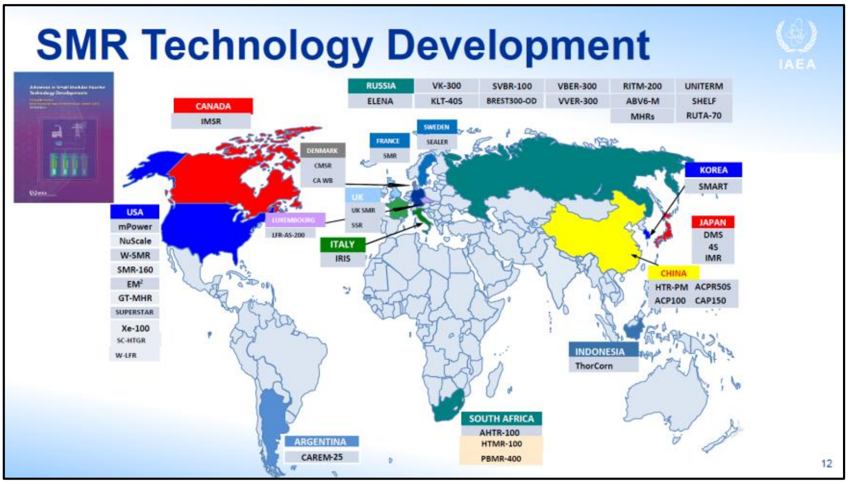
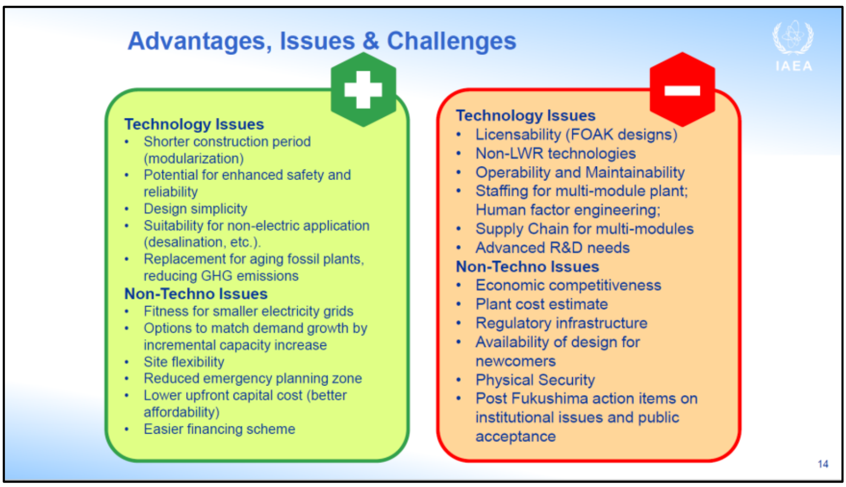


SMR Technology Development
IAEA
RUSSIA
VK-300
SVBR-100
VBER-300
RITM-200
UNITERM
ELENA
KLT-40S
BREST300-OD
VVER-300
ABV6-M
SHELF
MHRs
RUTA-70
CANADA
IMSR
SWEDEN
SEALER
FRANCE
SMR
DENMARK
CMSR
CA WB
KOREA
SMART
UK
UK SMR
SSR
LUXEMBOURG
LFR-AS-200
ITALY
IRIS
JAPAN
DMS
4S
IMR
USA
mPower
NuScale
W-SMR
SMR-160
EM²
GT-MHR
SUPERSTAR
Xe-100
SC-HTGR
W-LFR
CHINA
HTR-PM
ACPR50S
ACP100
CAP150
INDONESIA
ThorCorn
SOUTH AFRICA
AHTR-100
HTMR-100
PBMR-400
ARGENTINA
CAREM-25
12

SMR: definition & rationale for development
IAEA
Advanced Reactors with an installed capacity up to 300 MW(e), built in factories and transported as modules to sites for installation as demand arises.
A nuclear option to meet the need for flexible power generation for wider range of users and applications
Economic
• Lower Upfront capital cost
• Economy of serial production
Better Affordability
Modularization
• Multi-module
• Modular Construction
Shorter construction time
Flexible Application
• Remote regions
• Small grids
Wider range of Users
Smaller footprint
• Reduced Emergency planning zone
Site flexibility
Replacement for aging fossil-fired plants
Reduced CO_2 production
Potential Hybrid Energy System
Integration with Renewables
13



Advantages, Issues & Challenges
IAEA
Technology Issues
• Shorter construction period (modularization)
• Potential for enhanced safety and reliability
• Design simplicity
• Suitability for non-electric application (desalination, etc.).
• Replacement for aging fossil plants, reducing GHG emissions
Non-Techno Issues
• Fitness for smaller electricity grids
• Options to match demand growth by incremental capacity increase
• Site flexibility
• Reduced emergency planning zone
• Lower upfront capital cost (better affordability)
• Easier financing scheme
Technology Issues
• Licensability (FOAK designs)
• Non-LWR technologies
• Operability and Maintainability
• Staffing for multi-module plant; Human factor engineering;
• Supply Chain for multi-modules
• Advanced R&D needs
Non-Techno Issues
• Economic competitiveness
• Plant cost estimate
• Regulatory infrastructure
• Availability of design for newcomers
• Physical Security
• Post Fukushima action items on institutional issues and public acceptance
14

International Technical Working Group on SMR

- To advice and support IAEA programmatic planning and implementation in areas related to technology development, design, deployment and economics of SMRs
- 20 Member States and two International Organizations: European Commission and OECD-NEA as invited observers:

- Three technical subgroups established:
  - **SG-1:** Development of Generic Users Requirements and Criteria (GURC)
  - **SG-2:** Research, Technology Development and Innovation; Codes and Standards
  - **SG-3:** Industrialization, design engineering, testing, manufacturing, supply chain, and construction technology
- TWG will also address SMR for Non-Electric Applications and coupling with renewables
- 1st TWG Meeting for SMR held on 23 - 26 April 2018 in Vienna
- 2nd Meeting scheduled for 8 – 11 July 2019 in Vienna

IAEA acting as the Secretariat for

- Canada
- China
- Finland
- France
- Korea
- Russian Federation
- Saudi Arabia
- United Kingdom
- United States

SMR REGULATORS' FORUM

Safety of nuclear installations – Regulatory issues

- SMR Regulators' Forum:
  - Pilot Phase (2015-2017) with 3 Working Groups: graded approach; defence in depth and emergency planning arrangements
  - Phase 2 (2018-) with three new Working Groups: licensing; design safety and safety analysis; manufacturing, commissioning and operation
  - Next meeting planned for Q4 2019
- Capacity Building for SMRs (Planned Workshops)
  - Siting and External Hazards Evaluation
  - Design safety and safety assessment
  - Principles for Emergency Preparedness & Response
  - Regulatory framework and licensing issues

Emergency preparedness and response

- TM on Next Generation Reactors and EPR
  – Scheduled to take place in March 2020
  – Follow-up of a similar TM held in 2017
  – To be focused not only in SMR but also Generation IV reactors

- Based on the materials developed by the CRP on Emergency Planning Zones, technical guidance (EPR Series publications) is expected to be developed by 2021

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SMR: Support to Member States through TC

Ongoing SMR/HTGR Missions

- Indonesia
- Jordan
- Saudi Arabia

Technical Cooperation Project: Europe/Eurasia

- Armenia
- Azerbaijan
- Croatiiaa
- Czechia
- Hungary
- Lithuania
- Poland
- Romania
- Russia
- Slovakia
- Tajikistan
- Ukraine

- Design and technology status of water-cooled SMRs / non-water cooled SMRs
- Non-electric nuclear applications, options, technology readiness and toolkits
- Technology Assessment training
- Infrastructure, economic and financing aspects of SMRs
- Design Specific Issues on Engineering Project, Construction and Industrial Supply Chain for Small Modular Reactor Deployments
- Siting of SMRs
- SMR deployment scenarios in global energy portfolio
- Design safety and safety assessment of SMRs
- Principles for Emergency Preparedness & Response for SMRs
- SMR fuel cycles and waste management (specifically also for HTGRs)

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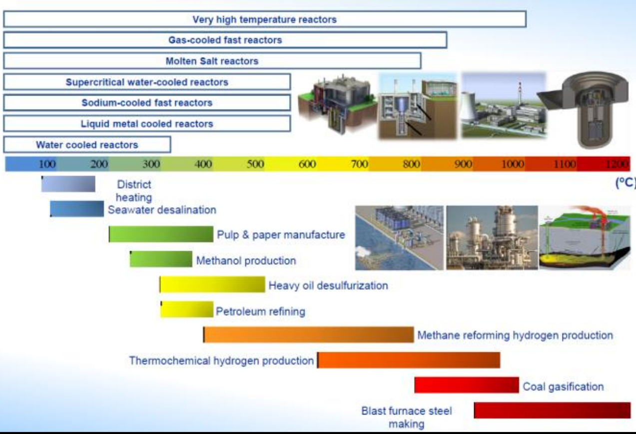
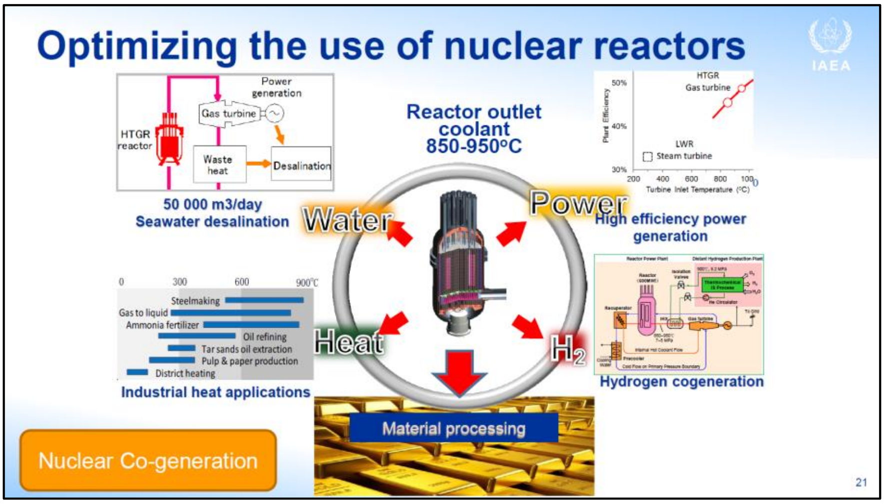
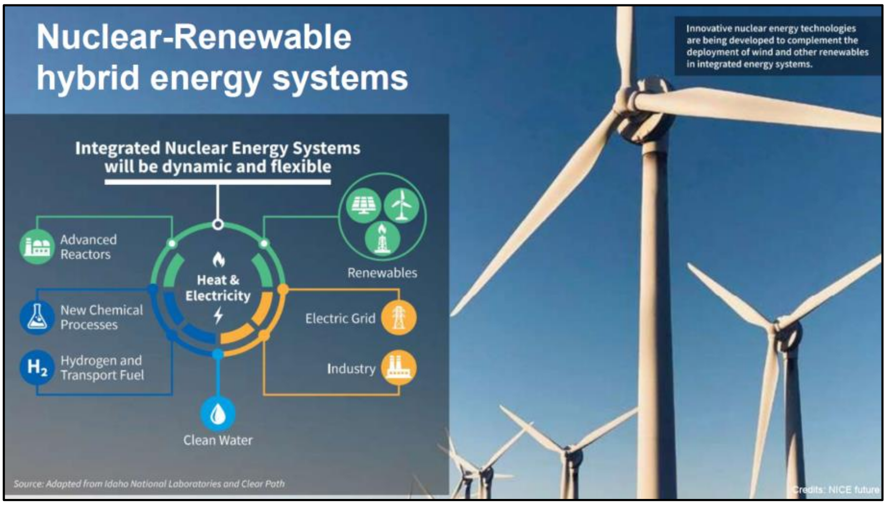
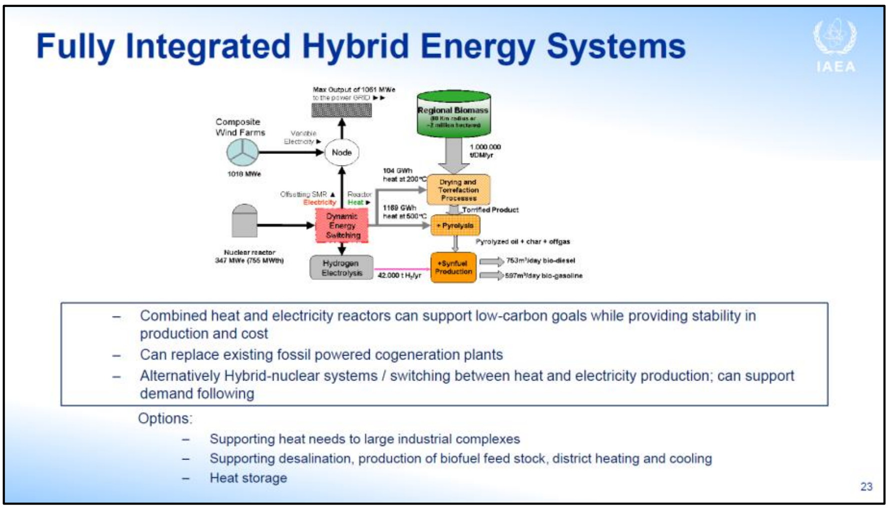
SMR for Non-Electric Applications



20


Optimizing the use of nuclear reactors
IAEA
Power generation
Gas turbine
HTGR reactor
Waste heat
Desalination
50 000 m3/day
Seawater desalination
Reactor outlet coolant 850-950°C
HTGR Gas turbine
LWR Steam turbine
Plant Efficiency
Turbine Inlet Temperature (°C)
Water
Power
High efficiency power generation
Steelmaking
Gas to liquid
Ammonia fertilizer
Oil refining
Tar sands oil extraction
Pulp & paper production
District heating
Industrial heat applications
Heat
H2
Hydrogen cogeneration
Material processing
Nuclear Co-generation
21


Nuclear-Renewable hybrid energy systems
Innovative nuclear energy technologies are being developed to complement the deployment of wind and other renewables in integrated energy systems.
Integrated Nuclear Energy Systems will be dynamic and flexible
Advanced Reactors
New Chemical Processes
Hydrogen and Transport Fuel
Heat & Electricity
Renewables
Electric Grid
Industry
Clean Water
Source: Adapted from Idaho National Laboratories and Clear Path
Credits: NICE future


Fully Integrated Hybrid Energy Systems
IAEA
Max Output of 1061 MWe to the power GRID
Composite Wind Farms
1018 MWe
Variable Electricity
Node
Regional Biomass
1 000 000 tDM/yr
104 GWh heat at 200°C
Drying and Torrefaction Processes
Torrified Product
1169 GWh heat at 500°C
Pyrolysis
Pyrolyzed oil + char + offgas
Offsetting SMR Electricity
Reactor Heat
Dynamic Energy Switching
Nuclear reactor 347 MWe (755 MWth)
Hydrogen Electrolysis
42 000 t H2/yr
Synfuel Production
753m³/day bio-diesel
597m³/day bio-gasoline
– Combined heat and electricity reactors can support low-carbon goals while providing stability in production and cost
– Can replace existing fossil powered cogeneration plants
– Alternatively Hybrid-nuclear systems / switching between heat and electricity production; can support demand following
Options:
– Supporting heat needs to large industrial complexes
– Supporting desalination, production of biofuel feed stock, district heating and cooling
– Heat storage
23

INPRO Dialogue Forum 17 in Coordination with NPTDS

- **INPRO Dialogue Forum (DF) 17 on "Opportunities and Challenges in Small Modular Reactors"**
- Venue: Ulsan, Republic of Korea, Jul 2019
- Opening, Technical Plenaries, Wrap Up and Closing Sessions
- Plenary Technical Sessions:
  - Market Opportunities
  - Design Requirements
  - Research & Technology Development
  - Near Term Deployment Designs (presented by design authorities – designs in licensing, construction or recent deployment)






- Technology Exhibition Space
- Technical Tours to local nuclear sites and industry
- Over 130 current expressions of interest for participation (DFs are usually less than 100 participants)

24

Conclusions

- Nuclear power has an important role to play to achieve UN Sustainable Development Goals and Paris Agreement targets
- Innovation applied to the current NPP fleet and R&TD supporting advanced NES are key for the expanded role of nuclear power
- IAEA is addressing growing interest of Member States regarding advanced/innovative reactors, non-electric applications as well as loosely and tightly coupled hybrid energy systems
- The broad variety of advanced reactors (in particular SMR) requires an integrated holistic approach to develop guidance regarding RWM, SNF and decommissioning considerations during the design phase of new reactors, fuel types and advanced fuel cycles

25 25

Thank you for your attention!

Contact:
Stefano MONTI
S.Monti@iaea.org

Atoms for peace and Development…

PIETRO AGOSTINI

INNOVATIVE GEN-II/III AND RESEARCH REACTORS' FUELS AND MATERIALS

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[2] NMS Institute, SCK•CEN, Boeretang 200, 2400 Mol – Belgium
[3] BA2505 Structural Integrity, VTT Technical Research Centre of Finland Ltd., Kivimiehentie 3, Espoo – Finland
[4] Power Engineering Technologies Department, Centrum výzkumu Řež, Hlavní 130, 258 65 Husinec Řež – Czech Republic

Abstract. This manuscript presents important material challenges regarding innovative Gen-II/III nuclear systems and research reactors. The challenges are discussed alongside the key achievements so far realised within the framework of 4 EU-funded projects: H2020 IL TROVATORE, FP7 MULTIMETAL, FP7 MATTER and FP7 SCWR-FQT. All the four Projects deal with innovative researches on materials to enhance the safety of nuclear reactors. IL TROVATORE proposes new materials for fuel cladding of PWR reactors and tests in order to really find out an "Accident Tolerant Fuel" (ATF). MULTIMETAL focused on optimization of dissimilar welds fabrication having considered the field performances and dedicated experiments. MATTER carried on methodological and experimental studies on the use of grade 91 steel in the harsh environment of liquid metal cooled EU fast reactors. SCWR-FQT focused on fuel qualification of Supercritical Water Reactor including the selection of the better material to resist the associated high thermal flux.

1. INTRODUCTION

The 2011 Fukushima Daiichi event demonstrated the need for improved nuclear safety. In the present work, which reports activities performed within four different EU Projects, the approach to enhance nuclear safety takes into consideration only the materials studies. In IL TROVATORE EU Project the focus was dedicated to new fuel cladding materials, able to resist the very high temperatures which are achieved during the Loss Of Coolant Accident of a PWR Reactor. These new materials are claimed to prevent the release of fission products so driving to the development of accident-tolerant fuels (ATFs). ATFs are expected to overcome the inherent technical shortcomings of the standard zircaloy/UO2 fuels, thus preventing the fuel cladding material failure and subsequent release of radioactive fission products to the power plant containment and the environment [1]. The main objective of IL TROVATORE ("Innovative cladding materials for advanced accident-tolerant energy systems") is to optimise promising ATF cladding material concepts for Gen-II/III light water reactors (LWRs) and validate them in an industrially-relevant environment via a dedicated neutron irradiation in PWR-like water

Besides high temperature peaks, another important reason of structural failure in nuclear reactors is represented by the material embrittlement, especially under neutron flux exposure. The dissimilar metal welds, represent, by operational experience, a typical location of brittle rupture of components. The first objective of the FP7 project MULTIMETAL ("Structural performance of multi-metal component") was to collect relevant information from the field experience, whereby typical locations of dissimilar metal welds (DMWs) in both Western and Eastern LWRs were identified, and their characteristics as well as applicable performance assessment methods considered. The analysis of ductile failure processes was supported by numerical methods considering ageing-related phenomena and realistic stress distributions in the weld area. Modelling was supported by a comprehensive material test program and procedures for measuring the fracture toughness of DMWs.

In liquid metal cooled fast reactors, besides the high temperature and the brittle rupture, also corrosion attack has to be considered as a third motivation for failure of structural materials. The MATTER EU Project took into consideration all these failure causes through extensive technological research on grade 91 materials for their applications in ESNII reactors. To this purpose, specific material testing procedures were developed for the ASTRID and MYRRHA projects and the design rules were proposed with particular attention to ferritic/martensitic (f/m) tempered steel.

The corrosive environment and the high temperature are also considered as the most relevant failure causes for the Supercritical Water Reactor. Although SCWR case is different from liquid metal cases, similar material studies to identify the best candidate material were performed in SCWR-FQP Project. The major challenges for the SCWR-FQP Project were to develop a viable core design, accurately estimate the heat transfer coefficient and develop materials for the fuel and core structures.

2. IL TROVATORE

IL TROVATORE (ID: 740415) is an ongoing H2020 project scheduled to run between 01/10/17 and 31/03/22. The EU contribution is 4 999 999,25 €, and the project coordinator is SCK•CEN, the Belgian Nuclear Research Centre. IL TROVATORE is an international collaboration that combines academic excellence with strong industrial support, boasting 30 beneficiaries across 3 continents (i.e., 28 beneficiaries from Europe, 1 from the USA, and 1 from Japan). IL TROVATORE focuses primarily on the following innovative accident tolerant fuel (ATF) cladding material concepts: (a) SiC/SiC composite clads (different designs) [2-3], (b) MAX phase-coated [4] and (c) oxide-coated commercial zircaloy clads [5], (d) Gepulste ElektronenStrahl Anlage (GESA) surface-modified commercial zircaloy clads [6], and (e) oxide-dispersed-strengthened (ODS) FeCrAl alloy clads [7]. Fig. 1 shows images associated with the innovative cladding materials which are proposed and fabricated within the Project IL TROVATORE; more details on these material concepts have been presented elsewhere [8]. Since the 1st reporting period (18 months) of IL TROVATORE has just finished and most of the technical achievements have not yet been published, the present document will not include data pertaining to the S&T status of this project. However, various (open access) publications have already appeared in high-impact peer-reviewed Journals, such as Scientific Reports, Inorganic Chemistry, etc. The activities in IL TROVATORE are thematically grouped in 3 domains: DM1 – processing; DM2 – characterisation of non-irradiated materials; and DM3 – characterisation of irradiated materials & predictive modelling activities. A fourth domain DM4 encompasses standardisation, exploitation of results, and dissemination & communication .

3. MULTIMETAL

MULTIMETAL (ID: 295968) was active in the period 01/02/12 to 31/01/15. The EU contribution was 1 683 480,98 €, and the project coordinator was VTT, Finland. FP7 MULTIMETAL involved 8 beneficiaries and was organised into the 8 work packages (WPs). The approach to studies of dissimilar metal welds (DMW) was carried out through dedicated actions. The first step of the project was to gather relevant information from field experience. Typical locations of DMWs in Western and Eastern type LWRs were identified, together with their physical and metallurgical characteristics, as well as applicable structural integrity assessment methods. The collection of relevant field information was followed by computational structural integrity assessment analyses of DMWs for dedicated test configurations and real cases.

These analyses involved simple engineering methods and numerical analyses. Ageing-related phenomena and realistic stress distributions in the weld area were considered. The computational analyses were supported by a comprehensive materials test program. Its aim was to develop a procedure for measuring the fracture toughness of DMWs. The project promoted the development of a common understanding for structural integrity assessment of DMWs in existing and future NPPs in EU member states. All DMW design variants showed high resistance to crack growth under the investigated conditions.

FP7 MULTIMETAL recommends the use of compact tension (CT) specimens (sub-sized, if necessary) for fracture toughness characterization of DMWs (Fig. 2).

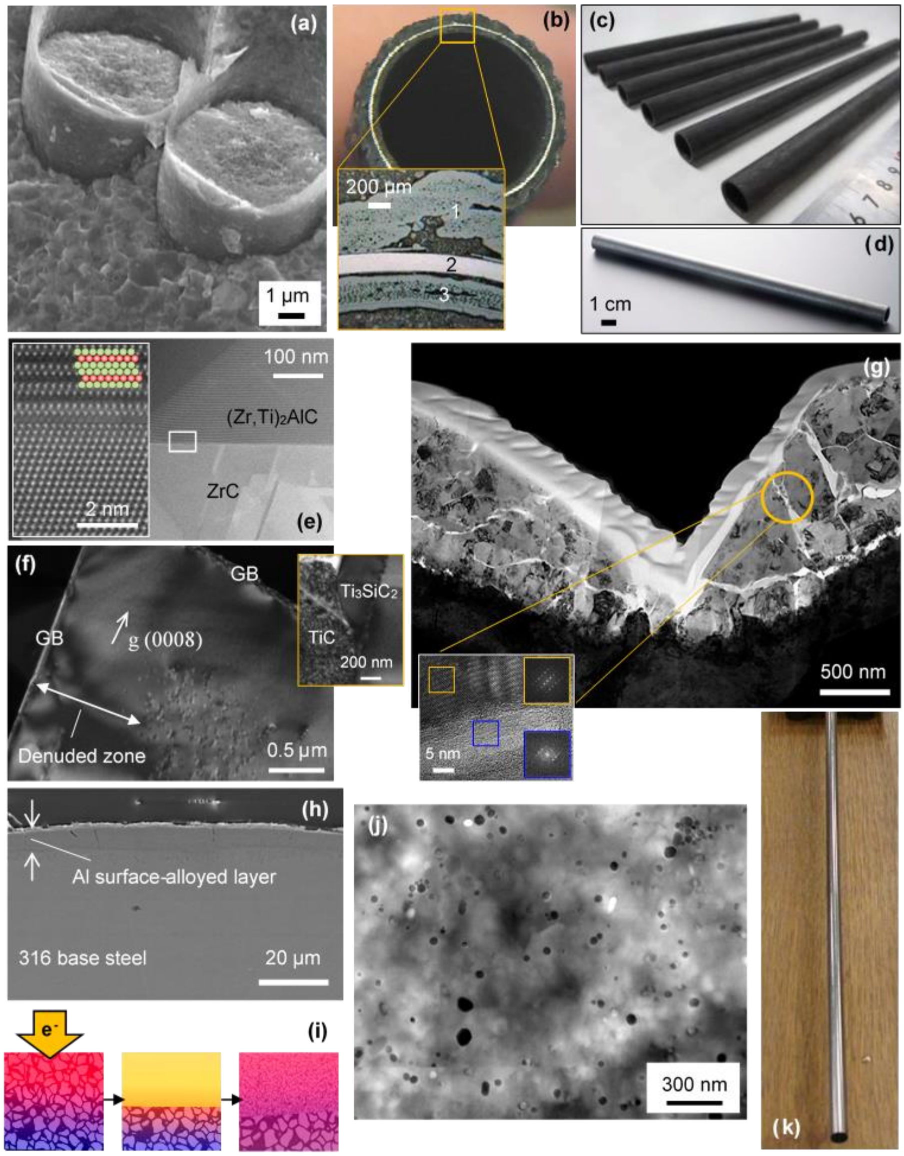

FIG. 1. (a-d) SiC/SiC composite clads: (a,c) DEMO-NITE SiC/SiC fracture surface and tubes; (b,d) CEA "sandwich" SiC/SiC cross-section and tube. (e) STEM image of a $(Zr,Ti)_2AlC$ MAX phase grain next to a ZrC 'impurity' grain. The magnified inset is a STEM image of the $(Zr,Ti)_2AlC$/ZrC interface. (f) Neutron-irradiated Ti_3SiC_2 (~735 °C, 3.4 dpa): defect-denuded zones are established next to grain boundaries (GBs) acting as potent defect 'sinks'. The magnified inset shows more damage in the 'impurity' TiC grain than in Ti_3SiC_2. (g) TEM images of a nano-impacted, ion-irradiated (150 dpa) Al_2O_3 coating: the crack-like features are filled with vitreous matter. (h) GESA Al surface-alloyed 316L steel exposed to liquid LBE (10,000 h, 600 °C, $C_O \approx 10^{-6}$ mass%). (i) GESA surface modification by an intense pulsed electron beam: volumetric heating → formation of a melt layer → restructured surface layer. (j) TEM image of a Fe-20Cr-5Al-0.5Ti-0.5Y_2O_3 alloy with nano-sized dispersoids. (k) Fe-14Cr ODS tube produced by CEA.

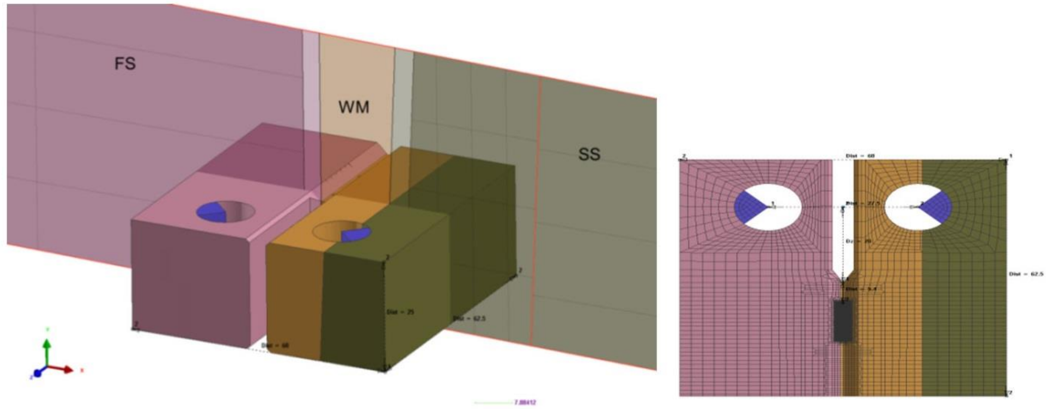

FIG. 2. Position and meshing of a CT25 specimen (MU1).

4. MATTER

MATTER (ID: 269706) was active in the period 01/01/11 to 31/12/14. The EU contribution was 5,993,919 €, and the project coordinator was ENEA, Italy. FP7 MATTER involved 27 beneficiaries from 13 countries.

The main objective of the FP7 project MATTER ("MATerials TEsting and Rules") was to conduct ESNII reactor design research in the field of materials, in particular for the accelerator-driven systems (ADS) ASTRID and MYRRHA. At the beginning of MATTER, the status of ASTRID and MYRRHA projects was identified as well as the requirements set by the two Projects in terms of researches to be dedicated to the employment of grade 91 steel. In the course of MATTER significant efforts were dedicated to new test procedures. Namely R&D activities were carried out in order to standardize liquid metal corrosion and mechanical tests on miniaturized specimens.

ESNII reactors are designed to work at high temperatures and high mechanical stress. The reference standards that are used in Europe for these projects, in particular the French RCC-MRx, refer mainly to the AISI 316L steel, the high-temperature characteristics of which are very different from those of grade 91 steels. Since the grade 91 steel softens under cyclic load and under creep conditions, it was necessary, in the course of MATTER, to conceive and conduct specific mechanical tests in order to draw the specific performance rules of the steel in terms of creep-fatigue, ratchetting and negligible creep.

For ratchetting, the work in FP7 MATTER included the development of viscoplastic constitutive models for more detailed simulation under more general conditions as well as the development and validation of an efficiency diagram in accordance with RCC-MRx approach. The proposed design rules for ratcheting, creep-fatigue and negligible creep were submitted to review by AFCEN for inclusion in RCC-MR, as probationary rules in a first stage. The designers of Gen-IV reactors need to demonstrate that non-replaceable components retain their integrity and reliable operation for at least 60 years, therefore long-term degradation mechanisms, including thermal ageing, irradiation and environmental effects from heavy liquid metal were addressed.

Tensile tests in lead-bismuth eutectic (coolant of MYRRHA) demonstrated that P91 steels are susceptible to liquid metal embrittlement as shown in fig.3. The consequent decision by the MYRRHA designers was to exclude this material from the construction of structural components.

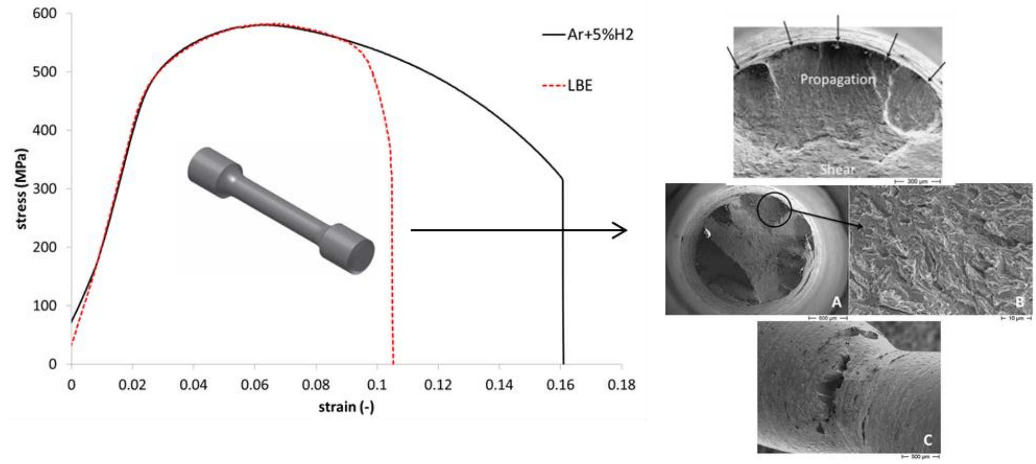

FIG. 3. Stress-strain curves of an T91 f/m steel tested in tension in Ar+5%H2 and oxygen-poor (CO ≈ 10-9-10-10 mass%) static liquid LBE. Both tests were conducted at 350°C under an applied strain rate of 5×10-5 s-1. The specimen tested in LBE was pre-exposed at 450°C in low-oxygen liquid LBE. The fracture surface of the specimen tested in LBE (A) shows areas that suffered quasi-cleavage (B) failure. Also, the inspection of the specimen necking region shows the formation of numerous side cracks (C).

The integrity of welds is a key issue for the design of all ESNII reactors. The development of fatigue weld factors, as well as the assessment of new filler materials and welding procedures, are of direct relevance for ESNII

In MATTER, fabrication efforts were dedicated to oxide dispersed strengthened (ODS) steels based on grade 91 composition, in order to enhance the EU knowledge in this sector.

5. SCWR-FQT

In 2011, the FP7 SCWR-FQT ("Supercritical Water Reactor – Fuel Qualification Test") project started. This project was active in the period 01/01/11 to 31/12/14. The EU contribution was 1 500 000 €, and the project coordinator was the Centrum Výzkumu Řež (CVR), Czech Republic. FP7 SCWR-FQT involving 7 European partners and 9 partners from China.

The FP7 SCWR-FQT project was built as 3 interconnected work packages that ran in parallel: the first work package contained all the design work and analyses of the fuel qualification test (FQT) facility; the second one dealt with the design of a similar, electrically heated test section that served for pre-qualification of the test section and that was designed and built in China; finally, the third work package dealt with the choice of a suitable cladding material, including necessary corrosion and mechanical tests. The objectives of the project were to make significant progress towards the design, analysis and licensing of the Fuel Qualification Test (FQT) facility cooled with supercritical water (figure 4) in the research reactor LVR-15. Test of the fuel assembly was addressed with the following concept: a pressure tube was placed instead of a fuel assembly in the LVR-15 reactor. It contained 4 fuel rods with 8 mm diameter and 9.44 mm pitch, similar to the HPLWR assembly concept, inside a square assembly box. The heated length was limited to 600 mm to match the core height of the reactor.

Final design and results of analyses of the test section, including the supercritical water loop, formed the basis of the licensing documents for the Czech regulator. Data from the operation of the electrically heated test section should serve both for pre-qualification operation as well as for validation of the codes used for analyses. Corrosion and mechanical data became available for the selected materials and a choice of the cladding materials was made during the project.

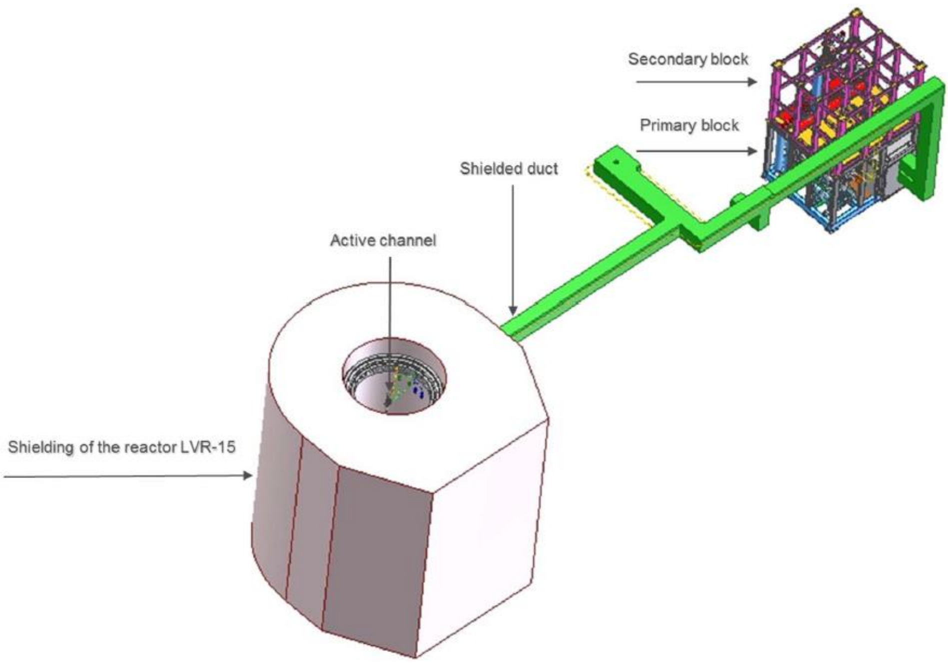

FIG. 4. SCWL-FQT loop and LVR-15 reactor [12].

6. ACHIEVED RESULTS

IL TROVATORE Project is not yet concluded, nevertheless the interim achievements are the fabrication and laboratory testing of six different candidate materials which are proposed as PWR fuel clads in order to resist the very high temperature experienced by the core during a LOCA transient.

The FP7 project MULTIMETAL confirmed that in different metal welds, the most critical zone, in terms of fracture, lies in a narrow band around the weld/low-alloy-steel interface.

The characterization of local tensile properties was a key issue for analyzing the toughness tests as well as the tests on weld mock-ups. New procedures were proposed for tensile testing.

In MATTER the standardization of liquid metal corrosion has led to test procedures and to the design of a test device currently used, within EERA JPNM, by all institutions contributing to corrosion tests in static heavy liquid metals (lead, Pb, and lead-bismuth eutectic, LBE). In terms of impact, the experimental evidence of the insufficient fracture toughness of T91 f/m steels after pre-wetting with LBE, determined its exclusion from the construction of MYRRHA load-bearing components.

In SCWR-FQT, the final design, the material selection and the results of analyses of the test section, including the supercritical water loop, formed the basis of the licensing documents for the Czech regulator.

7. DISSEMINATION & CAPITALIZATION OF THE KNOWLEDGE

Within IL TROVATORE, a series of six educational & training activities are planned. The first one in this series was the International Workshop on MAX Phases for Harsh Environments, which provided hands-on training sessions on powder metallurgy and electron microscopy techniques to PhD students. In order to maximise the open access and re-use of its results, IL TROVATORE participates to the H2020 Open Research Data Pilot without jeopardising the commercial exploitability of the achieved innovation, since a strict set of rules has been established in the Consortium Agreement to protect foreground intellectual property rights (IPRs). The openly accessible data sets, codes, etc., are preserved in the Zenodo repository. IL TROVATORE makes a conscious effort to make its research data findable, accessible, interoperable and reusable (FAIR) [9].

Also, in MULTIMETAL a training course and exchange program for young scientists, based on outcomes and experience gained within the area of weld fracture toughness testing, was organised.

At the end of the MATTER project, a total of 321 validated data sets for P91 and AISI 316 steels had been uploaded by 8 project partners to the JRC web enabled database MatDB. The uploaded data included: load- and strain-controlled low-cycle fatigue, small punch tests, uniaxial creep, uniaxial tensile, creep crack growth and fracture toughness data. Two international workshop and two summer school were organized. A special edition of Journal of Nuclear Material was issued to report the most relevant MATTER outcomes in related articles [13].

Within SCWR-FQT a broader communication route was established through informing the wider scientific community and involving students of Doctorate programs in the R&D work. Numerous papers have been presented at Conferences, topical Meetings and Workshops, such as:

International Symposium on Supercritical Water-Cooled Reactors; International Topical Meeting on Nuclear Thermal Hydraulics, Operation and Safety; International Topical Meeting on Nuclear Reactor Thermal Hydraulics; Nordic Nuclear Materials Forum for Gen-IV Reactors; 10th SCWR Information Exchange Meeting; International Conference on Nuclear Engineering; Joint HZDR & ANSYS Conference; The European Nuclear Conference; Siempelkamp Workshop "Kompetenzerhaltung in der Kerntechnik" ("Maintaining Competence in the Nuclear Technology"); European conference on Euratom research and training in reactor systems; European Research Reactor Conference; STAR Global Conference; and Pacific Basin Nuclear Conference; Annual Meeting on Nuclear Technology.

Results from the project were also published as articles in the following peer-reviewed Journals: Progress in Nuclear Energy; International Journal of Heat and Mass Transfer; Nuclear Engineering and Design; Safety of Nuclear Energy (Journal published by the Czech regulator – in Czech).

At Karlsruhe Institute of Technology (KIT), two PhD theses have been completed within the framework of this project.

8. CONCLUSIONS & RECOMMENDATIONS

All the four Projects addressed European studies to prevent structural material failures in reactors.

IL TROVATORE focuses on qualification in relevant environment of fuel clads able to resist the very high temperature subsequent to loss of coolant accident of PWR's.

MULTIMETAL addressed the brittle fracture of dissimilar metal welds through field experience, fracture toughness tests and simplified modelling. It is recommended to use the ASTM 1820 standard CT-specimens to assess fracture toughness of DMWs, where the location of the notch must be at the fusion line (± 0 mm) between ferritic heat-affected zone and the Ni-base alloy for Ni-based narrow-gap.

MATTER Project addressed all the typical failure causes of ferritic/martensitic steel in liquid metal cooled fast reactors. Besides the high temperature and the brittle rupture, also corrosion attack and many others were considered. The unfavourable outcomes of grade 91 steel, triggered the need to develop so-called "mitigation measures" to limit the degradation of materials from heavy liquid metals. Subsequent EU projects, such as the H2020 GEMMA and H2020 IL TROVATORE (side-activity), are studying promising "mitigation measures" that might be applicable to heavy liquid metal environments.

Corrosion and high temperature are also considered as the most relevant failure causes for the Supercritical Water Reactor. In SCWR-FQP the best performing material for fuel clads and core structures was selected. The study on consequences of a pressure tube rupture performed in the electrically heated test section allowed to prepare the recommendations to be included in the safety analysis for the "Fuel Qualification Test with Supercritical Water".

REFERENCES

[1] E. LAHODA, L. HALLSTADIUS, F. BOYLAN, S. RAY, "What should be the objective of accident tolerant fuel?," Paper #10231, American Nuclear Society 2014 Annual Meeting, Nuclear Fuels and Structural Materials, Reno, NV, USA, June 17 (2014)

[2] A. KOHYAMA, Y. KOHNO, H. KISHIMOTO, J.S. PARK, H.C. JUNG, "Industrialization of advanced SiC/SiC composites and SiC based composites; Intensive activities at Muroran Institute of Technology under OASIS," IOP Conference Series: Materials Science and Engineering 18 202002 (2011)

[3] J.C. BRACHET, C. LORRETTE, A. MICHAUX, C. SAUDER, I. IDARRAGA-TRUJILLO, M. LE SAUX, M. LE FLEM, F. SCHUSTER, A. BILLARD, E. MONSIFROT, E. TORRES, F. REBILLAT, J. BISCHOFF, A. AMBARD, "CEA studies on advanced nuclear fuel claddings for enhanced Accident Tolerant LWRs Fuel (LOCA and beyond LOCA conditions)," Proc. Fontevraud 8: Contribution of Materials Investigations and Operating Experience to LWRs'Safety, Performance and Reliability, Avignon, France, 14-18 September 2014, INIS Vol. 46, Report No. INIS-FR—15-0424, Ref. No. 46081720, IAEA-INIS (2015)

[4] M.W. BARSOUM, "MAX Phases – Properties of Machinable Ternary Carbides and Nitrides," Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany (2013)

[5] F. GARCÍA FERRÉ, A. MAIROV, L. CESERACCIU, Y. SERRUYS, P. TROCELLIER, C. BAUMIER, O. KAÏTASOV, R. BRESCIA, D. CASTALDI, P. VENA, M.G. BERGHI, L. BECK, K. SHRIDHARAN, F. DI FONZO, "Radiation endurance in Al2O3 nanoceramics," Scientific Reports 6 33478 (2016)

[6] V. ENGELKO, B. YATSENKO, G. MÜLLER, H. BLUHM, "Pulsed electron beam facility (GESA) for surface treatment of materials," Vacuum 62 211 (2001)

[7] K.A. TERRANI, S.J. ZINKLE, L.L. SNEAD, "Advanced oxidation-resistant iron-based alloys for LWR fuel cladding," Journal of Nuclear Materials 448 420 (2014)

[8] K. Lambrinou, M. Verwerft, J. Vleugels, A. Weisenburger, C. Lorrette, Y. de Carlan, F. Di Fonzo, M.W. Barsoum, A. Kohyama, "Innovative accident-tolerant fuel cladding materials: the H2020 IL TROVATORE perspective," Proc. of the 2017 Water Reactor Fuel Performance Meeting (WRFPM 2017), Jeju Island, Korea, 10-14 September 2017, pp. 1-10, paper F-250-PD1

[9] M.D. Wilkinson et al., "The FAIR guiding principles for scientific data management and stewardship, " Scientific Data 3:160018 (2016)

[10] T. Schulenberg, J. Starflinger, P. Marsault, D. Bittermann, C. Maráczy, E. Laurien, J.A. Lycklama à Nijeholt, H. Anglart, M. Andreani, M. Ruzickova, A. Toivonen, "European Supercritical Water-Cooled Reactor," Nuclear Engineering Design 241(9) (2011) 3505–3513

[11] T. Schulenberg, J. Starflinger, "High Performance Light Water Reactor, Design and Analyses," KIT Scientific Publishing, Karlsruhe, Germany, 978-3-86644-817-9 (2012)

[12] M. Ruzickova, A. Vojacek, T. Schulenberg, D. Visser, R. Novotny, A. Kiss, C. Maráczy, A. Toivonen, "European Project "Supercritical Water Reactor–Fuel Qualification Test": Overview, Results, Lessons Learned, and Future Outlook," Journal of Nuclear Engineering and Radiation Science 2:011002 (2016)

[13] J. Nuclear Materials 472 2016

STEPHANE VALANCE

INNOVATIVE AND SAFE SUPPLY OF FUELS FOR REACTORS

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Abstract. Within the Euratom research and training program 2014-2018, three projects aiming at securing the fuel supply for European power and research reactors have been funded. Those three projects address the potential weaknesses –supplier diversity, provision of enriched fissile material— associated with the furbishing of nuclear fuels. First, the ESSANUF project, now terminated, resulted in the design and licensing of a fuel element for VVER-440 nuclear power plant manufactured by Westinghouse. The HERACLES-CP project aimed at preparing the conversion of high performance research reactor to low enriched uranium fuels by exploring fuels based on uranium-molybdenium. Finally, the LEU-FOREvER pursues the work initiated in HERACLES-CP, completing it by an exploration of the high-density silicide fuels, and including the diversification of fuel supplier for soviet designed European medium power research reactor. This paper describes the projects goals, structure and their achievements.

1. Introduction

At the core of reactor operation, nuclear fuel is a consumable which necessitates a secure supply chain. In EU, that entails a diversity of suppliers with licensed fuel design and the availability of enriched uranium. Particularly, reactors with an original soviet design present a weakness in their supply chain as they depend on a single manufacturer. In Europe, this is the case for VVER 440 power plants and medium power research reactors. High Power Research Reactors (HPRRs), with more standardized fuel designs, are, on their side, vulnerable to the supply of high enriched uranium necessary to ensure their performance.

Diversification of fuel element supply requires the adaptation of non-historic fuel manufacturers to the specificities of the reactor. The first step of this diversification is thus reverse engineering to tackle all the technical functions of the element for any type of operating conditions. Then, a design has to be set-up which fulfils the identified functions and is adapted to the producing means of the new manufacturer. Finally, the new fuel element should be licensed within one or several countries. This last step might involve an irradiation depending on the reactor specific needs.

With respect to enriched uranium supply, global efforts are made to minimize the use of highly enriched uranium in research reactors. In the EU, this conversion from highly to lower enriched uranium has already begun and is currently ongoing towards the qualification phase. This concerns both medium and high power research reactors. To reach this goal, the adopted path is the development of fuels core which presents a higher fissile uranium content without overcoming the 19.75% non-proliferant enrichment limit. Three ways have been identified to reach this goal: high density dispersed silicide fuels, dispersed uranium-molybdenum fuels and monolithic uranium-molybdenum fuels.

In this paper, a presentation of each of the projects is done. Then the achievements for innovative and safe supply of the fuel permitted thanks to the EU funding are presented. Finally, a global picture of the challenges solved and remaining questions is drawn.

2. H2020 projects enabling innovative and safe supply of fuels

2.1. ESSANUF

Several countries in Eastern Europe rely heavily on electricity generated from Russian-design VVER-440 pressurized water reactors. Currently, the Russian company TVEL is the sole supplier of nuclear fuel to these facilities. The EU-funded ESSANUF project was launched with the goal to design a state-of-the art fuel for VVER-440 reactors in full compliance with nuclear safety standards.

ESSANUF (European Supply of Safe NUclear Fuel) (ESSANUF, s.d.) is the Euratom funded project from 2016 to 2017 with the overall objective to create greater security of fuel supply to countries operating VVER-440 nuclear power plants in Czech Republic, Finland, Hungary, Slovakia and Ukraine. The project enables the re-entry of Westinghouse as nuclear fuel supplier to VVER-440 offering diversification and greater security of fuel supply.

The project is led by Westinghouse Sweden and includes eight consortium partners: VUJE, ÚJV Řež (NRI), Lappeenranta University of Technology (LUT), National Nuclear Laboratory (NNL), NucleoCon, National Science Center Kharkov Institute of Physics and Technology (NSC KIPT), Institute for Transuranium Elements of the Joint Research Centre of the European Commission (JRC-ITU) and Enusa Industrias Avanzadas (ENUSA). The consortium covers by their geographical distribution the targeted countries operating VVER-440 nuclear power plants.

Within the project, an improved VVER-440 fuel design has been developed and the manufacturing capabilities assessed (Höglund & Kristensson, 2017). Furthermore, the project contributed to the generation of a generic licensing methodology for VVER-440 fuel and the set-up of tools enabling to perform the required analyses and investigations for licensing (Gyori, et al., 2017; Strömgren & Le Moigne, 2017).

The ESSANUF team selected the most suitable materials for all the fuel assembly components and identified necessary modifications to the earlier supplied VVER-440 assembly design to fulfil utility needs and regulatory requirements of each country. A development programme was established to test and verify the modified design and its manufacturability was assessed to identify any changes needed to the manufacturing processes and equipment.

Thereafter, the project partners developed and validated methods and methodologies necessary to qualify operation of the modified fuel design in the participating countries. In particular, the models to simulate the fuel rod thermo-mechanical behaviour, corrosion and hydrogen uptake were improved enabling significant advances in the design of the fuel rods.

In addition to the VVER-440 nuclear fuel design, the ESSANUF project partners established the methods and methodologies required to qualify the fuel design for operation in Finland, Hungary, Slovakia, Czech Republic and Ukraine.

Also, significant progress was made to verify and validate the methods and methodologies to simulate the neutronic and thermal hydraulic behaviour of the fuel design. Researchers developed a nuclear criticality safety methodology for the EU and Ukraine based on International Atomic Energy Agency guidelines and regulations, taking into account national requirements.

2.2. HERACLES-CP

HERACLES-CP (HERACLES-CP, s.d.), a Euratom project, funded from 2015 to 2019, is a central pillar of the overall fuel development program of the HERACLES, a pan-European group which gathers the high power research reactor operators ILL, SCK-CEN, CEA and TUM as well as the fuel manufacturer Framatome-CERCA. "CP" stands for "Comprehension Phase".

The general objective of this project is the provision of the technical and scientific foundations for the successful qualification of UMo, a new research reactor fuel based on uranium-molybdenum (UMo) alloys, which is developed in the framework of the joint international efforts to reduce the risk of proliferation by minimising the use of highly enriched uranium. UMo based nuclear fuels, monolithic and dispersed, are promising candidates to carry out the conversion of HPRRs (High Performance Research Reactors). In such a fuel system, the addition of molybdenum to uranium stabilises the body-centred cubic crystal structure of the high-temperature γ-phase of uranium under irradiation. Hence the transition to the low-temperature orthorhombic α-phase with its strongly anisotropic thermal expansion is prevented with an addition of 7 to 10 wt.% Mo. This stoichiometry has been proven to be the best compromise between achievable uranium density and stabilisation of the phase behaviour.

Despite being the most promising candidate, significant obstacles were encountered on the way to qualification of UMo fuels in the challenging environment of the HPRRs, particularly with respect to density of dispersion fuel, power and burn-up. The very first in-pile tests (IRIS2, FUTURE, IRIS3 0.3%Si) of nuclear fuels with a UMo/Al composition showed an unacceptable swelling under irradiation, in some cases even leading to plate breakaway, even though these tests were only performed with limited surface power ($\leq$350 W.cm^{-2}) (Dubois, et al., 2007) (Huet, et al., 2005) (Leenaers, et al., 2004). The failure has been traced back to a UMo/Al Inter-Diffusion Layer (IDL) growing during in-pile irradiation at UMo-Al interfaces and to its unsatisfactory properties under irradiation (Burkes, Huber, & Casella, 2016).

The developments performed worldwide over the last fifteen years have successfully limited the IDL growth (Van den Berghe & Lemoine, 2014). The beneficial effect of Si additions to the dispersion UMo fuel, and more recently the coating of UMo particles with a diffusion barrier can be observed in the gradual, controlled swelling up to higher burnups. A dispersion of UMo particles coated by Physical Vapour Deposition (PVD) with a 1 μm thick ZrN layer, dispersed in an Al matrix, is currently the baseline solution for the conversion of most European HPRRs.

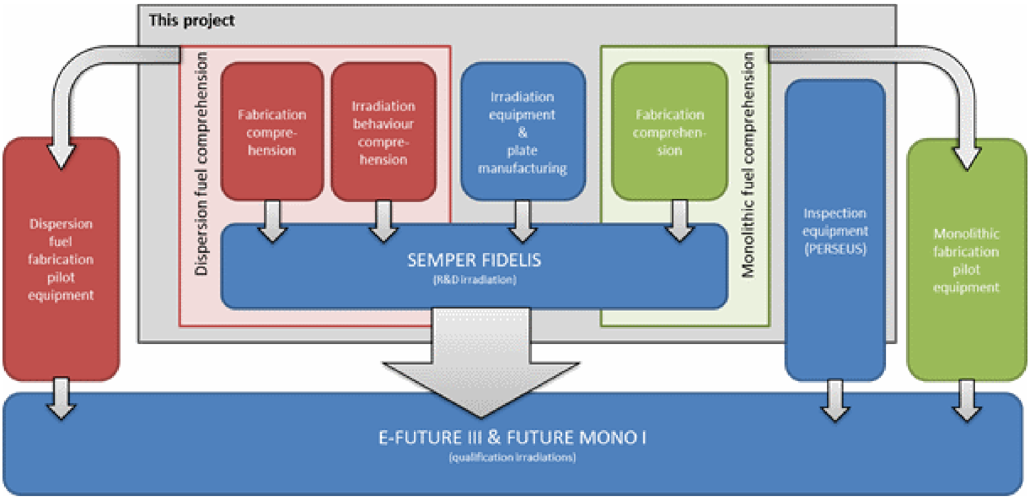

FIG. 1. Flow chart of the HERACLES-CP project.

The main objectives of the program are (see FIG. ***1***):

- For dispersed fuel:
  - To fill the knowledge gaps identified by performing the necessary experiments and measurements,
  - To conclude on the most promising fuel design based on the results of these,
  - To develop the necessary production techniques and
  - To prepare a SEMPER FIDELIS irradiation test to verify the theory and to fill the gaps that require new irradiation data.
- For monolithic fuel:
  - To develop the technology and knowledge necessary for fabrication and
  - To prepare test samples for the EMPIrE irradiation test.
- For both:
  - To develop the technology necessary for the irradiation test as well as the tools for analysis,
  - To launch and conduct the irradiation test and finally
  - To perform the Post-Irradiation Examinations (PIE) of SEMPER FIDELIS.

Through the first results of this project, it is already asserted that the UMo fuel is a thinkable way for the replacement of high enriched uranium in HPRRs.

2.3. LEU-FOREvER

Following the still on-going HERACLES-CP Euratom funded project, a second Euratom funded project, LEU-FOREvER (LEU-FOREvER, s.d.) (Valance, et al., 2018), has been launched for the period 2017-2021 with the following identified goals to secure nuclear fuel supply for European research reactors:

- the ongoing conversion of High Performance Research Reactors (HPRRs) from high to low enriched nuclear fuels (LEU), and
- the difficult market situation for obtaining fuel elements for Medium Power Research Reactors (MPRRs) with an original Soviet design.

A multi-disciplinary consortium - composed of fuel and core designers, nuclear research centers operating research reactors and fuel manufacturers - has been set up to tackle both issues in the framework of the H2020 European Project LEU-FOREvER (2017-2021). Key issues and operative solutions for this topic are underlined in the schematic drawing of FIG. ***2***. This project is carried-out together by CEA, CVR, Framatome, ILL, NCBJ, SCK•CEN, TechnicAtome and TUM. These actors are supplemented by an End-User Group (EUG), an advisory body consisting of representatives from potential end-users of the Project results.

As presented before, the HERACLES group has been developing UMo based solutions, both dispersed and monolithic. Within LEU-FOREvER, optimisation of the manufacturing process up to the construction of pilot equipment, modelling of the in-pile behaviour and post-irradiation examinations of European fuels irradiated in the EMPIrE test at the Advanced Test Reactor (ATR) of the Idaho National Lab (INL) are addressed.

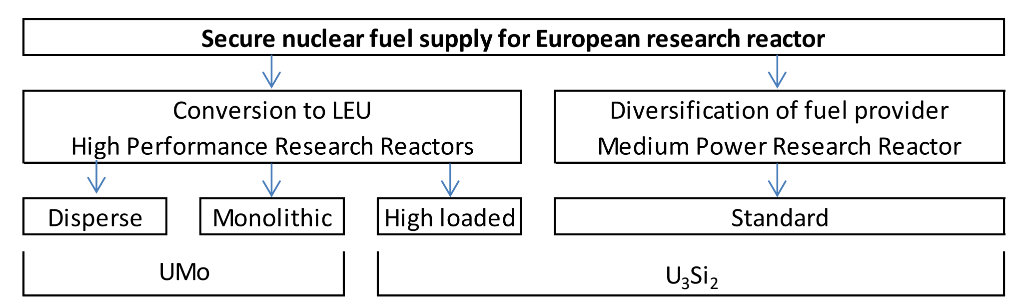

FIG. 2. Key issues and related nuclear fuel development to secure fuel supply for European research reactors.

For the dispersed uranium-molybdenum fuel case, the key tasks of the comprehension phase are undoubtedly the tests carried-out in the SEMPER FIDELIS irradiation facility (BR2, Mol – Belgium) and in its sister experiment EMPIrE (ATR, Idaho – USA). These tests, carried out in the framework of the HERACLES group, are aimed at filling the data gaps in the understanding of UMo fuel irradiation behavior and assessing a number of fabrication options for the dispersion UMo fuel. Identified additional knowledge and comprehension gaps will now be addressed in the LEU-FOREvER project.

Regarding the monolithic UMo fuel type, the developments and assessments performed in the HERACLES-CP project have made it possible to successfully demonstrate that the fabrication of monolithic UMo plates with the appropriate quality is entirely possible with the processes developed in Europe.

As backup strategy to UMo based fuels, high loaded U_3Si_2 is considered as a viable solution for the conversion of HPRRs. Within LEU-FOREvER, design and manufacturing of such fuel plates will be optimised and tested in an irradiation experiment under representative high power and burn-up conditions.

Lowering enrichment at constant ^{235}U content implies a significant raise of the uranium surface density of the plate. A correlate of this uranium density increase is an increased parasitic absorption due to the higher amount of ^{238}U in the core. This absorption needs to be overcome in order to maintain cycle length and neutron flux. Within a given dispersion fuel system, two options are available to increase the fissile phase content:

- increase the volume fraction of fissile compound in the meat for a dispersion fuel;
- modify the geometry of the fuel assembly and/or fuel plates to accommodate more fuel meat volume, e.g. using thicker plates, larger plates or more plates per assembly.

In an optimized geometry, it would then be possible to increase the quantity of fissile material in the fuel assembly while maintaining the volume fraction of fuel at an acceptable level. One of these options or a combination of both is necessary to create a viable fallback option.

Within the LEU-FOREvER project, manufacturing developments and an irradiation for this high loaded U_3Si_2 are planned. The manufacturing developments will permit to ascertain the manufacturability of such geometry modified fuels, and to set the boundary for the use of high loaded U_3Si_2 fuels. The High Performance research Reactors Optimized Silicide Irradiation Test (HiPROSIT) experiment will then evaluate the behaviour under irradiation of such modified fuels.

MPRRs (Medium Power Research Reactors) with an original Soviet design currently have only one fuel provider. An alternative to the fuel currently employed will be developed in LEU-FOREvER. Due to some differences between the manufacturing design, the detailed shape and characteristics of the new fuel assemblies, compliant with all the interfaces of the fuel assembly (geometry, performances, safety), will be different. The design of such a fuel therefore implies an in-depth analysis of the reactor and core from neutronics, thermo-hydraulics and overall design point of view. In addition to these technical aspects, special care shall be taken to develop a solution which is above all economically efficient. Thanks to the choice of a proven technology for the fuel element, the potential complementary qualification will only be at fuel assembly level.

For the design of a new fuel assembly, the LVR-15 research reactor will be the most detailed case study. Nevertheless, a first assessment of the BRR core, with a very different current fuel assembly will also be carrying out.

Currently, the reactor uses Russian IRT-4M sandwich-type fuel assemblies mainly composed of concentric square tubes (Matos, 2003), manufactured by NZCHK in Novosibirsk. The meat is composed of a dispersion of UO_2 and aluminium powders. The assemblies have the form of six or eight concentric square tubes.

The development of a fuel alternative for MPRRs by the LEU-FOREvER project will bring several enhancements for the operators of these reactors:

- Much larger ease of use, on a routine basis, of European origin fuel in reactors of Soviet origin ;
- Easer transition from historical fuel to new fuel, with respect to both technical and regulatory aspects ;
- Potential improvement of life cycle cost coupled with extended operating cycles.

As most HPRRs will also have to operate with a mixed core configuration during conversion and both HPRRs and MPRR are considering or even already using U_3Si_2/Al fuel plates, strong synergies are found between the two subprojects.

A fuel element design usable for MPRR has been proposed and is now being manufactured for testing. For HPRR a first batch of high density silicide fuel plates has been manufactured with depleted uranium. The UMo fuel solution is preparing the arrival of samples from the EMPIrE and SEMPER-FIDELIS test irradiations.*

3. Achievements

ESSANUF generated new knowledge, identifying improvements in the fields of mechanical design, thermo-mechanical fuel rod design, and safety analysis for VVER fuel. This helped to fulfil Europe's need for advanced and reliable nuclear fuel, thereby safeguarding the EU's energy supply by speeding up the diversification of the fuel supply for VVER-440 reactors in the EU and Ukraine.

Furthermore, the project enhanced the communication and relationship between the utilities and regulators of the different countries by encouraging open discussions and the exchange of information between the different parties. The initiative was an important step toward the diversification of the nuclear fuel market in the countries involved, providing long-term benefits to the utilities, industries and citizens that rely on secure electricity supply.

During the project, several workshop were organised to raise interest and share knowledge among the participants and with other bodies, such as potential users or regulations authorities. A The project was presented during a meeting of the Expert Group on Multi-Physics Experimental Data Benchmark and Validation of the OECD/NEA. Last but not least, the results were presented during the Finnish Fuel Days in August 2017.

The governing objective of HERACLES-CP is to lay the technical and scientific foundations for the successful qualification of UMo fuel. In this regard, the following progress has already been made.

Within HERACLES-CP, the SEMPER-FIDELIS irradiation experiment has been defined and carried out (Leenaers, Van Eyken, & Van den Berghe, 2019). The first non-destructive examinations show that the results are promising at least for one plate. Together with EMPIrE, the experiment will close most of the remaining knowledge gaps. Ion experiments showed no accelerated growth of the interdiffusion layer between UMo and Al in the first days of an irradiation.

For the design of the SEMPER FIDELIS irradiation matrix, dozens of experts from the EU and the US have (re-)measured, collected and evaluated data from more than one dozen prior irradiation experiments to ensure that SEMPER FIDELIS will deliver the maximum relevant information for the further development of UMo.

The technique of UMo powder atomization is now understood to an extent that enables the consortium to build the next stage of manufacturing equipment on the pilot level. The construction of the pilot induction furnace has already begun.

Monolithic UMo foils can now be coated with PVD and turned into plates with a very high yield. The technology for this is fully available in Europe.

The HERACLES-CP has been presented at its beginning during an event held at the Bavarian representation in Brussels (HERACLES, https://www.heracles-consortium.eu/news_item.php?id=7).The results and findings have been share and discussed outside the group both in open literature (Breitkreuz, et al., 2016; Stepnik, et al., 2016; Zaz, Calzavara, Le Clézio, & Despaux, 2015; Zaz, et al., 2015) and in meetings with US counter sides which are also involved in an intensive conversion program.

In the LEU-FOREvER project, both the actions targeting European HPRR and MPRR have been on track with the laid out plans.

For high density silicide fuels, the test matrix, finite element computations, and depleted uranium fabrications have been done. On the uranium-molybdenum fuels side, the research reactor fuel simulation finite element code MAIA is being updated with latest open literature models for the simulation of the SEMPER-FIDELIS experiment. With respect to monolithic uranium-molybdenum fuels, test for the realisation of graded geometries, on surrogate materials have been carried, a fresh sample of monolithic fuel has been received at CEA Cadarache for microscopic examinations, and the retrieval of irradiated samples from the EMPIrE test irradiation has been secured.

The samples issued from the EMPIrE irradiation will be examined in CEA and SCK.CEN. The HiPROSIT irradiation will give key findings on the sustainability of the high-density silicide solution, particularly précising the manufacture possibilities and setting the basis for the effective qualification of fuel for reactors.

To carry the design of a replacement element for the LVR-15 reactor, a multidisciplinary team involving representatives of all involved entities:

- Reactor operators, i.e. CVR ;
- Fuel designers, to optimise both fuel “meat” and fuel “assemblies” i.e. TechnicAtome and Framatome ;
- Research reactor designers with all the relevant core design experience and calculation codes i.e. TechnicAtome.

A preliminary dimensioning has already been developed for a LVR-15 fuel alternative based on assemblies with a European design, i.e. with parallel flat plates and U_3Si_2/Al meat. Significant manufacturing and operating experience already exists for this kind of fuel assembly in Europe, as the OSIRIS material testing reactor has been fuelled with assemblies of the same geometry and almost the same fuel composition.

Indeed, preliminary drawings have been made for both standard and control fuel elements, making it possible to verify the feasibility of moving from one type to the other. Even if it is still possible to optimize the 235U density, moderator volume, plate shapes, etc. Furthermore, it will be verified that the envisaged U_3Si_2/Al fuel plate usage in LVR-15 is covered by NUREG 1313 (United States Nuclear Regulatory Commission, July 1988) regarding the fuel operational parameters. This will make the qualification phase considerably shorter and cheaper.

By implementing an innovative methodology for fuel assembly design such as the design-to-cost methodology and by involving all relevant parties from designer to manufacturer and to reactor operator, LEU-FOREvER aims to design and produce an economically attractive alternative fuel assembly based on proven European technology, produced by a European manufacturer.

The design of a new element suitable for every European medium power research reactor has given rise to three workshops with the objective to share knowledge on operation and functions of original elements. The organization of a summer school on the research reactor fuels issues is on-going, with a summer school foreseen to take place in October 2020 in Belgium. Several communications on technical achievement have already been done (Duperray & Roux, 2019; Boyard, 2019; Koubbi, et al., 2019; Stepnik, B.; Allenou, J.; Rontard, C.; Schwartz, C.; Steyer, C.; Baumeister, B.; Petry, W.;Van den Berghe, S.; Leenaers, A.;Valance, S.; Palancher, H.; Hervieu, E.; Calzavara, Y.; Guyon, H.).

In the coming years, the designed fuel element will be tested for the thermo-hydraulic characteristics and for qualification in the LVR-15 reactor.

4. Conclusions

Although different in their targeted scope, all the three Euratom funded project presented in this paper have the goal to secure the supply chain of nuclear fuels, being for nuclear power plant or research reactors. Through their achievement (ESSANUF) or their current findings (HERACLES-CP, LEU-FOREvER), they pave the way for a greater security of supply for nuclear fuel in Europe. The output of these projects will benefit the entire society by ensuring the production of electricity, medical isotopes and cutting edge science.

The ESSANUF project leaded to a renewed, up-to-date replacement design for VVER-440 fuel element. Is also fostered collaboration between user and regulatory authorities in the countries using this type of reactor.

The HERACLES-CP project has been the key in understanding innovative fuel systems for high performance research reactors, therefore permitting a selection of the most promising solution to alleviate technological locks.

Finally, the on-going LEU-FOREvER project, is both pursuing the goal of converting European high performance reactors and securing the fuel element supply of European medium performance research reactors. First results are promising and should, in a coming future, result in the stronger supply chain of research reactor fuels.

At the end of these three project, EU will have effectively secured the supply chain of fuel elements, resulting in untroubled low carbon emissions for electricity supply, secured supply of medical-radio-isotopes and availability of high performance research instruments.

The ESSANUF project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No. 671546.

The HERACLES-CP project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No. 661935.

The LEU-FOREvER project has received funding from the Euratom research and training programme 2016-2017 under grant agreement No. 754378.

References

Boyard, M. (2019). International Meeting on Research Reactor Fuel Management (RRFM): Swemieh, Jordan.

Breitkreuz, H., Hingerl, J., Heldmann, A., Steyer, C., Zweifel, T., Jungwirth, R., . . . Petry, W. (2016). International Meeting on Reduced Enrichment for Research and Test Reactors (RERTR): Antwerp, Belgium.

Burkes, D., Huber, T., & Casella, A. (2016). Journal of Nuclear Materials: 473, 309-319.

Dubois, S., Noirot, J., Gatt, J., Ripert, M., Lemoine, P., & Boulcourt, P. (2007). Proceedings of the 11th International Meeting on Research ReactorFuel Management (RRFM): Lyon, France.

Duperray, R., & Roux, L. (2019). International Meeting on Research Reactor Fuel Management (RRFM): Swemieh, Jordan.

ESSANUF. (s.d.). *ESSANUF homepage*. Récupéré sur http://www.essanuf.eu

Gyori, C., Blair, P., Jonson, M., Robertson, G., van Uffelen, P., Schubert, A., . . . Meca, R. (2017). International Conference Nuclear Energy for New Europe (NENE): Bled, Slovenia.

Györi, C., Blair, P., Jonson, M., Robertson, G., van Uffelen, P., Schubert, A., . . . Meca, R. (2017). Development, Validation and Application of the TRANSURANUS Code for Westinghouse Fuel Designs. International Conference Nuclear Energy for New Europe: Bled, Slovenia.

HERACLES. (https://www.heracles-consortium.eu/news_item.php?id=7). HERACLES-CP kick-off.

HERACLES-CP. (s.d.). *HERACLES-CP homepage*. Récupéré sur https://heracles-consortium.eu/cp.php

Höglund, J., & Kristensson, S. (2017). ESSANUF - European Supply of SAfe NUclear Fuel.

Huet, F., Noirot, J., Marelle, V., Dubois, S., Boulcourt, P., Sacristan, P., . . . Lemoine, P. (2005). 9th International Meeting on Research Reactor Fuel Management (RRFM): Budapest, Hungary.

Koubbi, J., Boyard, M., Huet, F., Romanello, V., Dambrosio, A., & Hrehor, M. (2019). International Meeting on Research Reactor Fuel Management (RRFM): Swemieh, Jordan.

Leenaers, A., Van den Berghe, S., Koonen, E., Jarousse, C., Huet, F., Trotabas, M., . . . Verwerft, M. (2004). Journal of Nuclear Materials: 335, 39-47.

Leenaers, A., Van Eyken, J., & Van den Berghe, S. (2019). International Meeting on Research Reactor Fuel Management (RRFM): Swemieh, Jordan.

LEU-FOREvER. (s.d.). *LEU-FOREvER homepage*. Récupéré sur https://heracles-consortium.eu/forever.php

Matos, J. (2003). International Meeting on Reduced Enrichment for Research and Test Reactors (RERTR): Chicago, USA.

Stepnik, B., Grasse, M., Jarousse, C., Breitkreutz, H., Steyer, C., & Petry, W. (2016). International Meeting on Research Reactor Fuel Management (RRFM): Berlin, Germany.

Stepnik, B.; Allenou, J.; Rontard, C.; Schwartz, C.; Steyer, C.; Baumeister, B.; Petry, W.;Van den Berghe, S.; Leenaers, A.;Valance, S.; Palancher, H.; Hervieu, E.; Calzavara, Y.; Guyon, H. (s.d.). International Meeting on Research Reactor Fuel Management (RRFM): Swemieh, Jordan.

Strömgren, T., & Le Moigne, Y. (2017). Prediction of Critical Heat Flux in Fuel Bundles using CFD.

Strömgren, T., Le Moigne, Y., Mauritzson, D., & Perzon, S. (2017). CFD MODELING OF CRITICAL HEAT FLUX AND TEMPERATURE MIXING IN A FUEL BUNDLE.

United States Nuclear Regulatory Commission. (July 1988). NUREG-1313.

Valance, S., Palancher, H., Huet, F., Stepnik, B., Breitkreuz, H., Van den Berghe, S., . . . Gajewski, J. (2018). International Meeting on Research Reactor Fuel Management (RRFM): München, Germany.

Van den Berghe, S., & Lemoine, P. (2014). Nuclear Engineering and Technology: 46, 125-146.

Zaz, G., Calzavara, Y., Le Clézio, E., & Despaux, G. (2015). Adaptation of a high-frequency ultrasonic transducer to the measurement of water tempreature in a nuclear reactor. 70:195-198: Physics Procedia.

Zaz, G., Dekkious, A., Meignen, P., Calzavara, Y., Le Clézio, E., & Despaux, G. (2015). High frequency transducer dedicated to the high-resolution in-situ measurement of the distance between two nuclear fuel plates. 70:191-194: Physics Procedia.

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SAFETY ASSESSMENTS AND SEVERE ACCIDENTS, IMPACT OF EXTERNAL EVENTS ON NUCLEAR POWER PLANTS AND ON MITIGATION STRATEGIES

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Abstract. The Fukushima-Daiichi accidents in 2011 underlined the importance of severe accident management (SAM), including external events, in nuclear power plants (NPP) and the need of implementing efficient mitigation strategies. For these reasons, the Euratom work programmes for 2012 and 2013 placed a total emphasis on nuclear safety, in particular on the management of a possible severe accident at the European level.

Relying upon the outcomes of the successful Euratom SARNET and SARNET2 projects, new projects were launched addressing the highest priority issues, aimed at reducing the uncertainties still affecting the main phenomena. Among them, PASSAM and IVMR project led by IRSN, ALISA and SAFEST projects led by KIT, CESAM led by GRS and SC02-HeRO lead by the University of Duisburg-Essen. The aim of the present paper is give an overview on the main outcomes of these projects.

1. Introduction

Despite accident prevention measures, including design modification and operating procedures, adopted in present nuclear power plants (NPP), some accidents, in circumstances of very low probability, may develop into severe accidents with core melting and plant damage and lead to dispersal of radioactive materials into the environment, thus constituting a danger for the public health and for the environment. This risk was unfortunately evidenced by the Fukushima Dai-ichi accidents in Japan in March 2011, which underlined the importance of severe accident management and the need to implement and to improve the corresponding mitigation strategies and systems.

All-important severe accident phenomena cannot be addressed within the framework of a national research program, therefore optimized use of resources and the collaboration at European and international level is very important and sometimes even mandatory. Integrating European severe accident research facilities into a pan-European laboratory for severe accident and providing other European partners with resources for better understanding the possible accident scenarios and phenomena is necessary in order to improve safety of existing and, in the long-term, future reactors.

To achieve this ambitious objective, several projects were launched under the auspices of EURATOM with the aim at:

- filling the gap of knowledge and reduce the uncertainties on phenomena participating in severe accidents such as the core degradation, the core melt and the hydrogen deflagration as addressed in the framework of ALISA and SAFEST projects,
- developing new mitigation systems and strategies to reduce the source term release in the framework of PASSAM project and a system for heat removal in the framework of the sCO2-HeRo project,
- improving the mitigation strategies in support to the in-vessel retention as done in the framework of the IVMR project,
- improving the ASTEC code suitability to address severe accident phenomena and severe accident management for a large number of reactor design including PWR, BWR, VVER and CANDU.

The aim of the present paper is to give an overview of the main outcomes of the PASSAM, CESAM, SAFEST, ALISA, IVMR and sCO2-HeRo projects. Their main achievements regarding the safety improvement and their complementarity will be highlighted.

2. PASSAM project

The **PASSAM** [0][0] **(Passive and Active Systems on Severe Accident source term Mitigation)** project was launched within the 7th framework programme of the European Commission. Coordinated by IRSN, this four year project (2013 – 2016) involved nine partners from six countries: IRSN, EDF and university of Lorraine (France); CIEMAT and CSIC (Spain); PSI (Switzerland); RSE (Italy); VTT (Finland) and AREVA GmbH (Germany).

The PASSAM project was aimed at exploring potential enhancements of existing source term mitigation devices and checking the capacity of innovative systems to achieve even larger source term attenuation (acoustic agglomeration systems; high pressure spray agglomeration systems; electric filtration systems; improved zeolite filtration systems; combined filtration systems). Mainly of an R&D experimental nature, the program addressed phenomena able to reduce the radioactive releases to the environment in case of a severe accident.

Therefore, the project major outcome has been an extensive and sound database which can help the utilities and regulators to assess the performance of the existing source term mitigation systems, evaluating potential improvements of these systems and developing severe accident management (SAM) measures. In addition, simple models and/or correlations have been proposed for these investigated systems. Their implementation in severe accident analysis codes would result in an enhancement of their capability to model SAM measures and to develop improved guidelines.

Pool scrubbing has been addressed as a first priority topic. It has been demonstrated that the in-pool gas hydrodynamics under anticipated conditions is quite different from the model nowadays encapsulated in severe accident analysis codes, particularly at high velocities (i.e., jet injection regime and churnturbulent flow). Additionally, it has been proved that maintaining a high pH in the scrubber solution in the long run is absolutely necessary for preventing a late iodine release. Sand bed filters (plus metallic pre-filters) showed-out inefficient for gaseous molecular and/or organic iodides; moreover, it was demonstrated that caesium iodide aerosols trapped in the sand filter during a severe accident are unstable and, hence, a potential delayed source term is allowed. On the contrary, CsI particles trapped in the metallic pre-filter do not lead to any significant delayed release. Both acoustic agglomeration and high pressure spray systems were studied as innovative processes, mainly in the aim of leading to bigger particles upstream of filtered containment venting systems (FCVS), and so enhancing the filtration efficiency. An increase of the particle size by ultrasonic fields was experimentally observed and, more importantly, hard-to-filter particles (i.e., 0.1-0.3 µm) were drastically reduced in the particle size distribution. The increase in particle size by high pressure sprays could not be measured, but the system showed a better efficiency whether the airborne particle concentration was lower than for low pressure sprays. Experimental studies for trapping gaseous molecular and organic iodine using wet electrostatic precipitators (WESP) confirmed the importance of optimizing the WESP design and the need of some pre-WESP steps (e.g. oxidation of I2 or CH3I into iodine oxide particles) for a good trapping efficiency. Extensive testing of zeolites as gaseous iodine trapper was performed and showed very good trapping efficiencies, particularly the so-called silver Faujasite-Y zeolite. Finally, the combination of a wet scrubber followed by a zeolite filtration stage was extensively studied in representative severe accident conditions and showed the ability of this configuration to reach a significant retention for gaseous organic iodides. Small and mid-size facilities have been used for these experimental campaigns: Fig. 1 shows a few of them (mostly addressing pool scrubbing research).

FIG. 1. Some selected PASSAM experimental facilities.

The PASSAM project, heavily relying on experiments, was aimed at providing new data on the ability and reliability of a number of systems related to FCVS: pool scrubbing systems, sand bed filters plus metallic prefilters, acoustic agglomerators [0], high pressure sprays, electrostatic precipitators, improved zeolites and combination of wet and dry systems. Nonetheless, the scope of some of the PASSAM research topics - as fission products and aerosol retention in water ponds - goes beyond FCVS and might be applied for accident situation other than containment venting, e.g. for fission product scrubbing in the wetwell of a BWR or for Steam Generator Tube Rupture (SGTR) accident with submerged secondary side.

Besides an extension of the existing experimental database on existing and innovative filtration systems, the focus was put on trying to get a deeper understanding of the phenomena underlying their performance and to develop models/correlations that allow modelling of the systems in accident analysis codes, like ASTEC.

3. ALISA Project

The **ALISA project** [0] **(Access to Large Infrastructure for Severe Accidents)** is a European FP7 Project (Grant Agreement No: 295421). It is a unique project between European and Chinese research institutions in the area of severe accident research in existing and advanced Light Water Reactors. The project provides the European and Chinese organizations with a shared access to large research infrastructures to study severe accident phenomena.

Such an access to large research infrastructure through ALISA allows optimal use of the R&D resources in Europe and in China in the complex field of severe accident analysis for existing and future power plants. This research is demanding of relevant human and financial resources and, in general, the research field is too wide to allow investigation of all phenomena by any national program. To optimise the use of the resources, the collaboration among nuclear utilities, industry groups, research centres, TSOs and safety authorities, at both European and Chinese levels, is very important, and in some cases, mandatory. This is precisely the main objective of the ALISA project, which is aimed at allocating these resources and at facilitating this collaboration by providing state-of-the-art large-scale experimental platforms in Europe and in China for a shared access. Large-scale facilities of the ALISA project are designed to resolve the most important - still pending - severe accident safety issues, ranked with high or medium priority by the SARP group for SARNET NoE. These issues are the coolability of a degraded core, the corium coolability in the RPV, the possible melt dispersion to the reactor cavity, the molten corium concrete interaction and the hydrogen mixing and combustion in the containment. The main objective of the program is to understand how these events affect the safety of existing reactors and to define suitable soundly-based accident management procedures. The main aim is not only understanding the physical background of severe accidents but also providing with the underpinning knowledge that can help to reduce the severity of the consequences. It is crucially important mastering the core melt sequences in a whole and identifying opportunities to lower the risk.

Access to six Chinese facilities belonging to four Chinese research organizations was allowed to European users and six facilities from KIT and CEA were opened to the Chinese partners. The project started on July 1st, 2014 and lasted for four years. Two calls for proposals have been undertaken during the project followed by the evaluation and selection of proposals by the User Selection Panel. All the facilities offered for access in Europe and in China have received proposals. The European facilities are QUENCH, LIVE, DISCO, HYKA at KIT, and KROTOS, VITI at CEA, and the Chinese facilities are COPRA from Xi´an Jiaotong University (XJTU), HYMIT and WAFT from Shanghai Jiaotong University (SJTU), and IVR2D, IVE3D from CNPRI and MCTHBF from Nuclear Power Institute of China (NPIC). The nature of the majority of the Chinese proposals claims the high demand to evaluate the safety design of their own reactor types. Since some EU and Chinese proposals investigate similar phenomena but in different scale and geometry, such as LIVE and COPRA, HYKA, HYMIT and MCTHBF, the comparison of the test results will provide a broader range of applicability. Other proposals investigate different aspects of a same severe accident strategy, such as LIVE and IVR2D/IVR3D. The combined knowledge from the experiments can provide comprehensive understanding of the phenomena of in-vessel melt retention with external cooling.

A wide range of European and Chinese organizations have participated in the elaboration of the experimental proposals as well as the preparation and analysis of the experiments. Due to strong links to other European projects, ALISA offers a unique opportunity for all partners to get involved in the networks and activities supporting safety of existing and advanced reactors and to get access to large-scale experimental facilities in Europe and in China to enhance understanding reactor core behaviour under severe accident conditions.

FIG. 2. COPRA test facility in Xi'an Jiatong University to study melt behaviour in the RPV lower plenum.

4. SAFEST Project

SAFEST [0] **(Severe Accident Facilities for European Safety Targets)** is a European project networking the European corium experimental laboratories and CLADS/JAEA, Japan. The duration of the project is 4.5 years and it was scheduled to end in December 2018. Its objective is to address the variety of the still pending severe accident issues related to accident analysis and corium behaviour in Light Water Reactors.

Moreover, and due to the links to other European projects or platforms (e.g. CESAM, IVMR, NUGENIA/SARNET, etc.), the SAFEST project offers a unique opportunity for all parties to get involved in the networks and activities supporting safety of existing and advanced reactors and to get access to large-scale experimental facilities in Europe to enhance understanding of reactor core behaviour under severe accident conditions.

The project is a valuable asset for the fulfilment of the severe accident R&D programs that are being set up after Fukushima and the subsequent European stress tests, addressing both national and European objectives. It has the aim of establishing coordination activities, enabling the development of a common vision and research roadmaps for the next years, and of the management structure to achieve these goals.

Roadmaps on European severe accident experimental research for light water reactors and for GenIV technologies have been developed. Joint R&D has been conducted to improve the excellence of the SAFEST facilities: that includes measurement of corium physical properties, improvement of instrumentation, consensus on scaling law rationales and cross comparison of material analyses.

Joint experimental research was a clear objective in the SAFEST project to provide solutions for the mitigation of severe accident and the limitation of consequences for the current GEN II and III plants. Consequently, the knowledge obtained in SAFEST shall lead to improved severe accident management measures, which are essential for reactor safety. In addition, it offered competitive advantages for the nuclear industry and contribute to the long-term sustainability of nuclear energy.

A direct outcome from the SAFEST project was the progress towards the creation of an integrated pan-European laboratory for study of corium behaviour in severe accident conditions. Indeed, it encompasses a very large spectrum of nuclear reactors severe accident phenomenology dealing with corium (mainly oriented at LWRs, even though several aspects of Gen IV severe accidents can be studied in some of the SAFEST facilities). By strengthening the links between European corium facility operators, preparing a common roadmap for future EU research and improving the capabilities and performance of experimental facilities, this laboratory shows-up a valuable asset for the fulfilment of severe accident R&D programs which are being set up after Fukushima-Daiichi and the subsequent stress tests both at the national level and at the European level.

The main results of SAFEST activities include a better understanding of the physical background of severe accidents and a prototypic corium behaviour. It profits to the EU utilities and safety organizations, which will be able to validate (either directly through the access to the SAFEST distributed infrastructure or indirectly through R&D) the hypotheses and assumptions adopted for severe accident scenarios and propose pertinent procedures for accident mitigation taking into account experimental results. The experimental results will be used for the development and validation of models and their implementation in the severe accident codes such as ASTEC, MELCOR, ATHLET-CD, too. That enables capitalizing in the codes and in the scientific databases the outcomes of severe accident research, thus allowing to preserve and divulgate the knowledge to a large number of current and future end-users in Europe.

5. CESAM Project

The goal of the **CESAM project (Code for European Severe Accident Management)** was to enhance the ASTEC software system, which is the European reference for the study and the management of core melt accidents for all types of second- and third-generation nuclear power plants (Gen.II and Gen.III NPPs). CESAM [0][0][0] was launched in April 2013 under the European Commission's Seventh Framework Program for Research and Development (FP7) and concluded in March 2017. Coordinated by GRS (Germany) with a major contribution from IRSN, the project brought together 18 European and one Indian partners.

The objectives of the project were in first priority achieving a better understanding of all relevant phenomena of the Fukushima Dai-ichi accidents and of their importance for SAM (Severe Accident Management) measures, as well as improving the ASTEC computer code (see Fig. 3) to simulate plant behavior throughout the accidental sequences including the SAM measures. The analysis of current SAM measures implemented in European plants was the project starting point.

In order to achieve these goals, simulations of relevant experiments that allow a solid validation of the ASTEC code against single and separate effect tests have been conducted. Covered topics in the CESAM project have been grouped in 9 different areas among which are re-flooding of degraded cores, pool scrubbing, hydrogen combustion, and spent fuel pools behavior.

Furthermore, improvements in the modelling have been implemented in the current ASTEC V2.1 series for the estimation of the source term impact on the environment and the prediction of plant status in emergency situations.

Among the most significant developments in terms of functionality, we mention:

- the possibility of simulating all accident sequences involving a delayed injection of water into the vessel, even if the core is already severely degraded;
- the possibility to consider new types of objects (internal canisters or channel boxes, sub-channels, cross-shaped control rods) to represent the actual geometry of the BWR cores.
- the possibility to model non-axisymmetric cores which is also of interest for PHWRs (such as e.g. CANDU NPPs);

- the improvement of the model of transport and the chemistry of fission products and aerosols in the reactor coolant system and containment.

Moreover, the following physical model improvements have been achieved:

- integration of a new model of reflooding a degraded core, specifically designed to be applicable to the geometries of porous media;
- improvement of the oxidation model of Zircaloy cladding exposed to a mixed air/vapor atmosphere, while taking into account nitriding phenomena;
- improvement of corium behavior models, to deal with conditions representing transients external vessel cooling circuit (in-vessel melt retention (IVMR) strategy);
- integration of new corium cooling models with top water in the molten corium-concrete interaction (MCCI) phase, relating to corium ejection and water ingression;
- integration of a dedicated model for calculating pH in the containment sumps as well as various improvements to the physicochemical behavior models of iodine in the RCS as well as the containment.

Furthermore, significant progress has been made in the numeric performance which allows reducing computation time and more generally increasing the software reliability. Last but not least, ASTEC reference input decks have been created for all reactor types currently operated in Europe as well as for spent fuel pools. These reference input decks - which provide a gross description of plant types such as PWR, BWR, and VVER, without defining any proprietary data of particular plants - account for the best recommendations from code developers. In addition, also a generic input deck for a spent fuel pool has been elaborated. These input decks can be used as a reference guidelines by all (and especially new) ASTEC users. Within CESAM, benchmark calculations have been performed with other codes (such as MELCOR, MAAP, ATHLET-CD, COCOSYS) with a focus on the effectiveness of currently implemented SAM measures based on these generic inputs.

As an extension to CESAM, IRSN is now coordinating a new project called ASCOM, launched in October 2018 as part of NUGENIA's Technical Area 2, "Severe Accidents-SARNET" with the objectives to consolidate the ASTEC developments made during the CESAM project and to develop new functionalities as the partners' needs evolve. The extension of the "generic" data set library will also be continued. These new data sets will primarily concern Gen.III NPPs (AP1000 and VVER-1200), and possibly spent fuel pools and small modular reactors.

FIG. 3. ASTEC integral code for simulation of severe accidents.

6. IVMR Project

The **IVMR project** [0][0], coordinated by IRSN and started mid-2015, is lasting for 4 years, in the framework of H2020 EC work-program. It aims at providing new experimental data and a harmonized methodology for the in-vessel melt retention (IVR). The IVR strategy for LWR intends to stabilize and isolate the corium and the fission products inside the reactor pressure vessel and in the primary circuit. The IVR strategy has already been incorporated in the SAM guidance (SAMG) of several operating small-size LWR below 500 MWe (e.g. VVER-440) and it is part of the SAMG strategies for some Gen III+ PWRs of higher power such as AP1000, HPR1000 or APR1400. However, the demonstration of IVR feasibility for large power reactors requires the adoption of less conservative models so that the safety margins are reduced. During the project, several organizations outside Europe (South Korea, China, Russia, Ukraine, and Japan) have joined, providing additional contribution. This shows the wide world interest about the IVR topic and the concerns about reactors of new generation adopting the IVR strategy.

As a first step of the project, an in-depth analysis of the methodology and a screening of the available computer codes have been performed. Thus, a synthesis of the methodology applied to demonstrate the efficiency of IVR strategy for VVER-440 in Europe (Finland, Slovakia, Hungary and Czech Republic) was carried out. The quite comparable methodologies adopted by the designers lead to very consistent results. The main weakness of the demonstration was identified in the evaluation of the heat flux that could be reached in transient situations, e.g. under the "3-layers" configuration of the corium pool in the lower plenum of the reactor vessel.

Analyses have also started for various designs of reactors with a power between 900 and 1300 MWe [**Error! Reference source not found.**]. The large discrepancies of the results were justified by to the adoption of very different models for the description of the molten pool: homogeneous, stratified with fixed configuration, and stratified with evolving configuration. The latter provides the highest heat fluxes whereas the former, which provides the lowest heat fluxes, is not realistic due to the non-miscibility of steel with UO_2.

The first results obtained in the IVMR project have already enabled drawing preliminary conclusions. The most straightforward one is that the majority of current SA codes can be adopted for deterministic and probabilistic evaluations of IVR, but they must be used with care referring to the up-to-date knowledge of SA phenomenology and the SAMG logic for different reactor designs, using the material properties at extreme conditions, checking and respecting the code limitations and referring to appropriate user specific options. Some models must even be improved in order to improve their consistency and reliability. In particular, IVR studies require a very detailed meshing of the vessel and mechanical models enabling to evaluate the resistance of even a very thin residual layer of steel, submitted to a high thermal gradient. Such aspects, which are crucial for IVR, have a negligible impact on the more conventional sequences with early vessel failure and melt release into dry reactor pit. From a general point of view, a PIRT was elaborated in order to identify the models or parameters having the largest impact on the evaluation of risks in case of IVR [**Error! Reference source not found.**].

Another important conclusion is that the conventional investigations based on the comparison of steady state heat fluxes with critical heat fluxes (CHFs) at the vessel external surface are not sufficient for the demonstration of a successful IVR. Higher transient heat fluxes can occur during specific transients with molten pool formation and evolution, e.g. either after stratified layer inversion and steel relocation on the top of the pool or after a secondary inversion whether the heavy metal became light again. When using systems codes and dealing with transient situations, the second significant criterion for the success of IVR is the minimum residual thickness of vessel wall and its cold layer which reflects mechanical resistance of pressure vessel against non-isotropic thermomechanical loads.

To account for any transient peak heat flux causing significant ablation in the evaluation of the likelihood of IVR strategy success, a revised methodology is proposed [0]. It is based on the comparison of the residual thickness with the minimum thickness before failure, considering the internal load. That approach requires a tabulation of the minimum thickness as a function of internal pressure, for various types of vessel steel. Such tabulation is to be obtained from detailed mechanical calculations. That revised methodology, which can be easily implemented in deterministic approaches, may also be used for probabilistic studies. The revised methodology implicitly includes the standard criterion (steady-state heat flux lower than CHF at all locations along the vessel).

The most advanced models for stratified pools are able to simulate transient evolution with a possible inversion of the stratification (the heavy metal becoming lighter). This situation is identified as a possibly critical one because it drives highly superheated metal to the top of the pool. In the current state of knowledge, it is very difficult to conclude about the actual risk engendered by this situation because the models describing the kinetics of stratification inversion the heat transfers under transient conditions are not accurate enough. For this purpose, the project has focused on providing new experimental data (e.g. in facilities such as in NITI in Russian Federation: see the Fig. 4) for situations such as the inversion of corium pool stratification and the kinetics of growth of the top metal layer. The project also provided new data about the external vessel cooling from full-scale facilities: CERES (at MTA-EK in Hungary) for VVER-440 and a new facility built by UJV (in Czech Republic) for VVER-1000. It also included an activity on innovations dedicated to increase the efficiency of the IVR strategy such as delaying the corium arrival in the lower plenum, increasing the mass of molten steel or implementing measures for simultaneous in-vessel water injection.

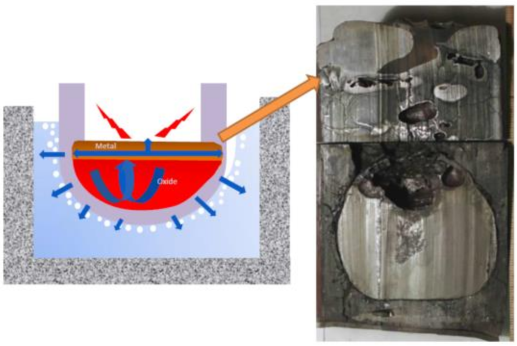

FIG. 4. CORDEB experimental data.

With respect to external cooling (ERVC) and CHF issues, only small scale tests were performed, investigating the effects of water chemistry and corrosion of the vessel wall, either under normal condition (EDF-MIT tests) or during the activation of ERVC with borated water. It was observed that natural corrosion of the vessel, producing a porous oxide layer, could have a positive effect on the increase of the local CHF.

7. sCO2-HeRo Project

The **sCO2-HeRo project** (2015-2018), led by the University of Duisburg-Essen with 6 partners from 3 countries was aimed at developing and proving the concept of a new self-launching, self-propelling, and self-sustaining safety system for nuclear power plants [0].

The supercritical CO_2 heat removal system (sCO2-HeRo) is a novel approach to deal with Fukushima-like accident scenarios with combinations of events such as a station blackout (SBO), the loss of ultimate heat sink (LUHS) and the loss of emergency cooling. The system uses the decay heat to power a Brayton cycle with supercritical CO_2 as working fluid. Since a Brayton cycle - which consists in a heat exchanger to the heat source, a turbo-compressor system and a heat exchanger to the ultimate heat sink - can fulfil the safety function "removing the decay heat from the core to the diverse ultimate heat sink" and simultaneously produce electricity, which is quite valuable in the case of a station blackout, e.g. for recharging batteries or supporting fans for cooling of the CO_2. Venker et al. [11, 12] have studied the feasibility of this decay heat removal system - with supercritical CO_2 (sCO_2) as working fluid - using the German thermal-hydraulic code ATHLET. For a boiling water reactor (BWR) the simulation results have shown that such a system has the potential to enlarge the grace time for interaction to more than 72 hrs.

Fig. 5 shows the Brayton cycle attached to a BWR. In case of an accident, the containment isolation valves will be closed and the safety valves (SV) will open. The steam flows into a heat exchanger (CHX), which must be very compact to fit into the limited space available in existing reactors. Inside the CHX the carbon dioxide is heated up. It flows through a turbine, which drives the compressor and generator sitting on the same shaft. Downstream of the turbine, the CO_2 is cooled by air and is delivered to the compressor and to the compact heat exchanger. Since the turbine of the Brayton cycle produces more power than the compressor needs to operate, the excess power is transformed into electricity, in Figure 5 used to power additional fans to improve the heat removal. However, the ATHELT results are based upon best estimates and must be validated with suitable experiments. Within the EU funded project "sCO2-HeRo", six partners from three European countries are working on the assessment of this innovative decay heat removal system. The goal is to investigate the technical potential of this system and to build up a small-scale demonstrator (technology readiness level (TRL) 3) at the PWR glass model at Gesellschaft für Simulatorschulung (GfS), Germany [6].

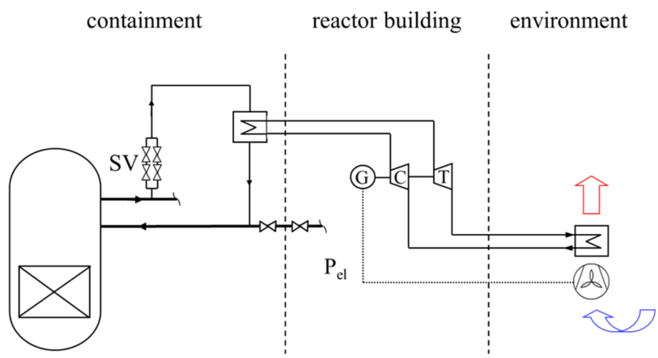

FIG. 5. Schematic Sketch of the Turbo Compressor System [11].

Fig. 6 shows the compact heat exchanger from University of Stuttgart attached to the glass model. Fig. 7 depicts the sCO2-HeRo turbine alternator compressor from University Duisburg-Essen during the cold air tests, and Fig. 8 shows heat rejection unit during test at UJV, Rez. The main components of the sCO2-HeRo system have been shipped to GfS, Essen and were installed at the PWR glass model.

FIG. 6. sCO2-compact heat exchanger attached to glass model.

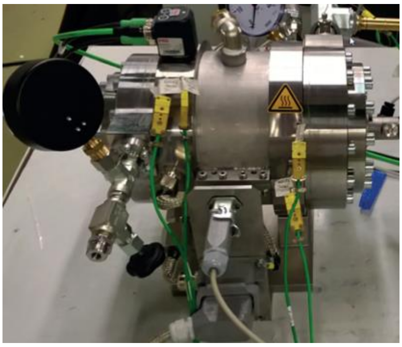

FIG. 7. sCO2-HeRo turbine alternator compressor.

FIG. 8. sCO2-HeRo heat rejection unit during test at UJV, Rez.

The tests at Gesellschaft für Simulatorschulung GfS are used to prove the concept and assess technology readiness level 3. Furthermore, the cycle shall be used to gain experience on the design, performance, and operation of sCO2 loops and the consisting components [13]. Additionally, the results may also provide a pathway for a future use of sCO2-cycles in nuclear e.g. for Gen IV reactors.

8. Knowledge dissemination and education

The projects presented above were also committed to the dissemination of the knowledge among the partners and the general scientific community through several Master training and more than 9 PhDs. Moreover, the demonstration prototype of sCO2-HeRo was installed at PWR glass model in Essen, Germany and used as part of teaching / training courses.

The results gained and the lessons learned from those projects were also widely disseminated through several peer reviewed articles and have been presented in international conferences (such as ICONE, ICAPP, NURETH and EUROSAFE...). As an example, the sCO2-HeRo project supported the organization of the "European sCO2-conference", (**Error! Hyperlink reference not valid.**).

Moreover, dedicated workshops were organized in the framework of each project to present and discuss the achievements and the results, to identify the remaining and pending issues. The outcomes of these projects were also used as inputs in international frameworks organized, e.g., under the auspices of the OECD/NEA and the IAEA, such as the IAEA Technical Meeting on severe accident mitigation [0].

Conclusions

The Fukushima Dai-ichi accidents claimed the crucial need to improve the safety equipment and the mitigation strategies for severe accident. To achieve this ambitious goal, several projects were launched in the severe accidents field of endeavour to address the topics considered of highest priority and reduce the still pending uncertainties on several selected main phenomena. As the great majority of the major severe accident phenomena cannot be addressed within the framework of a national research program only, the PASSAM, SAFEST, ALISA, IVMR and the sCO2-HeRo projects were launched under the auspices of EURATOM enabling the collaboration among R&D partners at European and international level.

The achievements of these projects allow getting a better understanding of the severe accident phenomena, such as the core degradation, the core melt and the hydrogen deflagration, and contribute significantly to reduce the related uncertainties. The outcomes of the above mentioned projects contributed also to increase, improve and demonstrate the ASTEC code suitability to address severe accident phenomena and severe accident management for a large number of reactor designs including PWR, BWR, VVER and CANDU.

Moreover, the lessons learned from the projects supported the development of novel mitigation equipment for heat removal and the improvement of innovative strategies in support of the in vessel retention and the source term reduction.

References

[1] B. Fluhrer et al., "Main outcomes of the European SAEST project towards a pan-European Lab on Corium Behaviour in Severe Accidents," Proceedings of the 9TH European Review Meeting on Severe Accident Research (ERMSAR 2019), Paper No. 98, Czech Republic, March 18-20, 2019.

[2] Gaus-Liu, Xiaoyang; Miassoedov, Alexei, Peng, Chen, "The Outcome of the ALISA Project: Access to Large Infrastructures of Severe Accident in Europe and in China," Proceedings of the 9TH European Review Meeting on Severe Accident Research (ERMSAR 2019), Paper No. 90, Czech Republic, March 18-20, 2019

[3] J.P. Van Dorsselaere, A. Auvinen, D. Beraha, P. Chatelard, L.E. Herranz, C. Journeau, W. Klein-Hessling, I. Kljenak, A. Miassoedov, S. Paci, R. Zeyen, "Recent severe accidents research: Synthesis of the major outcomes from the SARNET network", Nuclear Engineering and Design, vol.291 (Sept.2015), p.19-34

[4] P. Chatelard, S. Belon, L. Bosland, L. Carénini, O. Coindreau, F. Cousin, C. Marchetto, H. Nowack, L. Piar., "Main modelling features of the ASTEC V2.1 major version", Annals of Nuclear Energy, Vol.93 (July 2016), pp. 83–93.

[5] H. Nowack, P. Chatelard, L. Chailan, S. Hermsmeyer, V.H. Sanchez, L.E. Herranz, "CESAM– Code for European Severe Accident Management, EURATOM project on ASTEC improvement", Annals of Nuclear Energy, Volume 116, June 2018, Pages 128-136

[6] Benra, F.-K., Brillert, D., Frybort, O., Hajek, P., Rohde, M., Schuster, S.,Seewald, M., and Starflinger, J., 2016, "A Supercritical CO2 Low Temperature Brayton-Cycle for Residual Heat Removal," The Fifth International Symposium—Supercritical CO2 Power Cycles, San Antonio, TX, Mar. 28–31, pp. 1–12.

[7] L. E. Herranz, T. Lind, K. Dieschbourg, E. Riera, S. Morandi, P. Rantanen, M. Chebbi and N. Losch, "PASSAM "State-of-the-art report" - Technical Bases for Experimentation on Source Term Mitigation Systems", PASSAM-THEOR-T04 [D2.1], (2013).

[8] T. Albiol, L. Herranz, E. Riera, C. Dalibart, T. Lind, A. Del Corno, T. Kärkelä, N. Losch, B. Azambre, C. Mun and L. Cantrel, " PASSAM Final Synthesis Report", PASSAM–DKS-T28 [D5.5] (2017)

[9] Fichot, F., Carenini, L., Bonnet, J.M., "Main physical questions raised by In-Vessel Melt Retention", International Workshop on In-Vessel Retention, Aix-en-Provence (France), 6-7 June 2016

[10] Carénini L., Fichot F., Seignour N., (2017) Modeling issues related to molten pool behavior in case of In-Vessel Retention Strategy, in: Proceedings of ERMSAR conference, Warsaw.
[11] J. Venker, "Development and Validation of Models for Simulation of Supercritical Carbon Dioxide Brayton Cycle and Application to Self-Propelling Heat Removal Systems in Boiling Water Reactors", University of Stuttgart, IKE2-156, ISSN 0173-6892 (2015).
[12] J. Venker, "A passive heat removal retrofit for BWRs", Nuclear Engineering International, 58, 711, 14-17 (2013).
[13] J. Starflinger, M. Straetz, A. Hacks, D. Brillert , A. Vojacek, P.Hajek. "The Supercritical CO2 Heat Removal System - Status and Outlook" 12th International Topical Meeting on Nuclear Reactor Thermal-Hydraulics, Operation and Safety (NUTHOS-12) Qingdao, China, October 14-18, 2018
[14] PASSAM Final Workshop on source term mitigation of severe accidents, Paris (france), February 28th, March 1st, 2017.
[15] T. Lind, N. Losch, L. Herranz, C. Mun and S. Morandi, "Advances on understanding of pool scrubbing for FCVS based on the PASSAM project", IAEA: I3-TM-50122 Technical Meeting on Severe Accident Mitigation, Vienna, 31 August to 3 September 2015.

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PROBABILISTIC SAFETY ASSESSMENT FOR INTERNAL AND EXTERNAL EVENTS / EUROPEAN PROJECTS H2020-NARSIS AND FP7-ASAMPSA_E

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Abstract. The 7th EU Framework programme project Advanced Safety Assessment Methodologies: "Extended PSA" (ASAMPSA_E, 2013-2016) was aimed at promoting good practices to extend the scope of existing Probabilistic Safety Assessments (PSAs) and the application of such "extended PSA" in decision-making in the European context. This project led to a collection of guidance reports that describe existing practices and identify their limits. Moreover, it allowed identifying some idea for further research in the framework of collaborative activities. The H2020 project "New Approach to Reactor Safety Improvements" (NARSIS, 2017-2021) aims at proposing some improvements to be integrated in existing PSA procedures for NPPs, considering single, cascade and combined external natural hazards (earthquakes, flooding, extreme weather, tsunamis). The project will lead to the release of various tools together with recommendations and guidelines for use in nuclear safety assessment, including a Bayesian-based multi-risk framework able to account for causes and consequences of technical, social/organizational and human aspects and a supporting Severe Accident Management decision-making tool for demonstration purposes, as well.

1. Introduction

The methodology for Probabilistic Safety Assessment (PSA) of Nuclear Power Plants (NPPs) has been used for decades by practitioners to better understand the most probable initiators of nuclear accidents by identifying potential accident scenarios, their consequences, and their probabilities. However, despite the remarkable reliability of the methodology, the Fukushima Dai-ichi nuclear accident in Japan, which occurred in March 2011, highlighted a number of challenging issues (e.g. cascading event - cliff edge - scenarios) with respect to the application of PSA questioning the relevance of PSA practice, for such low-probability but high-consequences external events.

Following the Fukushima Dai-ichi accident, several initiatives at the international level, have been launched in order to review current practices and identify shortcomings in scientific and technical approaches for the characterization of external natural extreme events and the evaluation of their consequences on the safety of nuclear facilities.

The collaborative ASAMPSA_E project has hence been supported by the European Commission, aiming at identifying good practices for PSA and at accelerating the development of "extended PSA" in Europe with the objective to help European stakeholders to verify that all the major contributions to the risk are identified and managed. Due to the Fukushima Dai-ichi accident, the ASAMPSA_E project had to focus also on risks induced by the possible natural extreme external events and their combinations. Despite this limitation, the ambition of this project (number of technical issues to be addressed) was considerable and required assembling the skills of many experts and organizations located in different countries.

Based on the ASAMPSA_E lessons and also on the theoretical progresses and outcomes from other recent European projects (e.g. FP7-SYNER-G, FP7-MATRIX, FP7-INFRARISK), the NARSIS project has then been initiated in 2017, in order to propose a number of improvements on the probabilistic assessment and the uncertainty treatment, notably in case of cascading and/or conjunct external natural events, which would enable also extended use of PSA in the field of accident management. Profiting from the presence of practitioners and operators within its consortium, NARSIS will test the proposed improvements of the safety assessment procedures on virtual and actual PWR plants, postulating some hazard-induced damage states representing the variety of their initial conditions in terms of relevant parameters and availability of relevant systems, functions and equipment. For the existing plants, the focus will be mainly put on Beyond Design Basis (BDB) sequences.

2. The FP-7 ASAMPSA_E project

2.1. Presentation of the project and its results

The **ASAMPSA_E (Advanced Safety Assessment Methodologies: extended PSA)** project was aimed at investigating in details how far the PSA methodology application enables identifying any major risk induced by the interaction between NPPs and their environment, and deriving technical recommendations for PSA developers and users. The project was open to European (and non-European) organizations having responsibility in the development and application of PSAs in response to the Regulators' current and hardened requirements.

The following definition has been adopted for the project: "An extended PSA (probabilistic safety assessment) applies to a site of one or several Nuclear Power Plant(s) (NPP(s)) and its environment. It intends to calculate the risk induced by the main sources of radioactivity (reactor core and spent fuel storages) on the site, taking into account all operating states for each main source and all possible accident initiating events affecting one NPP or the whole site". An "extended PSA" should consider, for all reactors and spent fuel storages on a nuclear site, the contributions to the risk originating:

- from internal (operation) initiating events in each reactor,
- from internal hazards (internal flooding, internal fire, etc.),

- from single and correlated external hazards (earthquake, external flooding, external fire, extreme weather conditions or phenomena, oil spills, industrial accident, explosion, etc.),
- from the possible combinations of the here-above mentioned events,
- from the interdependencies between the reactors and spent fuel storages on a same site.

An "extended PSA" shall include a minima a Level 1 PSA (L1 PSA), which calculates scenarios of fuel damage (and their frequencies), a Level 2 PSA (L2 PSA) which calculates scenarios of radioactive releases (frequencies, kinetics and amplitude of such releases) and could include a Level 3 PSA (L3 PSA) which calculates the risk for the population, the environment and/or the economy.

The PSA methodology is, in principle, able to combine and account for all components of risks (frequencies, consequences) but, in actual practice, the reliability of results and conclusions has always to be proven, because the relevance of a PSA depends on the quality of data, the assumptions and hypothesis adopted as well, which must account for:

- the plant or site operating states definition,
- the definition, characterization and frequency of accident initiating events (internal events, internal and external hazards and their combinations),
- the human and equipment failure modelling (fault trees),
- the accident sequences modelling (event tree approach),
- the accident consequences assessment,
- the supporting studies to assess the event trees adopted to address all previous topics,
- the results presentation and their interpretation to serve as an input for the decision-making process.

European countries agreed that harmonization of practices and technical exchanges could contribute to the above-mentioned steps. Specific care was recommended for external hazards as well as high impact events.

The stress-tests, organized by ENSREG, based on a deterministic approach (postulated conditions), examined the European NPPs resilience against events like earthquake or flooding, and the response in case of partial or total loss of the ultimate heat sink and/or loss of electrical power supply.

The review concluded that the level of robustness of the NPPs under investigation was sufficient but, for many plants, safety reinforcements have been defined or recommended to face the likelihood of beyond design basis (BDB) events. These reinforcements include:

- protective measures (against flooding, earthquake),
- additional equipment (mobile equipment, hardened stationary equipment) able to control the NPP in case of BDB events,
- protective structures (reinforced local crisis centres, secondary control room, protective building for mobile equipment …),
- severe accident management provisions, in particular for hydrogen management and containment venting,

- new organizational arrangements (procedures for multi-units accidents, external interventions teams able to secure a damaged site …).

It was claimed that there is an interest to confirm through "extended PSA" results, the high level of robustness of NPPs after the implementation of the safety reinforcements described above. But, building a meaningful risk assessment model for NPPs and their environment is a difficult task which is resource and time consuming, even if some guidance already exists on many topics.

The ASAMPSA_E project has been initiated after the Fukushima Dai-ichi accident and the above mentioned "stress-tests" organized in Europe with the objective to assess the NPPs robustness against extreme events and to identify whether some reinforcements where needed [see http://ensreg.org/EU-Stress-Tests].

The ASAMPSA_E project was intended to help the acceleration of the development of such "extended PSA" in the European countries with the objective to help European stakeholders to verify that all dominant risks are identified and managed. Due to the Fukushima Dai-ichi accident, the ASAMPSA_E project had to give importance to the risks induced by the possible natural extreme external events and their combinations.

The project, which provided an opportunity to examine which PSA methodologies have already been implemented and how efficient they are (optimization of resources, potential for identification of NPP weakness …), has gathered 31 organizations (utilities, vendors, service providers, research companies, universities, technical support of safety authorities …from Europe (21 countries), USA, Japan and Canada) represented by more than 100 experts who shared their experience on probabilistic risk assessment for NPPs.

27 technical reports [1] to [27] have been developed by the project partners and cover:

- bibliography,
- general issues for PSA: lessons learned from the Fukushima Dai-ichi accident for PSA, list of external hazards to be considered, methodology for selecting initiating events and hazards in PSA, risk metrics, the link between PSA and the defence-in-depth concept and the applications of extended PSA in decision making,
- methods for the development of earthquake, flooding, extreme weather, lightning, biological infestation, aircraft crash and man-made hazards PSA,
- severe accident management and PSA: optimization of accident management strategies, study of spent fuel pool accident and recent results from research programs.

These reports have been obtained after the three phases developed from 2013 to 2016: (1) the identification of the PSA End-Users needs for "extended PSA", (2) the development of guidance reports and (3) a peer review of the reports issued in the project. All these reports are available on the project web site (http://asampsa.eu).

2.2. Some of the lessons learned

The technical reports developed by the project partner's present number of considerations that should help the PSA developers and users to increase the quality and relevance of the risks quantifications.

At the end of the project, the few general lessons summarized here below were released.

During the project, achieving an "extended PSA" as defined here above was still considered a pending objective for most (all ?) the teams. That has been obviously identified as an area for progress, because no NPP site (among those considered) had got (in 2016) a PSA that allowed covering:

- all reactors initial states,
- all possible sources of radioactivity,
- all possible types of initiating events (internal and external),

and accounted for a multi-unit accident management.

In complement to the development of the "extended PSAs" the willingness was claimed to define and evaluate a "global risk metrics". Such metrics could turn out extremely advantageous for PSA application but should be highly questionable if the precisions of the different components of the PSAs were not homogeneous. Typically, huge uncertainties affect the annual frequency of rare natural events (high magnitude earthquake frequency, correlated extreme weather conditions …) and can challenge such "global risk metrics". In practice, it may be more effective clearly separating the different components of the PSA (internal events PSA, earthquake PSA, flooding PSA, fire PSA, extreme weather PSA, …).

For natural hazards, the geosciences may not yet provide convenient solutions to calculate the frequency and the features of rare natural events for PSA. For example, today, earthquake predictions are mainly based on seismic historical data and on the available outcomes of investigations on the possible active faults displacement; for extreme weather conditions, even if they are identified as possible significant contributors to the risk of severe accidents, only a few methodologies are available to assess the frequencies of the worst cases (combined/ correlated events). That is a societal concern, not only for nuclear industry. Progress in geosciences for rare extreme natural events modelling is highly desirable for day-to-day applications in PSAs. Some new tendencies in seismology - such as physical modelling of fault rupture, improved validation of simulation tools on real seismic events - could open alternatives to the application of statistical/historical data.

As far as external hazards are concerned, the PSA analyst shall not limit its modelling to a single reactor but widely address its boundary conditions such as: (1) the neighbouring sources of threats around the site (e.g. sources of flooding - sea, river, dam failure, rain impacts - and their combinations, presence of other industrial facilities, transports, …), (2) the site features (including the case of multi-unit sites). It is recommended to develop firstly simplified approach but considering a quite large area around the reactors.

Concerning multi-units PSA, it was concluded that the single unit risk measures (core (or fuel) damage frequency, large (early) release frequency,…) can be applied and that the external hazards screening performed for single unit PSA can be used (no additional work needed). But there is a need for methodological developments on event trees structure and content: how to limit the size of event trees, how to introduce site human risk assessment, how to define multi-unit common cause failures, how to consider the interface between level 1 and level 2 PSA. A multi-unit PSA should conduct to difficulties for risk aggregation like single unit PSA (due to highly uncertain data, as explained above). In addition, it appeared that quantitative safety targets are defined and applied (in some countries) for single unit PSA but for multi-unit PSA, it is not clearly established whether the same quantitative safety targets can be applied.

2.3. Dissemination activities, potential impacts

Communications (papers, presentations) were done to promote the project results in the nuclear PSA community or generally speaking in the risk assessment international community. For example, communications were done at an ARCADIA project workshop (2014), the EGU (European geoscience Union) conference in 2015 (EGU 2015), the ESREL 2015 and 2017 conference, the NENE 2016 conference, the NUCLEAR 2016 conference, the annual OCDE/NEA CSNI-WG-Risk meetings (2013,2014,2015,2016,2017), the PSAM13 conference (2017), in the Disaster Risk Management Knowledge Centre (DRMKC) report 2017 or at an IAEA, workshop on multi-units PSA (2016).

A public web site (http://asampsa.eu) is available since the beginning of the project.

The PSA End-Users from all countries have been associated at the beginning of the project to discuss the needs of guidance for extended PSA and at the end of the project to discuss the reports prepared by the project partners. Each time, an international survey and then an international workshop have been organized.

The ASAMPSA_E was intended to promote and help the development of high quality complete PSA for NPPs in Europe. This task is now on-going in many countries and a clear tendency is to extend the scope of existing PSA. The ASAMPSA_E guidance reports can be applied as starting point for many issues. The project results can also be used for the development of national of international standards (by IAEA for example).

2.4. Interest for follow-up research/collaborative activities

In the framework of the ASAMPSA_E project and the relationship established with PSA End-Users international community, some interests for further research or collaborative activities have been discussed. Among the highlighted topics the following ones can be mentioned:

- the exchanges of information at international level on risk-informed decision making and "extended PSA", including comparison of risk metrics applications,

- the sharing of available methodologies to demonstrate that the defence-in-depth is appropriately implemented,
- the development of methods enabling modelling the hazards combinations (especially extreme weather correlated events),
- the study of the importance of non-safety systems and their secondary impacts in external hazards assessment,
- for seismic PSA, the aftershocks modelling, the application of faults rupture modelling for PSA or the calculation of the fire probability in case of earthquake,
- for flooding PSA: the multi-unit flooding PSA, the methods to introduce combination of hazards, the uncertainties on flooding event frequency for the different causes, the system, structure and component fragilities for flooding (including water propagation modelling),
- for extreme weather PSA: the research on combined extreme weather events frequency and (due to slow progress in this area), the alternative approaches for risk identification and management,
- the comparison of existing PSA with regard to loss of ultimate heat sink (risk quantification, ultimate heat sink design comparison (with back fitting examples)),
- in tight connection with PSA activities (or risk informed decision making), the calibration of lightning protections and comparison of protection solutions in different area (data server; e.g. google, military applications, communication devices, airplane traffic, ...),
- the comparison of level 2 PSA for external hazards (only few are available),
- the implementation of the crisis team modelling (teams that rescue a NPP with mobile equipment defined after the Fukushima accident) in level 1 and 2 PSA,
- the dry spent fuel storages risk assessment,
- the conditions that allow spent fuel pool stabilization in case of accident.

2.5. Conclusion for ASAMPSA_E project

The ASAMPSA_E project has been successful and remarkable from any viewpoint, also considering the number of PSA experts involved, their high and effective commitment, as well as the quality and extent of exchanges among the partners. That claims, in the European framework, - even difficult and ambitious - projects can be profitable and must be supported and sustained.

The 27 technical reports mentioned here-above on one hand enable an accurate and comprehensive view of the status of current PSAs, on the other provide the users with numerous recommendations to develop meaningful, pertinent and efficient "extended PSA" and to identify some pending difficulties, to be overcome through shared research, development and innovation, as well.

Now, PSA teams have a lot to do to develop extended PSAs. In this context, a framework oriented towards realization of extended PSAs could be an interesting perspective, providing a place to share knowledge, tools and methodologies and contribute to disseminate know how on extended PSAs.

For the future, ASAMPSA_E identifies some key-issues to define new perspectives for collaborative projects on PSAs in, at least, 4 main fields of endeavour:

- the improvement of methodologies that support PSAs (the NARSIS project is a good example of such projects),
- the extension of the range of PSA (including initial operating states, initiating events, internal and external hazards, multi-units issues and site environments issues),
- the sharing of NPPs risk dominant contributions: PSAs are not theoretical tools but representations of the reality of risks. They should help safety analysts to identify, rank and address the dominant risks with the highest priority at the design level and in operation,
- the improvement and harmonization of uses of extended PSAs and decision making processes.

That way, the likelihood of having to face another major accident in nuclear industry in the medium-short term should be significantly reduced.

3. The NARSIS project

3.1. NARSIS general overview

The NARSIS project is a project initiated relying upon the ASAMPSA_E lessons to address more specifically the following challenges:

- A better characterization of external hazards, focusing on those identified as first-level priorities by the PSA End-Users community in ASAMPSA_E (earthquakes, flooding, extreme weather), as well as the development of a framework enabling the modelling of hazards combinations (e.g. extreme weather correlated events) and related secondary effects, useful for PSA;
- A better risk integration combined with a suitable uncertainty treatment (also for expert-based information), to support the risk-informed decision making and a risk metrics comparison within extended PSA;
- The possibility to better assess the fragilities of NPP Systems, Structures & Components (SSCs), by including functional losses, cumulative effects (aftershocks modelling in case of seismic PSA), ageing mechanisms, human factors;
- An improvement of the processing and integration of expert-based information within PSA: methodologies for quantification and propagation of uncertainty sources underwent significant improvements in some other fields (e.g. related to human-environmental interactions), but is still

pending the demonstration of their applicability to PSA of NPPs and the benefits of using modern uncertainty theories both to represent in flexible manner experts' judgments and to aggregate them.

To address the aforementioned challenges, the NARSIS project proposed to review, analyse and improve aspects related to:

- external hazards including events arising from combination of hazards, frequency estimation of high intensity low probability events with potentially very large consequences and re-evaluation of screening criteria;
- modelling of the SSCs response to external events and development of new concepts of multi-hazard fragility functions, correlation effects and consequent damage scenarios;
- theoretical development for: (i) constraining Expert Judgment, (ii) treatment of parameters, (iii) models and completeness uncertainties and finally, (iv) development of methods based on Bayesian approach and Human Reliability Analysis;
- L2 PSA aspects of external hazards analysis including evaluation of accident management measures.

NARSIS does not aim at performing a complete review of the PSA procedures.

In order to propose some improvements to be integrated in PSA, the project puts together three interconnected components, organized in 5 main scientific work-packages (cf. Fig. 1):

- theoretical improvement in scientific approach of multiple natural hazards assessment and their impacts, including advance in evaluation of uncertainties and reduction of subjectivity related to expert judgments,
- verification of the applicability and effectiveness of the findings in the frame of the safety assessment and iii) application of the outcomes at demonstration level by providing improved supporting tools for operational and severe accident management purposes.

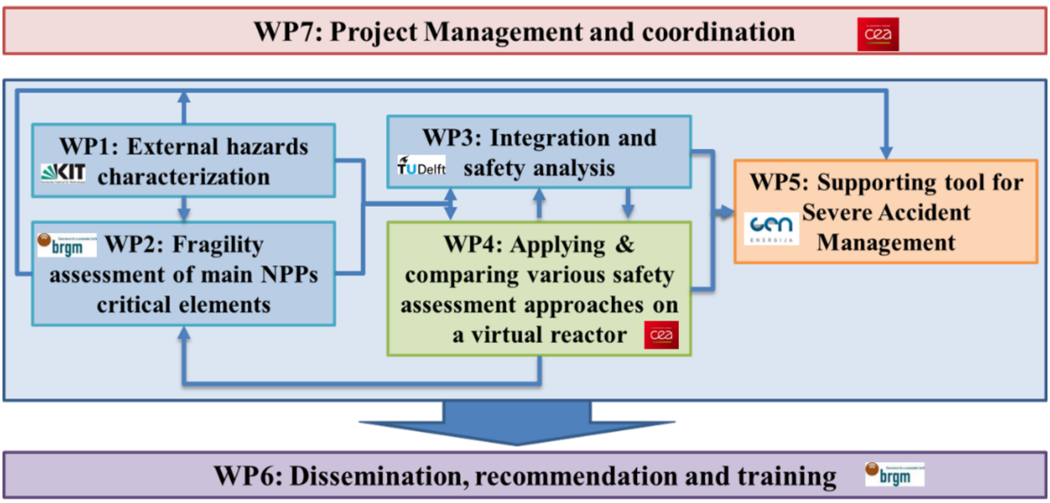

FIG. 1. Global workflow of the NARSIS project.

Thanks to the diversity of the 18 participants constituting the NARSIS consortium (Fig. 2), from academic to operators and TSOs, the foreseen theoretical developments and the effectiveness of the proposed improvements will be tested on simplified and real NPP case studies..

FIG. 2. The NARSIS consortium at a glance.

About 60 deliverables are planned in NARSIS, including technical reports, recommendations, education and training materials, as well as software tools.

Hereafter, are reported some of the main achievements expected from NARSIS:

- Reviewing the state of the art in hazard/multi-hazard characterization and combinations and in risk integration methods for high risk industries;
- Improving methodologies for single probabilistic hazard assessment (flooding, extreme weather, extreme earthquakes and tsunamis);
- Developing an integrated multi-hazard framework for combined hazard scenarios relevant for safety assessment as well as recommendations for use of this framework;
- Providing methods to:
  - analyse extreme hazards using multi-varied statistics;
  - account for secondary hazards of each NPP component separately adopting physical approaches;
  - develop scenarios through a stochastic approach, allowing characterization of the input hazard curve to integrate all possible uncertainty, temporal and spatial combinations for Design Basis Events;

- account for cumulative effects, soil-structure interactions, ageing mechanisms in the fragility assessment of SSCs in case of seismic events;
- derive hazard-harmonised fragility functions, which can be updated by integrating the whole amount of available information (numerical results, qualification and other experimental testing data, in situ measurements, expert judgment), through the combined use of statistical extreme value analysis and Bayesian updating,
- incorporate human factors into multi-hazard fragility functions, as they are considered the originating cause of major disasters, and yet are difficult to predict under extreme conditions (one of the major source for epistemic uncertainty);
- adapt advanced assessment approaches to identify and prioritise the most influential sources of uncertainty in the parameters (external threats, etc.) and NPP elements modelling, so that uncertainty on results can be constrained before integration in the multi-risk framework;

– Developing a Bayesian Network (BN) framework for multi-risk integration and nuclear safety assessment;
– Developing a model reduction strategies at the components and NPP scales, to be used for probabilistic analyses in case of external hazards (earthquakes, flooding): the focus in NARSIS is put on meta-modelling techniques (e.g. surrogate models), as well as on Proper Generalized Decomposition (PGD) with LATIN method, which will be further developed to address complex, nonlinear, dynamic systems;
– Providing with the safety analysis of a simplified generic PWR model representative of the European fleet, comparing purely deterministic (conventional), purely probabilistic (BN) or combined deterministic-probabilistic (BEPU / E-BEPU) approaches;
– Developing a decision-making (DM) tool to support SAM Guidelines, which will be fed by projected accident progression sequences and associated SAM strategies: the primary purpose of this tool is to provide support in preventing the BDB condition from developing into severe accident condition (i.e. condition involving severe fuel damage) or mitigating it at earliest stage before it produces significant radioactive releases. The goal is here to strengthen the earliest in-plant / Technical Support Centre (TSC) response and thus avoid significant source terms, as compared to strengthening and supporting the emergency preparedness, response and exercises which are investigated by projects such as H2020 FASTNET.

3.2. The NARSIS NPP "multi-risk model"

Beside the need to better characterize natural hazards and their possible combinations, as well as to provide robust methods to assess response and fragility of SSCs, consequences (e.g. large early release frequencies, core damage and plant damage states), including sensitivity analyses, have also to be addressed in a dedicated integrated multi-risk framework.

In order to encompass the many aspects related to the complexity of a NNP "risk model" (e.g. multiple hazards and vulnerabilities, cascading effects, complex dynamic systems, human and organisational factors, uncertainty …), different risk integration methods have been proposed and used in high risk industries (other than nuclear ones). It was concluded that the combination of probabilistic and deterministic approaches generally yields better results for multi-risk integration.

Moreover, Bayesian Networks (BNs) have been used to model multi-risk aspects of real systems, instead of Fault Trees (FTs) or Event Trees (ETs), as the latter ones are rather static methods, based on reductionism and linear causal chains. An ET is a graph representation of events - in which individual branches are alternative steps from a general prior event, state or condition through increasingly specific subsequent events (intermediate outcomes) to final outcomes. Accordingly simplifying assumptions made for its quantification as well as for inclusion of common cause failures (CCF) are often affected by high uncertainties. Furthermore generally adopted conventional distribution functions may misestimate high standard deviation (leptokurtosis).

The extension to the Bayesian setting allows describing the state of each node of the network through richer information (e.g. full probability distribution), instead of a single value. Any information can then be used to update the probabilistic information, as the entire BN represents the probability of every possible event as defined by the combination of the values of all the random variables (i.e. Joint Probability Distribution). That way, both aleatory (due to the random nature of the external threats) and epistemic uncertainties (due to incomplete knowledge of the system) may be accommodated and assessed in the system failure. Unlike conventional FT formulations, BNs can account for correlations both at the hazard and the component damage levels: that ensures that the most critical failure modes, which may result from the joint or cascading adverse events, will be properly identified and quantified, with respect to the occurrence of the top event. Moreover, such an approach allows for efficient risk comparisons.

In NARSIS, a dynamic BN has been adopted and is being developed, as a multi-risk integration framework able to account for time evolution. This approach has been successfully demonstrated in other critical infrastructures. Fig. 3 shows a very simplified picture of what such a BN can look like in case of combined external hazards leading to a Station Black-Out (SBO) event.

The key challenges when deriving such a BN framework for safety analysis are to be able to:

- define the accident scenario progression with the events of interests and their dependencies;
- select the random variables, which will populate the BN nodes and deriving the conditional probability distributions and causality relations (edges of the BN);
- model quite detailed risk-subnetworks to cover many aspects (technical, social, organisational) and integrating them in the larger BN model;
- assess the impact of the different assumptions and BN inputs on the final joint probability related to a given top event (e.g. SBO).

Hence, a clear description based on existing PSA FTs/ETs should be used at first, in order to develop into a probabilistic description compatible with the BN approach. To build the technical sub-networks (e.g. flood defence failure, piping system failure, etc.), some physics-based numerical simulations can be used to account for realistic off- and on-site conditions and may be complementary to available data to define critical scenarios. Regarding the human and organisational sub-networks, they should include aspects related to human performance shaping factors, maintenance activities, etc.; a focus has to be made as well, on group processes and decision making at times of high pressure, i.e. in the case of accidental conditions.

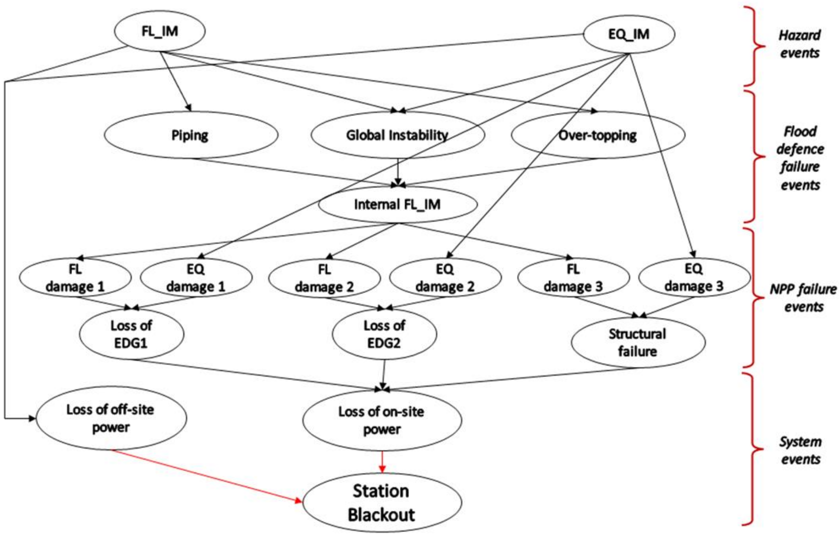

FIG. 3. Illustration of a very simplified BN construction considering combined hazard events (e.g. flooding & earthquake): each node corresponds to a full probability distribution.

3.3. Some key results expected from the NARSIS project

From a methodological point of view, the two main expected achievements of the project will provide the stakeholders with a useful basis to address a number of topics identified as relevant by the PSA community such as (see section 2.3):

- the integrated multi-hazard framework enabling probabilistic modelling of the hazards combinations, and
- the dynamic BN multi-risk modelling approach derived for the safety assessment purposes of NPPs, integrating plant complexity (technical, social & organisational aspects) and multi-hazards scenarios. If applicable, the BN approach will also allow risk comparison considering different risk metrics.

In addition, the study of the importance of various plant systems in a multi-hazard context and the derivation of hazard-harmonized fragility models accounting for functional consequences and/or human factors, will enable to address the estimation of the secondary impacts in the assessment of external hazards.

Regarding single hazard PSAs and fragility assessment:

- the SSCs fragilities for flooding (including water propagation modelling) will be addressed;
- the cumulative effects of the solicitations (e.g. earthquake mainshock and aftershocks) and the ageing mechanisms (e.g. damaging phenomena, corrosion) of structural elements, will be integrated.

Moreover, as the experts' judgment is mandatory in the PSA of nuclear facilities, NARSIS intends to provide flexible approaches based on recent advances of the theory of uncertainty:

- to represent and aggregate the experts' judgments, managing possible controversial views and
- to propagate uncertainties in order to assess their impact on PSA results and hence, to better constrain the uncertainty engendered by the knowledge incompleteness.

The applicability, validity and robustness of the proposed advanced procedures in the safety assessment practice will be tested in situations where empirical data are scarce, incomplete, imprecise and vague (e.g. by using an expert-based knowledge modelling tool).

3.4. Dissemination and training activities in NARSIS

Different goals are sought within NARSIS regarding dissemination and training activities:

- Raising awareness about the challenges of nuclear safety and shearing potential improvements provided by the project;
- Informing and educating different target audiences as appropriate;
- Engaging target audience groups and notably regulators and decision-makers to get input /feedback on their expectations;
- Promoting the use of the project outputs and their implementation through practical knowledge transfer;
- Raising public confidence in nuclear energy.

Regarding education and training activities, apart from master trainings and postdocs proposed in the project, 5 PhD theses have been launched in cooperation with universities, in order to cover a number of research topics useful for NARSIS:

- extreme weather characterisation,
- seismic fragility of ageing structures,
- vector-valued fragility functions for multi-hazards assessment,

- LATIN-PGD model reduction strategy for seismic response of structures,
- Bayesian networks integration framework for probabilistic risk assessment.

The project has also an on-going collaboration with the European Nuclear Education Network (ENEN). This will for instance permit to invite a number of selected students and young researchers to participate in the first NARSIS International Workshop to be held in Warsaw on September 2019 and which proposes a training on Probabilistic Safety Assessment for Nuclear Facilities (http://nuclear.itc.pw.edu.pl/narsis-workshop). At this occasion and all along the project duration, pedagogic materials and lectures targeted towards students (e.g. masters) and young researchers or professionals will be produced. Proceedings of the two international workshops planned in the project will be also available through the NARSIS web site (http://www.narsis.eu).

Finally, regarding dissemination activities, apart from newsletters and participation in international conference (e.g. NUGENIA Forums, scientific conferences), the project has regular meetings with its International Advisory Board, which members are part of international organisations with close links to nuclear safety issues (NUGENIA, IAEA, JRC, etc.).

4. General conclusion

The ASAMPSA_E and the NARSIS projects prove that the European R&D framework is the convenient environment to develop and promote the improvement of the PSA methodologies and, by the way, contribute to the risk identification and assessment in nuclear industry.

New horizons for collaborative projects on PSAs in Europe shall be defined. They should promote and support the improvement of the methodologies, sustain the extension of the issues considered in PSAs as well as the sharing the knowledge upon the main and dominant contributions to NPP risk.

The building of a European Forum in this area, relying upon the network created through ASAMPSA_E, will be an intermediate step to stimulate the continuous development of European activities in this area in the aim at enhancing nuclear safety by design and operation.

Acknowledgements

The ASAMPSA_E and NARSIS projects have been co-funded by the European Commission and performed as part of the EURATOM 7th Framework and Horizon 2020 Programmes respectively, under contract 605001 (ASAMPSA_E) and 755439 (NARSIS).

References

All ASAMPSA reports are available at http://asampsa.eu.

ASAMPSA - General issues for PSA

[1] Lessons of the Fukushima Dai-ichi accident for PSA, ASAMPSA_E/WP30/D30.2/ 2017-32, January 2017
[2] List of external hazards to be considered in ASAMPSA_E, ASAMPSA_E/WP21/D21.2/2017-4
[3] Guidance for Decision Making based on Extended PSA - summary report) Vol 1, ASAMPSA_E/WP30/D30.7/2017-31 vol 1
[4] Methodology for Selecting Initiating Events and Hazards for Consideration in an Extended PSA, ASAMPSA_E/WP30/D30.7/2017-31 vol 2
[5] Risk Metrics and Measures for an Extended PSA, ASAMPSA_E/WP30/D30.7/2017-31 vol 3
[6] The Link between the Defence-in-Depth Concept and Extended PSA, ASAMPSA_E/WP30/D30.7/2017-31 vol 4
[7] The PSA assessment of Defense-in-Depth – Memorandum and proposals, ASAMPSA_E/WP30/D30.7/2017-31 vol 5

External hazards and PSA

[8] Guidance document on practices to model and implement EARTHQUAKE hazards in extended PSA ASAMPSA_E/D50.15/2017-33-vol 1&2
[9] Guidance document on practices to model and implement FLOODING hazards in extended PSA, ASAMPSA_E/ D50.16/2017-34-, January 2017
[10] Guidance document on practices to model and implement EXTREME WEATHER hazards in extended PSA ASAMPSA_E/D50.17/2017-35
[11] Guidance document on practices to model and implement LIGHTNING hazards in extended PSA, ASAMPSA_E/D50.18/2017-36
[12] Guidance document on practices to model and implement BIOLOGICAL hazards in extended PSA ASAMPSA_E/D50.19/2017-37
[13] Guidance document on practices to model and implement MAN-MADE HAZARDS AND AIRCRAFT CRASH in extended PSA, ASAMPSA_E/D50.20/2017-38

L2 PSA and severe accident management strategies

[14] Best-Practices Guidelines for L2PSA Development and Applications, Volume 1 - General, Reference ASAMPSA2, Technical report ASAMPSA2/ WP2-3-4/D3.3/2013-35, dated 2013-04-30.
[15] Best-Practices Guidelines for L2PSA Development and Applications, Volume 2 - Best practices for the Gen II PWR, Gen II BWR L2PSAs, Extension to Gen III reactors, Reference ASAMPSA2, Technical report ASAMPSA2/ WP2-3-4/D3.3/2013-35, dated 2013-04-30
[16] Best-Practices Guidelines for L2PSA Development and Applications, Volume 3 - Extension to Gen IV reactors, Reference ASAMPSA2, Technical report ASAMPSA2/ WP2-3-4/D3.3/2013-35, dated 2013-04-30
[17] Final guidance document for extended Level 2 PSA - Summary, Technical report ASAMPSA_E / WP40 / D40.7 / 2017-39 vo1,
[18] Guidance document on practices to implement External Events in L2 PSA, ASAMPSA_E/WP40/D40.7/2017-39vol2
[19] Verification and improvement of SAM strategies with L2 PSA, ASAMPSA_E D40.7, ASAMPSA_E/WP40/ D40.7/2017-01 volume 2
[20] Complement of existing ASAMPSA2 guidance for shutdown states of reactors, Spent Fuel Pool and recent R&D results, Technical report ASAMPSA_E / WP40 / D40.6 / 2016-25, June 2016

PSA End-Users survey learnings

[21] Synthesis of the initial survey related to PSAs End-Users needs, Technical report ASAMPSA_E/WP10/D10.2/2014-05, January 2015

[22] Synthesis report of the End-Users survey and review of ASAMPSA_E guidance, and final workshop conclusions. Identification of follow-up useful activities after ASAMPSA_E, ASAMPSA_E/WP10/D10.5/2017-40, January 2017

Bibliography

[23] Bibliography – Existing Guidance for External Hazard Modelling, ASAMPSA_E / WP21 / D21.1 / 2015-09, March 2015

[24] Summary report of already existing guidance on the implementation of External Hazards in extended Level 1 PSA, ASAMPSA_E/WP22/ D22.1/2015-11, August 2015.

[25] Summary report of already published guidance on L2 PSA for external hazards, shutdown states, spent fuel storage, ASAMPSA_E / WP40 / D40.2 / 2014-08, December 2014

[26] Bibliography on regulatory requirements on the implementation of defense in depth for nuclear power plants , ASAMPSA_E / WP30 / D30.1 / 2016-29, July 2016

[27] Gehl P. and D'Ayala D. (2016). "Development of Bayesian Networks for the Multi-Hazard Fragility Assessment of Bridge Systems", Structural Safety, 60: 37-46.

[28] Ladeveze P., Passieux JC. and Néron D. (2010). "The LATIN multiscale computational method and the Proper Generalized Decomposition", Comput. Methods Appl. Mech. Engrg., 199: 1287–1296.

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NUCLEAR AND RADIOLOGICAL EMERGENCY MANAGEMENT AND PREPAREDNESS

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Abstract. Recent EURATOM research efforts on Emergency Preparedness and Response (EP&R) have been focussed on programs addressing some main knowledge gaps clearly identified in the outcomes of investigations carried-out in Europe in response to the Fukushima accident. The PREPARE and FASTNET projects tried to solve similar problems adopting very complementary and synergic approaches. The main achievements of both projects are detailed in this paper. In particular, the problem of the fast estimation of time-dependent, long-lasting Source Terms is discussed. This problem is not only a technical one but is also related to the experience and skill of the code users. As the EP&R is spanning a wide range in Europe, certainly far beyond the borders of individual states, it is mandatory creating a common and shared understanding of emergencies. Both PREPARE and FASTNET recognized the fundamental role of exercises to increase the experience of emergency responders in Europe. A general recommendation can then be formulated, in that more efforts should be dedicated in the future to the realization of such important exercises.

1. Introduction

Research and Development in the area of Nuclear and Radiological Emergency Management and Preparedness under the EURATOM umbrella went on in the last years with two major projects, namely the PREPARE Collaborative Project (from 1 February 2013 to 31 January 2016, coordinated by KIT) [1,2] and the FASTNET Research and Innovation Action (from 1 October 2015 to 30 September 2019, coordinated by IRSN) [3,4]. The first project was funded through the FP7-Euratom program and the second through the H2020-Euratom program. Both projects aimed at improving the existing Emergency Preparedness and Response (EP&R) in Europe, and at addressing and closing some important gaps identified during, and in the aftermath of, the Fukushima Daiichi accident [5]. The outcomes of the analysis of the European reaction to the Japanese accident showed several important and common issues, which can be summarized as follows:

- missing early and rapid information on the potential Source Term (ST);
- absence of coordinated plan at European level to estimate the ST;
- absence of an harmonized response to the safety of the European residents living in Japan;
- partly chaotic communication with the public;
- insufficient guidance on how to deal with incoming goods from Japan.

Both projects tried to tackle these points addressing them from different perspectives, adopting different methods, with synergic and highly complementary approaches, avoiding any duplication of efforts, as well. Both projects gave their own contributions to the solution of the extremely complex problem of enhancing the coherence in the preparedness and response to a nuclear emergency for a continent, Europe, which is very dense both in population and in nuclear power installations, and - at the same time - very diversified and heterogeneous as far as the nuclear technologies, the national legal frameworks, and the orography are concerned. The fast and timely delivery of comprehensive information about an existing or developing future situation is certainly a key point for decision making in the early stage of an emergency. Fast and reliable ST assessments, not necessarily of a strongly conservative nature, are at the very heart of the problem. In this regard, PREPARE included among its goals the initial development and implementation of tools to derive a ST, using inversion algorithms as well as real-time ambient gamma dose-rates measured at the boundary of NPPs. To achieve the same goal, FASTNET developed fast-running tools to predict STs using a minimum set of plant data. Both approaches are valid and both need to be implemented and further strengthened; nevertheless, in case of missing dose-rate data, only the second approach can work, while dose-rate data may help correct calculated STs if wrong assumptions have been made in the calculations themselves. An example of synergy between the two approaches could be found in the fact that source inversion algorithms need a first-guess ST, the accuracy of which impacts directly the effectiveness of the inversion; this first-guess Source can be obtained with the tools developed in FASTNET. The complementarity between the two working methods shows-up in situations which require an early prognosis of an emergency, in order to timely activate and trigger protective countermeasures; such a prognosis must be made prior to any release to the environment, and therefore before the availability of any measured data; this prognosis is therefore enabled by fast-running tools. Measured data can be used, later on, either to confirm or to improve the calculated prognosis.

Both projects have then got the common goal of achieving a more harmonized interpretation of an emergency situation, and therefore supporting more coherent decisions on protective actions to be implemented; that is mandatory to strengthen the confidence of the public in the safe use of nuclear power. Again, both projects contributed to this goal in different but synergic manners. PREPARE tried to foster analytic skills, providing a better guidance on how to communicate with the public and other stakeholders. FASTNET improved and, most importantly, shared among the stakeholders a common methodology for diagnosis and prognosis of emergencies and for the fast estimate of STs.

A third example of the complementarity and synergy of the two projects is the emphasis and efforts that both projects devoted to long-lasting radioactive releases. One of the lessons-learned from the Fukushima Daiichi accident is that a release of contaminants can be unevenly spread in time over several days, if not weeks. That was something rather unexpected and surely unprecedented, and immediately triggered reactions in the EP&R community worldwide to support the development and release of codes and tools, both for ST estimate and for atmospheric dispersion, able of dealing with such long lasting situations. For example, the US-NRC asked for improvements in the RASCAL fast-running code, the range of which, prior to Fukushima, was limited, in time, to 48 hours of release and atmospheric transport and, in space, to 80 km distance from the source, only. Now its operation domain has been extended to 96 hours and 160 km distances. PREPARE tackled this issue through a stress test-like simulation of the existing national operational procedures in Europe to verify their compliance to scenarios with very long-lasting releases. FASTNET, on the contrary, focused on the development of tools able to deal with situations up to a couple of weeks long-lasting, and even more, and to increase the awareness of the users of the tools in the fact that the time-dependence of a release is of the utmost importance to set-up properly protective countermeasures.

Detailed descriptions of the main findings and results of both projects will be given in the next sections.

2. The PREPARE Project

This project started in February 2013 and ended in January 2016; it gathered 45 partners from Europe and the Fukushima University from Japan. The activities have been performed in seven workpackages, with the following main aims and achievements:

- **Operational procedures for long lasting releases**: following the Fukushima Daiichi accident, a review of existing EP&R procedures for long lasting releases and identification of possible needs for improvements by performing scenario calculations has been performed at a European level. Suggestions for improvements have been formulated.
- **Platform for information collection and exchange**: the so-called Analytical Platform for information exchange in time of nuclear or radiological crisis has been created. It allows discussion between institutional and non-institutional experts on an expert-level, and spreads congruent information on the current situation to the public, including mass media.
- **Management of contaminated goods**: stakeholder panels have been prepared, and panels had meetings in 10 European countries to review existing guidance and to identify areas for improvement.
- **Improvement of decision support systems**: the atmospheric dispersion models implemented in the two Decision Support Systems (DSS) ARGOS [6] and RODOS [7], as well as the hydrological model chain of RODOS, were extended. Among others, two methods for source-term estimation were developed and implemented. The long-term watershed model MOIRA was integrated, and the global ocean model MyOcean was linked to RODOS allowing using the simulations of this model as boundary conditions for the simulation of radionuclide dispersion in RODOS.
- **Communication with the public**: the overall objective of the work package was to investigate the conditions and means for relevant, reliable and trustworthy information to be made available to the public. Here, both traditional and social media were studied.
- **Training, exercises and dissemination**: training and exercising was an important aspect and therefore treated as a separate work package.

Concerning the operational procedures for long lasting releases, PREPARE made a stress test-like simulation to verify compliance with ICRP reference levels. In all countries with nuclear installations, detailed emergency management strategies have been developed in the past. In nearly all cases, such strategies are based on accident scenarios where the duration of the release of radionuclides to the environment is limited to either some hours or a few days at maximum. The Fukushima accident has demonstrated the likelihood of long lasting releases of radionuclides from an NPP over several weeks. That made it necessary to check the current off-site nuclear emergency plans in European countries against accident scenarios based on lessons learned from the Fukushima accident, and to derive recommendations on how to improve them. The tests should enable verifying whether protective measures foreseen in the current emergency plans could adequately reduce the radiological consequences of NPP accidents with long-lasting releases, similar to those from the Fukushima-Daiichi NPP. The methodology adopted consisted in identifying 10 representative STs, with a duration of releases ranging from 22 to 188 hours. Seven of these tests can be classified at the INES[1] 7 level, two at the INES 6 and one at the INES 5. The total amount of ^{131}I released varied between 3 and 600 PBq. These scenarios were then combined with different atmospheric conditions (between 46 and 365 cases) to calculate doses to the population around several NPPs and the radiological consequences were compared to those assumed in the emergency planning. Areas and distances where national intervention criteria were exceeded have been identified; an example of such a case is given in Fig. 1.

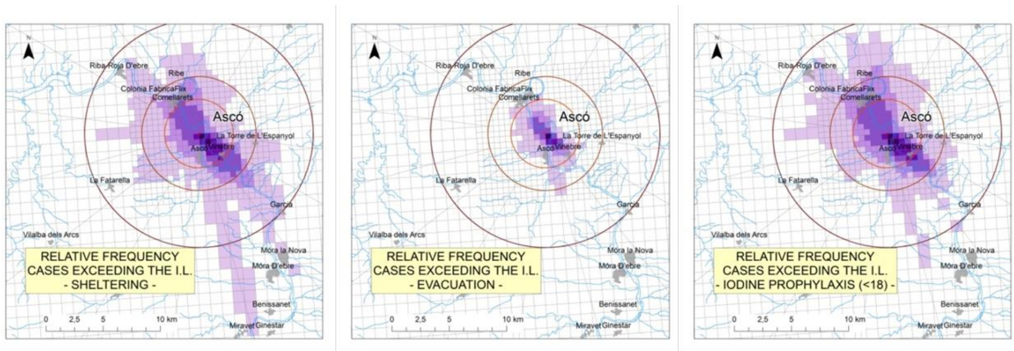

FIG. 1. Frequency of scenarios exceeding Spanish intervention limits.

As a comprehensive result, it can be claimed that in a majority of release scenarios the areas calculated for protective actions do not exceed current planning zones. Were these ranges exceeded, the amount of affected population remains quite small. The number of sectors affected clearly increases with the duration of the release. If the release duration is lower than 12 hours, the affected sector is limited to less than 90 degrees in most cases. For very long lasting releases, however, the whole circular area (around the release point) could be affected (up to 360 degrees).

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[1] International Nuclear and Radiological Event Scale, maintained by IAEA and developed to classify STs according to their severity for people and the environment; currently the INES scale goes from level 1 (least severe) to level 7 [8].

The current intervention criteria in all countries guarantee that the residual dose in the first year (ICRP reference level) does not exceed 100 mSv. Even if the general findings of the project support the current planning, some shortcomings were identified, such as, for long lasting severe releases, a one-time intake of stable iodine is often not sufficient for protecting the population against large thyroid doses. Multiple intakes of stable iodine tablets may have not been sufficiently considered in emergency planning.

As a side activity, also the consequences with respect to drinking water were investigated. The following findings can be reported:

- In case of a nuclear accident, surface water can be contaminated by large amounts of radionuclides and may not be suitable for drinking water production.
- Advanced treatment processes as ion-exchange and reversed osmosis do remove radionuclides effectively, but these processes are not common practice.
- Soil passage (dune infiltration, river bank filtration, groundwater) is a safe barrier for I-131 and Cs-137.
- If surface water is the main direct source for drinking water production, emergency plans for drinkable water supply are needed.
- Drinking water utilities in the European countries are required by the EU Drinking Water Directive to provide emergency drinking water in case of a major accident, including nuclear accidents.

Two important open questions remain unanswered:

- A long lasting, low release rate, atmospheric discharge would probably require a very large capacity in air-sampling monitoring to achieve good measurements; have these special and non-standard monitoring devices ever been considered in the emergency plans and then put into operation?
- Is the evacuation of the population during the passage of the plume nearby always preferable against sheltering?

This second question refers to the fact that a choice is to be made quickly, either to evacuate or to order sheltering, during the passage of a plume. Typically, evacuation is recommended in the current emergency plans; however, it appears that in many cases sheltering is preferable because of the uncertainties in the ST and weather conditions, which may cause an erroneous choice of the evacuation routes. In this regard, the recently amended EU Safety Directive (article 8a(a), [9]) asks that safety arrangements are to be made in order to avoid “early radioactive releases that would require off-site emergency measures but with insufficient time to implement them.” In principle, then, evacuation can still be implemented, but there should always be enough time to implement it safely.

Concerning contaminated foodstuff and feedstuff, in the framework of PREPARE an inter-comparison among 10 countries was made. An open discussion on the findings was launched, involving also EC, FAO, OECD-NEA, IAEA, HERCA and ICRP.

As far as improvements introduced in European DSSs, these were concentrated by PREPARE on ARGOS and RODOS. In particular, in the field of atmospheric transport, five different particle size classes were introduced in the dispersion models. They comprise small particles, around one micron in diameter, up to heavy particles, about 60 micron in diameter. As a boundary condition, the gravitational settling velocity for particles larger than 10 microns will dominate the deposition process. These 5 different particle sizes were introduced in the dispersion models of the two decision support systems, and a corresponding deposition scheme developed and implemented. Additionally, two approaches of ST estimation, based on measurements and atmospheric dispersion models, were developed:

- A simple and fast technique that uses very simple dispersion modelling and gamma dose rate measurements in the near vicinity of a NPP.
- A more advanced technique that uses either detailed dispersion modelling and gamma dose rate or other measurements also at larger distance from the NPP.

The numerical methods are based on the source-receptor matrix (SRM), a linear regression technique. Prior information about the ST, the so-called first guess ST, is needed to regularize the linear regression and to assure uniqueness of the solution. The issue of unknown nuclide composition of the release has been handled enlarging the SRM and measurement vector using the ratios of release rates calculated through the first guess ST. The parameters of the regression include error variances of the first guess ST, error variances of observations, of simulated results and of nuclide ratios used in the enlarged minimization problem. Both tools, however, need more robust implementation and some activity on this has also been planned within the FASTNET project. Testing of the inversion algorithms has been performed using artificially generated 'measurements' obtained for the meteorological and geographical conditions of the well-known ETEX experiment. Results of the test are reported in Fig.2.

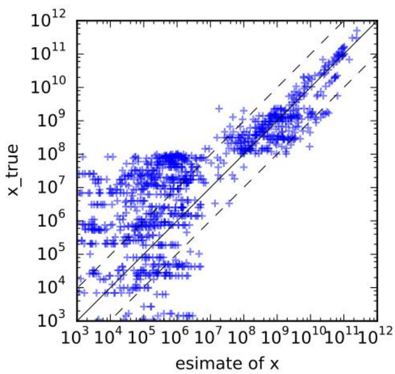


FIG. 2. Comparison of "true" and "estimated" ETEX source strength.

Concerning the transport of radionuclides in water, the aim was to extend the Hydrological Dispersion Module of RODOS (RODOS-HDM), incorporating in it also the MOIRA DSS. MOIRA is a DSS created for the management of fresh water ecosystems contaminated by radionuclides and heavy metals [10].

An important issue for PREPARE, which is also of interest for FASTNET, is training and exercising. Two exercise sessions were organised, one focused on radiological assessment, supported by the use of JRODOS, and the other consisting of a more extensive table-top exercise with a simulated accident scenario. In addition, two table-top exercises were organized, dealing with a transport accident and with monitoring of a large scale cross-border contamination respectively.

In summary, it can be said that the PREPARE project was successful in many aspects, as it dealt with some of the main gaps in Emergency Preparedness and Response, which were found from the Fukushima experience. It created much more awareness in the strength and robustness on one side, and in the weak points on the other, of current emergency plans, as far as long-lasting releases are concerned. It also paved the way to the development of inverse methods to estimate STs from measurements and their implementation in the main European DSSs.

3. The FASTNET Project

The **FASTNET (Fast Nuclear Emergency Tools)** project started in October 2015 and is expected to end in September 2019. It gathers 20 partners, coordinated by IRSN, together with IAEA. The aims of FASTNET are centred on three major pillars:

– the development of a reference SA scenarios database [11], inclusive of time-dependent, isotopic STs, created using best-estimate SA codes (ASTEC [12], MAAP [13] and MELCOR [14]);
– the extension of existing methods (3D3P) and fast-running codes (PERSAN and RASTEP) to predict STs to all current nuclear power plant technologies deployed in Europe (PWR, BWR, VVER, CANDU, EPR, including a generic model for SFPs) and their further development;
– the dissemination of best-practices on the use of the methods and tools developed within the project to estimate STs in real-time and during conditions typical of real emergencies.

During a real case of emergency, the time to perform ST calculations is undoubtedly very limited, as it is limited the amount and precision of the available information and plant data from the affected NPP. Therefore, best-estimate codes cannot be used to address the needs of a nuclear emergency; fast-running codes need instead to be developed and, most importantly, experience in their efficient and effective use must be built and spread out. As evidenced by the outcomes of the OECD-NEA FASTRUN project [15], which actually prompted and urged the creation of the FASTNET project, the knowledge and experience in Europe in the use of fast-running tools for ST prediction is, actually speaking, at best, very limited. Surely not enough to serve the purpose of getting a shared and common vision of the accident progression and its consequences in terms of releases to the atmosphere. To address this major challenge, it was suggested within FASTNET to improve and disseminate a methodology for the diagnosis of plant status and for the prognosis of accident sequence, the 3D/3P (developed by IRSN), as well as two European fast-running tools, the French code PERSAN (developed by IRSN) and the Swedish code RASTEP (developed by LR), by extending their capabilities to all European NPP technologies, and to start to disseminate best practices in their use.

The 3D/3P, acronym for Triple Diagnosis/Triple Prognosis, is an analytical method which enables providing a simplified quick diagnosis of plant condition and the prognosis of a postulated future situation, evaluating the status and integrity of the typical three barriers of the defence-in-depth: fuel and cladding, primary circuit, and reactor containment. The method consists in filling a matrix composed of simple assessment judgements on the safety functions associated to the three barriers, namely: subcriticality and primary liquid inventory for the integrity of the first barrier, heat removal from primary system and from pump seals for the second barrier, and heat removal from the containment for the third barrier. The judgements are made both for the current situation and for a prognosis for the future. This method has been developed by IRSN for PWRs and within FASTNET it has been extended to other reactor types, including BWR, current VVERs, CANDU and SFPs. For CANDU technology the method has been renamed 4D/4P, given the peculiar nature of the safety barriers of these reactors, which include also the calandria vessel in series with the containment.

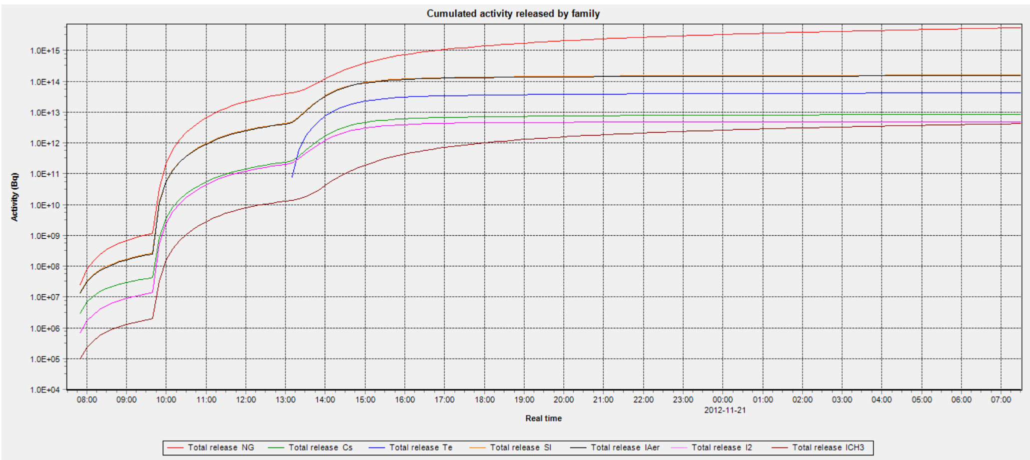


FIG. 3. Example of time-dependent ST obtained with PERSAN.

PERSAN is a deterministic code able to evaluate time-dependent STs in a time-frame of a few minutes, provided that some realistic assumptions, such as either the timing of core dewatering or the specific leak-rates to the environment are given as input (see Fig. 3). The calculation methods are based on the solution of balance equations for radioisotopes defined over several volumes, in which the NPP is subdivided, schematized as lumped parameters, the imposed leak-rates serving either as boundary conditions to the atmosphere or as a link between the lumped parameters. Removal of radioisotopes from the volumes is based on conservation laws and on physical mechanisms like dry or wet (i.e. through the activation of spray systems) deposition, leak, filtering, radioactive decay, etc. All physical pathways to the atmosphere are considered, as a combination of parallel or series of flows. Chemical phenomena are modelled by very simple correlations. Initial core inventories are provided. Like for 3D/3P, PERSAN had been developed by IRSN for PWRs, and within FASTNET it has been extended to other reactor types, including BWR, VVER, CANDU and SFPs.

RASTEP [16] is a probabilistic code which can select, among a set of several pre-calculated STs for a given reactor type, the ST with the highest probability of occurrence for given plant conditions. The code is made of three main components: a Graphical User Interface (GUI, see Fig. 4), a Bayesian Belief Network (BBN) for each reactor type, and a database of pre-calculated accident sequences with related STs. These can be either obtained from the outcomes of PSA-2 studies of a given, real plant, or calculated ad-hoc with SA codes using generic plant schemes. Aim of the BBN is to connect partially available plant status data to one or more possible and compatible end states, represented by given STs, like in fault-tree analyses. Introducing some plant conditions, some branches of the BBN are either isolated and further excluded from the analysis, or kept "open" and navigated up to an end state (or states) with associated conditional probability or likelihood of occurrence. The more information on the plant status is provided by the user, the higher is the probability of reaching a good ST for the situation under scrutiny. The approach is clearly based on the assumptions of having a sufficiently large database of sequences to cover the most of the accidental situations and a robust BBN to map correctly the database. The GUI is used to provide information to the code by answering a limited set (some tens) of simple questions on the safety barriers and safety safeguards. Their availability or unavailability determines which boughs of the tree are to be selected and, in case of more than one final plant status, which probabilities can be associated to the different results. RASTEP has been initially developed by LR for SSM for BWR and within FASTNET its use has been expanded to include also PWR, VVER and CANDU. The extension consisted in the creation of dedicated BBNs for each reactor type as well as the ad-hoc database of reference STs.

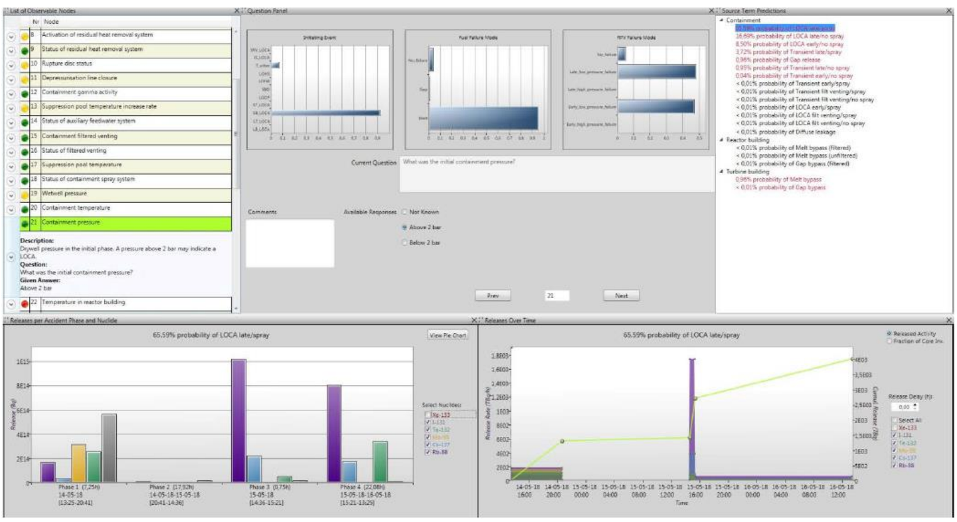


FIG. 4. RASTEP Graphical User Interface.

To fill the RASTEP databases, another goal of FASTNET was the development of a comprehensive database of reference STs, calculated with best-estimate codes like ASTEC, MAAP and MELCOR, for as many sequences as possible: a huge effort indeed for the partners because were not the STs already available, they had to be evaluated from scratch. The reference STs had obviously to be given in terms of time-dependent isotopic releases, which was really challenging for partners using SA codes, which only deal with chemical classes. The database is also a set of reference scenarios against which it is possible to test and validate the behaviour of the fast-running codes. That implies that they should contain not only data for the temporal progression of the accident sequences and time-dependent STs, but also many thermal-hydraulic time-dependent data on the primary circuit, as well as physical data on the containment status. Accordingly, given the precious nature of the information contained in the FASTNET database, it was decided to transfer it to the IEC of IAEA for the purposes of maintenance in time, beyond the lifetime of FASTNET, and for further future expansion. IAEA CPs would be allowed, in principle, to search the database on-demand, in case of specific needs (including training), or during real emergencies, which might be similar to a scenario already available in the database. The development of the FASTNET database proved to be a very ambitious, time-consuming, and highly demanding task. Two problems are still pending concerning the sequences currently available: the number of sequences itself, and the quality control of their data. As of today, the database comprises about 120 sequences, and a few more are planned to be added before the end of the project. Despite this big number, the database is far from being complete and exhaustive, and many more years of work should be needed to reach a level, which can be considered more or less satisfactory for EP&R needs. While that on one side confirms the need of having fast-running codes, on the other cannot be seen as an excuse to limit the use of best-estimate codes for general EP&R needs. Concerning the quality control of the provided STs, this was obviously beyond the scope and the limited resources of FASTNET, and therefore the FASTNET database is to be considered for now "as is". A further and final aim of the FASTNET database was to provide data for the preparation of another extremely important product of the project, namely training in the form of emergency exercises.

To address the above-mentioned problem of training in EP&R, the FASTNET project envisaged a twofold approach. On one side a one-week training on 3D/3P, PERSAN and RASTEP has been organized, during which the participants (not limited to project partners but open also to interested stakeholders forming the s.c. End Users Group) were trained on the practical use of the tools. On the other side, two exercises were organized. The first one consisted in the calculation of STs for four sequences (a PWR, a BWR, a CANDU and a VVER) using both PERSAN and RASTEP. The aim of this exercise was to strengthen the user capabilities but it was also useful to acquire better confidence in the codes; therefore, time pressure was not given to participants and a full month was allocated to them to provide results. The outcomes of this exercise were manifold: further improvements of both PERSAN and RASTEP, and better consciousness of partners in their current knowledge and capabilities in using correctly fast-running tools. After this first exercise, targeted to ST estimation, a second was organized in the form of a real-time table-top exercise, during which partners had to calculate a ST for a given accidental situation and then provide, with their own atmospheric dispersion tools, estimates of the radiological consequences to the population.

This exercise was very challenging, because of the time constraints, however proved to be enormously useful in getting more experience in the real-time use of the FASTNET products.

In the objective the STs can be used in different atmospheric dispersion codes and also shared among different emergency responders, they are to be standardized in terms of format of data and files. To address this requirement, a few years ago, IAEA developed the IRIX (International Radiological Information Exchange Format) [17], which is an xml-based information exchange format designed to facilitate web-based exchange of relevant emergency information and data among organisations that respond to nuclear and radiological incidents and emergencies, and in particular the exchange of emergency information among national authorities that have responsibilities assigned under the Convention on the Early Notification of a Nuclear Accident. An important by-product of the FASTNET project has been the adoption in the fast-running tools, as well as in the exporting options of the database for the IAEA, of the IRIX format.

While still under development (the current version is 1.0), the IRIX format, allows to decouple from an IT point of view ST calculation tools from atmospheric dispersion codes. Within FASTNET, IRIX output capabilities were introduced for both PERSAN, RASTEP and the database, while input capabilities have been introduced in JRODOS. During the second exercise, some partners were therefore able to use PERSAN or RASTEP in conjunction with JRODOS thanks to the IRIX input/output functionalities (see Fig. 5). This is of course to be maintained for the future, since new and improved versions of the IRIX standard may be foreseen in the incoming years.

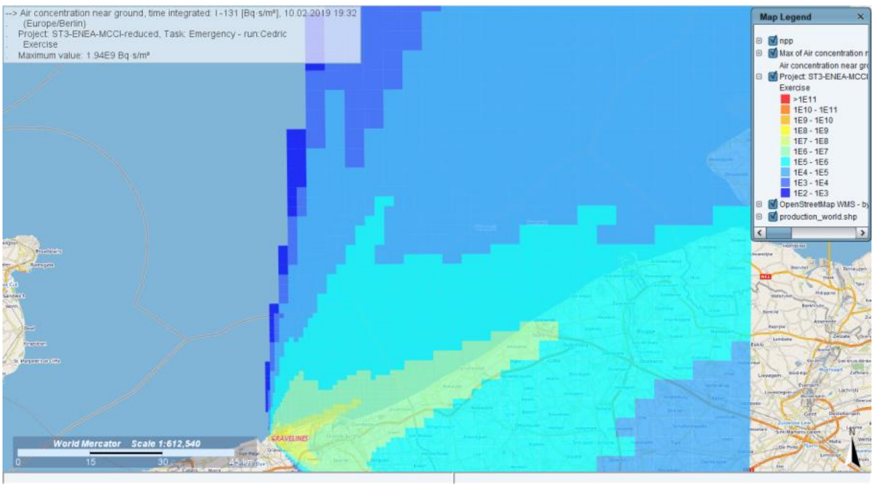


FIG. 5. Example of JRODOS dispersion calculation results from Exercise 2.

While still ongoing, it can already be stated that FASTNET has been a successful first opportunity to establish a link and a dialogue between the communities of scientists devoted to the best-estimate evaluation of STs, and that of those scientists using STs in their daily work of protecting people and the environment.

Moreover, the development and the sharing of fast-running tools for STs and of associated, common, working methodologies is to be welcomed, as a first step in filling the most important gap in EP&R, that of the fast, timely and accurate predictions of releases to the atmosphere.

4. Dissemination and Education and Training

Both projects dedicated resources and efforts to dissemination and education and training. These are important aspects of European projects, because they are the most effective way of sharing the knowledge gains, and to preserve them in time beyond the lifespan of the projects themselves. Both projects gathered end-user communities, which could directly benefit from the scientific results; these communities were invited to events and were given the opportunity to test the products of the research and to give feedback. Both projects organized trainings, workshops, seminars, schools and international conferences. For example, FASTNET organized a one week-long training on PERSAN and RASTEP in Paris in 2018. A one week-long, international School on EP&R took place in Bologna in January 2019, with lectures also on PERSAN and RASTEP. The School was attended by several PhD students. Two international workshops have taken place within FASTNET, and a final one is going to be organized as a joint Side-Event by France, Sweden and Italy at the next IAEA General Conference. IAEA has been invited to the various FASTNET scientific events and some partners presented the project and its achievements at various meetings in Europe (f.i. NKS workshops) and USA (US-NRC CSARP meetings). An important presentation was given on FASTNET at the 2017 ECURIE Competent Authorities meeting. PREPARE organized a dissemination workshop in Bratislava in 2016, and several presentations were given at the NERIS workshop in 2015 in Milan. It also organized two basic courses on emergency management and rehabilitation. The first course (2014) focused on the early to intermediate phases after a nuclear/radiological accident, whereas the second course (2015) was related to the long term management of contaminated territories. Finally, a training course on the PREPARE Analytical Platform has been organized in Trnava in 2015. The aspect of financing Master degree theses, PhD or post-doc positions was considered by both projects, however it resulted very difficult to find candidates, given also the fact that (a) these three figures (Masters, PhDs and post-docs) can, by law, be dealt with only by universities and not by research entities, and that (b) the costs to fund these positions vary enormously from country to country. These two drawbacks and limitations should be better considered by the European Commission, for examples with special funding rules, if in the future more efforts are to be devoted to direct higher education actions.

5. Conclusions

Both PREPARE and FASTNET projects tried to close some gaps identified in EP&R capabilities in Europe; they both tried to implement in practice some lessons learned from the Fukushima Daiichi accident. Both gave complementary contributions to solve fundamental problems of EP&R. Much has been done, as detailed in the previous paragraphs, but much still needs to be achieved.

For example, one major challenge, which was anticipated and actually experienced in the FASTNET project, is related to the dialogue between the severe accident management scientific community and the emergency management one. These two communities have the same final aim of protecting people through increase in safety; they, however, speak different languages and are used to tackle similar problems but with different perspectives. FASTNET was the first European project on EP&R in which these two communities were gathered together and were asked to cooperate; there was then an additional operational aim within FASTNET: to find a common language, harmonize the practices, use the tools the most relevant and easy to use for them, and facilitate their appropriation of the common methodology proposed. This first dialogue attempt was certainly fruitful, but not complete. In the future it is then highly recommended, that opportunity is given to strengthen the developed links between these two communities, for example by organizing (1) operational trainings based on every technology and the feedback from the exercises organized within FASTNET; (2) a new series of exercises, targeting the protection of population and having a higher level of reality (full-scale formats, scenarios based on every technology, etc.). It must in fact be recognized that much more training is needed on the fast-running tools developed, especially in their use in emergency centres. As evidenced for the PREPARE project and as already introduced before about the outcome of the FASTRUN OECD/NEA project, training in EP&R is really an absolute need for Europe. The development of fast-running codes is per se not enough if potential emergency responders are not properly trained in dealing with such tools and the phenomena they describe. Further development of the reference SA database is also necessary. The complementarity between the results of PREPARE and FASTNET should be taken to the level of productive interaction, for example by using STs derived from fast-running tools to aid the procedures of ST estimate from dose-rate measurements (inverse methods). This kind of interaction was also suggested by the NERIS gap analysis (Area 1, Key Topic 3) [18,19] where it is explicitly stated "Link of inverse with in-plant (e.g. FASTNET project) ST estimation methodologies". Another important improvement for the future could be the development of uncertainty propagation using STs evaluated by fast-running tools and ensemble data from numerical weather predictions.

References

[1] PREPARE https://cordis.europa.eu/project/rcn/106584/factsheet/en

[2] PREPARE Final Report, PREPARE(WP8)-(16)-03, 2016.

[3] FASTNET https://cordis.europa.eu/project/rcn/198668/factsheet/en

[4] I. Devol-Brown, F. Di Dedda, J.E. Dyve, O. Isnard, F. Rocchi, E. Urbonavicius, D. Vola, FASTNET: FAST Nuclear Emergency Tools, ERMSAR 2017, Warsaw, Poland.

[5] R. Mustonen, C. Rojas-Palma, W. Raskob, EURATOM FP7 Projects on Management of Nuclear and Radiological Emergencies, FISA 2013 Proceedings, Spain, 2014, 261-268.

[6] S. Hoe, P. McGinnity, T. Charnock, F. Gering, L. H. Schou Jacobsen, J. Havskov Sørensen, P. Astrup, ARGOS Decision Support System for Emergency Management. In Proceedings of the Argentine Radiation Protection Society, 2009.

[7] A. Wengert et al., JRodos: An off-site emergency management system for nuclear accidents, KIT, 2017.

[8] https://www.iaea.org/publications/10508/ines-the-international-nuclear-and-radiological-event-scale-users-manual

[9] Council Directive 2014/87/EURATOM of 8 July 2014.

[10] L. Monte, L. Håkanson, D. Hofman, J. E. Brittain, E. Gallego, A. Jiménez, G. Angeli, MOIRA-Plus, A Decision Support System for the management of complex fresh water ecosystems contaminated by radionuclides and heavy metals, Computers & Geosciences, 35, issue 5, May 2009, 880-896.
[11] F. Mascari et al., FASTNET Scenarios Database Development and Status, submitted to ERMSAR 2019, Prague, Czech Republic.
[12] P. Chatelard, S. Belon, L. Bosland, L. Carénini, O. Coindreau, F. Cousin, C. Marchetto, H. Nowack, L. Piar, L. Chailan, Main modelling features of ASTEC V2.1 major version, Annals of Nuclear Energy, Vol. 93, July 2016, 83-93.
[13] Fauske & Associates, LLC "Transmittal document for MAAP5 code revision MAAP 5.02", FAI/13-0801, 2013.
[14] MELCOR Computer Code Manuals, Vol.1: Primer and Users' Guide, SAND 2015-6691 R; Vol. 2: Reference Manual, SAND 2015-6692 R; Vol. 3: MELCOR Assessment Problems, SAND 2015-6693 R; Sandia National Laboratories, USA, 2015.
[15] Benchmarking of Fast-running Software Tools Used to Model Releases during Nuclear Accidents, Report NEA/CSNI/R(2015)19.
[16] F. Di Dedda, A. Olsson, J. Klug, A. Riber Marklund, RASTEP – A novel tool for nuclear accident diagnosis and source term prediction based on PSA and Bayesian Belief Networks, LR Nuclear Technical Digest 1, 2018, 14-26.
[17] International Radiological Information Exchange (IRIX) Format, Version 1.0, IAEA Incident and Emergency Centre, 2013.
[18] Research needs identified from the NERIS gap analysis, October 2018.
[19] Strategic Research Agenda of the NERIS Platform, September 2017.

SESSION 3

ADVANCED NUCLEAR SYSTEMS AND FUEL CYCLES

SUMMARY SESSION 3 – ADVANCED NUCLEAR SYSTEMS AND FUEL CYCLES

Chair: Franck CARRE (CEA, FR), Scientific Director at Nuclear Energy Division
Co-chair: Roger GARBIL (DG RTD, EC), Project and Policy Officer
Expert Rapporteur: Teodora RETEGAN (CHALMERS Univ., SE)

Objectives

The sessions have been starting by the introduction of Dr. Franck CARRE (CEA, FR), which presented the international background on advanced nuclear systems and fuel cycles as well as the state of the art on new technologies and reactor types in Europe.

After the brief introduction, the following presentations were held, and the interest and participation of the audience have been very high.

Presentations and Q&A

The numerous projects and results presented during this session, of both finished and on-going project have clearly showed the success of the EURATOM funding program. The presentations were grouped on topics and technologies and were largely discussed during the session. The main brief highlights are given below.

Noël CAMARCAT (EDF, FR)
Keynote: SNETP-ESNII and EERA-JPNM Research and Innovation

The presentation highlights the state of the art of ESNII II and presents the projects which have been evolving in the last 10 years, highlighting a few of very important changes which recently took place in Europe. There are three remaining systems technologies which are studied in Europe: LBE or lead cooled reactors, Sodium (SFR) and Gas (GFR) which were to reach the demonstrator stage. Notably, in early 2019, Na-cooled reactors are no longer deemed a priority, France is focusing on current fleet and current technologies and other means of closing their fuel cycle with help of current technologies. MYRRHA demonstrator is currently the leading technology for a Generation IV project in Europe, besides the other above presented which are not as advanced. Each system is presented along with the concept and the teams involved and the nuclear fuel state of the art in the world is also presented, the conclusion being that there are only about three types used in the world, with a high priority on developing MOX. The main conclusion is that long term research is needed in all areas presented.

Some questions were raised on the fact that for the SMRs (Small Modular Reactors), MOX might not be the appropriate fuel. The answer is that it might depend on the neutron spectrum and costs associated with this. Also, when it comes on the future of ESNII, the next 20 years are envisioned as a continuation of the current mission, that MYRRHA will be a leading technology in Europe, ALFRED will have a good launch and hopefully the SMRs will develop. With respect to molten salts reactors, the answer is that it needs to have enough support so maybe it will work.

ESNII is supporting projects for big concerns lead by industry and is not for academic purpose.

Konstantin MIKITIUK (PSI, CH)
R&D in support to safety assessment, design and licensing of ESNII/Gen-IV (ESFR-SMART, ESNII+, SESAME, SAMOFAR, VINCO, FP7- ALLIANCE, FP7-SILER, FP7-SARGEN-IV, FP7-JASMIN)

The presentation has been a review of Euratom projects on design, safety assessment, R&D and licensing for ESNII/GEN IV fast neutron systems. Selected results were presented for each project and the main conclusion emerging from this have been that the project touched 5 different designs or concepts (SFR, LFR, ADS, GFR and MSR) with regards to Design, R&D, Safety and Licensing.

One of the emerging questions have been which technology (among all presented) had the best projects, where the answer was that definitely the Na fast reactor was probably the most advanced concept, partially due to ASTRID program and the numerous projects and very efficient collaboration between partners. Another question was related to the significant break-thought's achieved during these projects, where the answer was that every project per se was a significant break-through and a lot of added value was achieved due to high amount of information produced.

Stéphane BOURG (CEA, FR)
From fuel to fuel: Dissolution, Partitioning and fuel manufacturing (GENIORS, FP7-SACSESS, FP7-ASGARD)

The projects presented were the clear link between the reactor concept and sustainability, presenting how recycling of nuclear fuel contributes to better efficiency of a such fuel cycle. Also, the concepts presented in these projects are going further, to the long-term waste management (where transmutation is better for e.g. Americium). Also, the life-cycle analysis for the fuel cycle is presented, with illustration and highlights from every project. Some very advanced separation for transmutation systems were presented as well as the next step on fuel fabrication and further reprocessing of that fuel. International collaboration, among other with DOE and JAERI is highlighted and a book on Roadmap to the P&T is mentioned. Also, a very successful program for teaching and training is described.

On the question on which of the presented systems have the highest potential for industrialization, the answer has been that is the Am extraction, but it needs a process which can be tested, maybe AMSEL. Also, the management of Cm has been raised, since there is a potential waste generator. The issues has been solved by the fact that Am can be separated from Am, thus no further waste is generated.

Hamid AIT ABDERRAHIM (SCK-CEN, BE)
Partitioning and Transmutation, contribution of MYRRHA to an EU strategy for HLW management (MYRTE, FP7-MARISA, FP7-MAXSIMA, FP7-SEARCH, FP7-MAX, FP7-FREYA, FP7-ARCAS)

The projects were presented highlighting their achievements, where the obvious link between the projects was MYRRHA reactor, the hybrid and ADS. Also, the introduction on why MYRRHA is needed and how it can work is thoroughly explained. The concept of the MYRRHA international consortium is presented as well as all the steps towards scaling-up and industrialization of the concept.

There have been questions about the roadmap of MYRRHA, when will it be commissioned and the answer has been that the first assessment part will be ready by 2026, the start build by 2027 and most probably the finish will be about 2035.

The fuel and matrix to be used for the future MYRRHA system have been another issue, where the answer is that there are a series of different concepts for fuel, from advanced MOX to a mis of actinides, but more research is needed. A new facility for fuel production is under research and partly taking shape.

Lorenzo MALERBA (CIEMAT, ES)
Innovative Gen-IV Fuels and Materials, EERA-JPNM, Fission and Fusion (GEMMA, INSPYRE, M4F, TRANSAT, FP7-MATISSE, FP7-PELGRIMM)

The projects are presented and highlights of each of them as well. There is a clear conexion between fission and fusion, where some common issues can be studied through the same program, like structural materials and fuel materials, which was the subject of six of these presented projects. Four of the projects were under the Euratom umbrella while the other two are of the research portfolio of EERA JPNM. A project M4F is the project closing the gap between fission and fusion and between the two communities as well as the TRANSAT project is an important link between the fission and fusion, namely tritium issues and inventory.

One question was raised with regards to the distance existing between the fission and fusion, which was acknowledged that it is indeed considerable, mostly due to working groups dynamics and very poor communication, even in smaller institutions. Another question was directed to the instrumentation issue, what type and how. The answer was that instrumentation was so far of low concern and not considered so far in any of the current projects.

Grzegorz WROCHNA (NCBJ, PL)
Nuclear Cogeneration with High Temperature Reactors (GEMINI-PLUS, FP7-NC2I-R)

The two presented project are directed to nuclear cogeneration with high temperature reactors, where the state of the art is well advanced in the world, but despite this, not widely used. The obvious question is why, and the two projects were aiming at answering these questions. The cogeneration is studied from different point of view, for example the similarity of certain part with classic steam turbine, steam generation for chemical plants, district heating, potential hydrogen production and the clear delimitation between the reactor and the user of non-nuclear part. There is a lot of work for licensing acceptability, enhancing the attractiveness for industry and political and societal support.

A question has been raised with regards to safety of the reactor, that it should be an independent matter and supervised by the regulators. The answer is yes, it is true, and it is a complicated issue due to the proximity to the user (chemical plant or other). It will however be presented as a synergic concept, nevertheless.

Enrique GONZALEZ (CIEMAT, ES)
Nuclear data activities (FP7-CHANDA, FP7-ERINDA, FP7-EUFRAT)

The presented projects are the missing link between the research and the deployment and function of nuclear reactors, namely nuclear data cycle. It is an European effort and the data generated are of global use, thus making the field extremely well structured with well synchronized collaborations between the key expert institutions. It also needs efficient transnational access to experimental facilities needed for the activities, where coordination is needed (JRC action EUFRAT). Different laboratories and facilities were presented, and the fields of application highlighted (as e.g. the GELINA research infrastructure, with high-resolution of neutron time-of-flight facility, the RADMET radionuclide metrology laboratories, etc).

The general discussion followed is in full agreement that this type of project and the generated data are of paramount importance and is the base of the on-going operations.

General discussions

Ms Anastasia Lazykina, Consultant, International Atomic Energy Agency (IAEA), Department of Nuclear Energy, Vienna Austria and representative of the new generation of experts and young professionals, was initiating the discussion through three general questions:

Q: *What are the impediments for Europe to be on the forefront of nuclear initiative, as it used to be before?*

A: The general conclusion is that nobody thinks that we are not innovative in EU. We are and many other countries and research centers are using innovative concepts and solutions emerged from Europe. Also, by comparison, Europe has several good examples to show. It is however a very clear upward trend in economy, which makes that workforce is very mobile, thus many experts or engineers tend to move around in many other industries, unrelated to nuclear. It is currently difficult to find and keep new personnel, despite availability of funding. It might be apparent that the innovation is slow in Europe, on the other hand the view on safety in the nuclear field is very high here, making some more advanced concepts to seem delayed for implementation. However, for good reasons. Also, it might also be the fact that despite the need for clean and cheap energy, there is very little encouragement for new-buit in Europe. Also, there is a point that for example in US there are private actors which are investing in this field, while in Europe there is no such initiative.

Q: *How would you see the balance at international level to accelerate this?*

A: The general agreement was that there is collaboration and there is initiative, however some partners consider that at a certain level of development of a technology there is a need of clear IPR and there might be the need of secrecy for certain steps. However, it is unanimously agreed that we do need to collaborate, especially on safety issues. Also, the involvement of the regulators (which are very different in different countries of Europe) need to be involved at early stages and they need to have a very high knowledge base in order to efficiently help.

Q: *Nuclear fission and nuclear fusion seem to be competing. How would it be possible that nuclear fission gets enough funds as well for the future?*

A: The general conclusion to this question is that there is no real competition between fission and fusion (for future generation technology) despite the popular concept. It is a very clear difference in how the technologies are supposed to be funded and deployed: everyone gives money through EURATOM, however the consensus is that everyone is investing in fusion but nuclear fission is a national issue. Each country is making own decision on the level of participation or involvement or deployment in their own country.

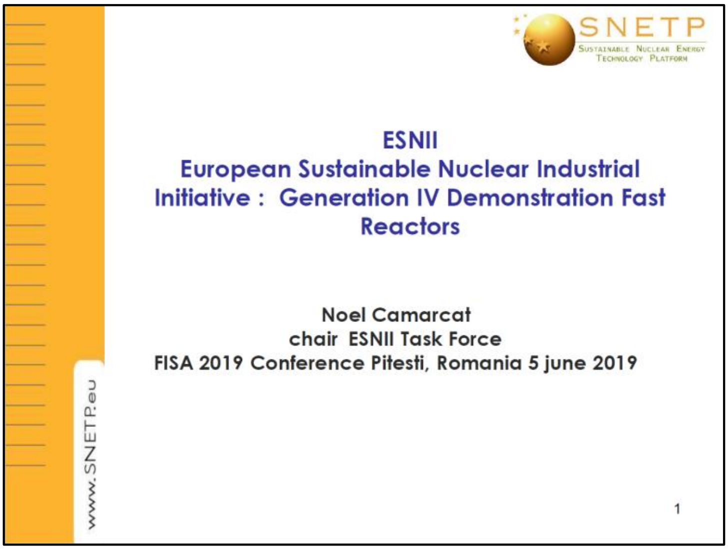
We do have however a very large diversity of new concepts of fission reactors which are or have been researched.

NOËL CAMARCAT

FISA 2019 – EURADWASTE '19

Presentation of Mr Noël Camarcat (EDF, FR), Chair ESNII Task Force

SNETP-ESNII and EERA-JPNM Research and Innovation



ESNII Scope (3 Gen IV technologies, 4 projects)

SNETP
Sustainable Nuclear Energy Technology Platform

- ESNII is an Instrument for coordinating the implementation of the SNETP pillar on **sustainability of nuclear fission, based on Gen IV fast reactors with closed fuel cycle.**
- 3 main technologies are studied in Europe with the objective to reach the demonstrator stage : Lead-Bismuth and pure Lead, Sodium (SFR), Gas (GFR)
- ESNII Projects and System maturity have evolved in the last 10 years:
  - From 2010 to 2018 : Sodium SFR's were the leading technology and demonstration project in Europe
  - Early 2019 : announcement by the French government that sodium demonstration projects are no longer needed for the short and medium term as industrial perspectives for sodium reactors are postponed. The new French strategy for closing the fuel cycle has been detailed by P. Stohr the CEA Director at the recent ICAPP conference (may 2019)
  - The Myrrha demonstrator (SCK-CEN) is now the leading generation IV project in Europe. It uses lead-bismuth as coolant.
  - Pure lead, Sodium and Gas technologies are also studied in Europe. Their demonstrator stage is not as advanced as MYRRHA

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3

MYRRHA

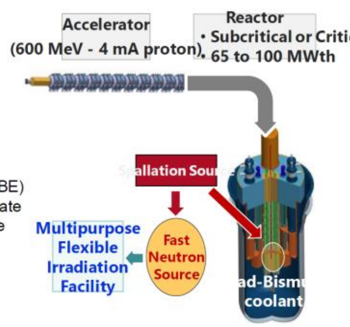
SNETP
Sustainable Nuclear Energy Technology Platform

Construction of an Accelerator-Driven System (ADS) consisting of

A 600 MeV – 2,5 to 4,0 mA proton linear accelerator

A spallation target/source

A lead-Bismuth Eutectic (LBE) cooled reactor able to operate in subcritical & critical mode



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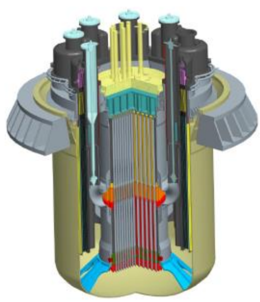
4

ALFRED (pure) Lead Technology

SNETP
Sustainable Nuclear Energy Technology Platform

To provide Europe with:

- a **Demonstrator** devoted to the **Development** of the **LFR** technology
- a **Reactor** addressing the concerns on **Safety** and **Sustainability** of **Nuclear Energy**
- a **Research Infrastructure** to build and maintain the **European Leadership** on scientific excellence



Lead Fast Reactor -120 MWe

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The ALFRED Project in a nutshell

SNETP Sustainable Nuclear Energy Technology Platform

ALFRED Construction is fostered by the FALCON Consortium (Ansaldo Nucleare, ENEA and Romanian R&D Institute ICN)

ALFRED has strategic and socio-economic relevance at EU, National and local level

Mioveni nuclear platform in Romania is the candidate site for ALFRED

ALFRED construction is foreseen to be completed by 2030

ALFRED will be supported through a distributed Research Infrastructure covering 9 scientific objectives

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ALFRED Project: EU support

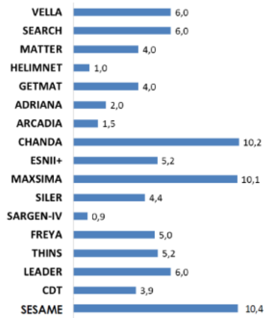
SNETP Sustainable Nuclear Energy Technology Platform

EURATOM FP5, FP6, FP7

- more than **25 R&D indirect** actions and **10 R&D direct** actions (on LFR)
- about **90 M€** between direct and indirect actions (45 M€ in-kind)

Through FALCON:

- **3 full-members + MoAs** with associated partners
- Membership and associated partners support based on **in-kind contributions**



Ref: *Euratom Contribution to the Generation IV International Forum Systems in the period 2005-2014 and future outlook*, EUR 28391 EN, Publications Office of the European Union, Luxembourg, 2017, ISBN 978-92-79-349328-7, doi:10.2760/256957, JRC104056

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ALFRED Project: the Romanian support

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2014: Government memorandum for the **construction of ALFRED in Romania**

2015: ALFRED included in **Smart Specialization Strategy** of South-Muntenia

2017: ALFRED included in National strategy and Plan for RDI 2015-2020 as a **European project of national interest**

2017: ALFRED in the **National Research Infrastructure Roadmap**

2018: ALFRED **in National Energy and Climate Plans (NECPs): draft submitted to EC**

funds		
Past initiatives[1]	R&D	50 M€
Short term availability	R&D[2] RDI Project[3] Minor Project[4]	7,5 M€ up to 2 M€ 20 M€
Planned for the future	Facilities ALFRED	45 M€ 200 M€

[1] Including Italian contribution
[2] Covering a period of 5 years
[3] Currently under proposal
[4] Waiting for award

2018: Call for support Infrastructure projects: proposal submitted as World relevant experimental facilities at Mioveni site (**20 M€**)

2019: RDI project for Generation IV reactor ALFRED (**2 M€** expected in 2 years)

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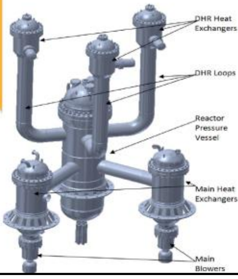
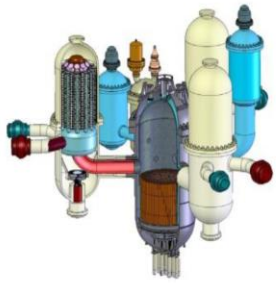
ALLEGRO Project : Gas Fast Reactor (GFR)

Allegro design : 75 MWth demonstrator





Full scale 2400 MWth Reactor

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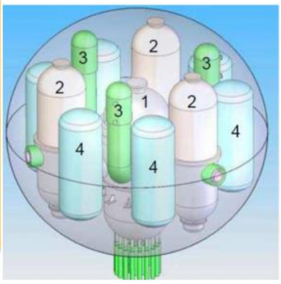
Gas Fast Reactor Technology

(B. Hattala, Vüje Esnii april 2018)



The whole primary system is enclosed in a small pressure guard containment.

1 - vessel

2 - three Main Heat Exchangers

3 - three Decay Heat Removal loops

4 - six gas reservoirs

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ALLEGRO

- New Strategy announced by the 4 partners V4G4 in central Europe in early 2015
- Reduce ALLEGRO power from 75 MWth and optimize the core configuration
- To increase main blowers inertia (Management of LOCA and SBO), gas turbine coupled to the primary blowers
- UO2 pellet or MOX Pellet in AIM1 Stainless Steel cladding and develop in phase 2 a ceramic design

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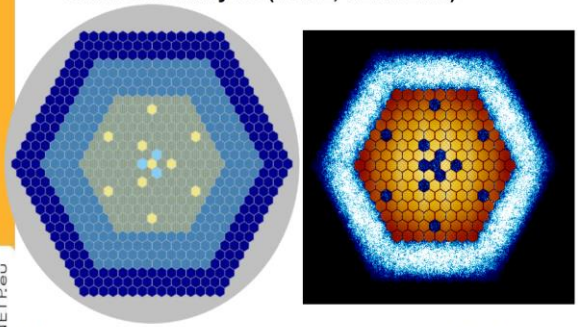
UOX ALLEGRO

UOX core analysis (VUJE, SERPENT)



UOX Core, 2 rings more + axial enlarge, 3 exp. positions only, 75 MW_{th} and 37.5 MW_{th}.
With UOX core, 560°C outlet temperature. With Ceramic (U,Pu)C – SiC fuel, outlet temperature can reach 850°C

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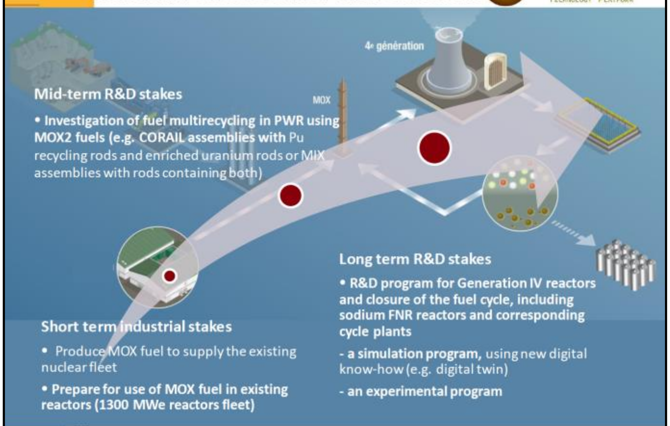
FRENCH STRATEGIC INDUSTRIAL AND R&D ROADMAP FOR CLOSURE OF THE FUEL CYCLE



Mid-term R&D stakes

- **Investigation of fuel multirecycling in PWR using MOX2 fuels (e.g. CORAIL assemblies with** Pu recycling rods and enriched uranium rods or MIX assemblies with rods containing both)

Long term R&D stakes

- **R&D program for Generation IV reactors and closure of the fuel cycle, including sodium FNR reactors and corresponding cycle plants**
- **a simulation program,** using new digital know-how (e.g. digital twin)
- **an experimental program**

Short term industrial stakes

- Produce MOX fuel to supply the existing nuclear fleet
- **Prepare for use of MOX fuel in existing reactors (1300 MWe reactors fleet)**

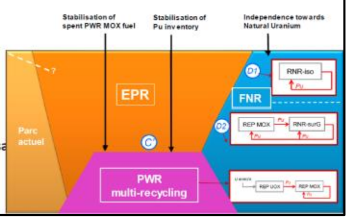
R&D perspectives to investigate Multi-recycling in PWR's

Multi-recycling in PWR's research program

- R&D program under development by CEA and industrial players (EdF, Framatome and ORANO)
- Global vision of a possible industrial cycle to be constructed
- Potential industrial deployment of multi-recycling in PWR to be assessed through scenario studies (continuum from mono-cycling to complete fuel cycling with FNR)

Scientific and technical challenges to be addressed

- Neutronics and core design
- Adaptation of PWR reactors
- Radioprotection
- Adaptation of fuel cycle plants (La Hague and Mélox)
- Impacts on deep geological disposa



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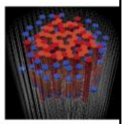
R&D perspectives for advanced reactors

SNETP Sustainable Nuclear Energy Technology Platform

Gen-IV reactors and cycle : focusing on SFR while assessing other FNR concepts

- Consolidation of technical knowledge on sodium FNRs and further R&D development of 4th advanced generation technologies
  - Development of SFR concept and qualification of industrial components
  - Sketch studies and R&D assessment of other FNR technologies
- Fuel reprocessing: advanced processes and technologies for recycling
  - MOX manufacturing for FNR
  - Multi-recycling process for U and Pu (CORAIL/MIX)
  - Assessment of multi-recycling (on Pu flow and Minor Actinides inventory to deep geological disposal)



SMR : a new paradigm for nuclear plants and for the energy system ?

- **Modular design and realization** with pre-manufacturing in industrial facilities for minimizing on-site construction and optimizing costs.
- **Access to nuclear power**, e.g. for countries with limited needs (networks, additional power capacity or financial constraints)
- **Flexibility** in an energy mix with renewable energy production
- **Non electronuclear and hybrid concepts**

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Results of ESNII and orientations for the future (1/2)

SNETP Sustainable Nuclear Energy Technology Platform

- ESNII promotes 4 main projects and technologies but does not distribute money
- Its important accomplishments are evaluation of projects and systems maturity, coordination of research and of European research teams and technical advice to emerging projects
- In the technical field it has achieved some harmonisation of fast reactor fuel R&D in Europe. Other Generation IV Fora and comunities are more diverse : in Asia (3 fuels), in Russia (3 fuels), GIF treats all types of fuels
- For the next 20-25 years, Europe through ESNII will use one R&D fuel for its leading projects : **mixed uranium and plutonium oxide, (pelletized) MOX** with an offshoot for Allegro phase 1 and phase 2.
- This important technical choice must be consolidated in the detailed research programs and projected in the future for the next 10 years.

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Results of ESNII and orientations for the future (2/2)

SNETP Sustainable Nuclear Energy Technology Platform

- For the 2019-2023 Euratom R&D program, MOX Fuel research is funded through the INSPYRE and ESFR SMART projects with EC money and Member States money. Some Member States and **industrial partners are also funding Fast Spectrum MOX fuel research at a higher level**
- MYRRHA has moved ahead significantly and is now the **first European Fast Spectrum** demonstrator project in the ESNII community
- Worldwide, Sodium technology is becoming industrial (5,57 TWh produced in 2017 by BN800, Russia). Large power reactors will remain the mainstream of the technology, but other ideas can emerge in Europe (Sodium SMR's,…….)
- Allegro and ALFRED are particular since they have access to european structural funds
- But the 4 projects will need public support and acceptance from the research community at large. They **will need long term research** in parallel with project basic and detailed design. Construction will depend on funding

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KONSTANTIN MIKITIUK

REVIEW OF EURATOM PROJECTS ON DESIGN, SAFETY ASSESSMENT, R&D AND LICENSING FOR ESNII/GEN-IV FAST NEUTRON SYSTEMS

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Abstract. Nine Euratom projects started since late 2011 in support of the infrastructure and R&D of the seven fast reactor systems are briefly presented in the paper in terms of key objectives, results and recommendations.

1. Introduction

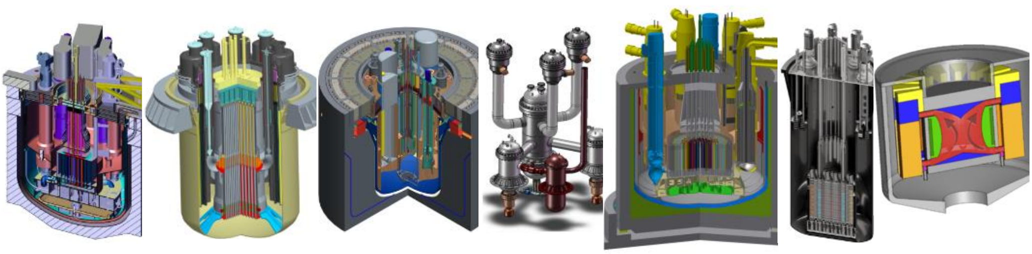
In November 2010 Sustainable Nuclear Energy Technology Platform (SNETP) set up a Task Force comprising research organisations and industrial partners to develop the European Sustainable Nuclear Industrial Initiative (ESNII) addressing the need for demonstration of Generation-IV Fast Neutron Reactor technologies, together with the supporting research infrastructures, fuel facilities and research and development (R&D) work.

SNETP has prioritised the different Generation-IV systems and is proposing to develop the following projects: the sodium-cooled fast neutron reactor technology ASTRID as the reference solution; the lead-cooled fast reactor ALFRED supported by a lead-bismuth irradiation facility project MYRRHA as a first alternative; the gas-cooled fast reactor ALLEGRO as a second alternative. The Molten Salt Fast Reactor (MSFR) is considered as a very attractive long-term option.

The EU framework programs have supported the R&D activities on these five systems as well as on two other Generation-IV technologies: European Sodium Fast Reactor (ESFR) and Swedish Advanced Lead Reactor (SEALER). All seven fast neutron systems are presented at FIG. 1.

The paper briefly presents in terms of key objectives, results and recommendations nine Euratom projects started since late 2011 in support of the infrastructure and R&D of the seven fast reactor systems presented above (see FIG. 1).

Table 1 presents the list of the project acronyms, participants and coordinators. **Error! Reference source not found.** presents domains and categories of advanced systems, while **Error! Reference source not found.** gives more details about the R&D areas. Finally, FIG. 3 presents the budgets and time spans of the presented projects.



a) b) c) d) e) f) g)

FIG. 1. Seven fast neutron systems supported by the considered EU project: ASTRID (a); ALFRED (b); MYRRHA (c); ALLEGRO (d); ESFR (e); SEALER (f); MSFR (g)

Table 1. Participants and coordinators of the considered EU projects.

	AT	BE						CH		CZ		DE								ES					EU	FI	FR	
	VCE	BEL V	SCK-CEN	TRACTEBEL	UNI DE LOUVAIN	UNI GENT	INST VON KARMAN	PSI	ASCOMP	UJV REZ	CV REZ	GRS	KIT	HZDR	RWTH AACHEN	MAURER	BOA GROUP	UNI STUTTGART	TU MUENCHEN	UPM	UPV	IDOM	EAI	CIEMAT	JRC	VTT	IRSN	CEA
SARGEN_IV		x	x					x		x		x	x	x	x					x					x	x	C	x
SILER	x		x													x	x					x	x		x			x
ALLIANCE										x	x				x												x	x
JASMIN												x	x					x						x	x		C	
ESNII PLUS			x	x				x		x		x	x	x						x	x		x	x	x			C
VINCO										x	x																	x
SESAME			x		x	x	x	x	x		x	x	x	x					x								x	x
SAMOFAR								x					x												x		x	x
ESFR-SMART								C				x	x	x						x				x	x		x	x

	FR						HU			IT												LT	LV	NL		PL	RO		SE		SK	SI	UK				
	AREVA/FRAMATOME	EDF	NUVIA	LGI	UNI DE LORRAINE	CNRS	MTA KFKI	MTA EK	BME	ENEA	ANSALDO	FIP	SINTEC	NUMERIA	SRS	CIRTEN	RSE	SAPIENZA	CRS4	UNIMORE	UNI PISA	LEI	IPUL	NRG	TU DELFT	NCBJ	ICN	RATEN	KTH	CHALMERS	VUJE	IJS	AFW/WOOD	UNI MANCH	UNI CAMBRIDGE	NNL	SUM
SARGEN_IV	x	x					x			x	x											x									x		x	x			22
SILER	x		x							C	x	x	x	x	x								x						x								18
ALLIANCE								C	x																	x					x						9
JASMIN	x	x								x																											9
ESNII PLUS	x	x	x	x				x		x	x		x	x		x	x	x					x	x	x	x	x	x	x	x	x		x			x	36
VINCO								x																		C					x						6
SESAME				x						C								x	x	x	x			x	x				x			x					23
SAMOFAR	x	x				x										x									C												10
ESFR-SMART	x	x		x	x					x													x							x			x		x	x	19

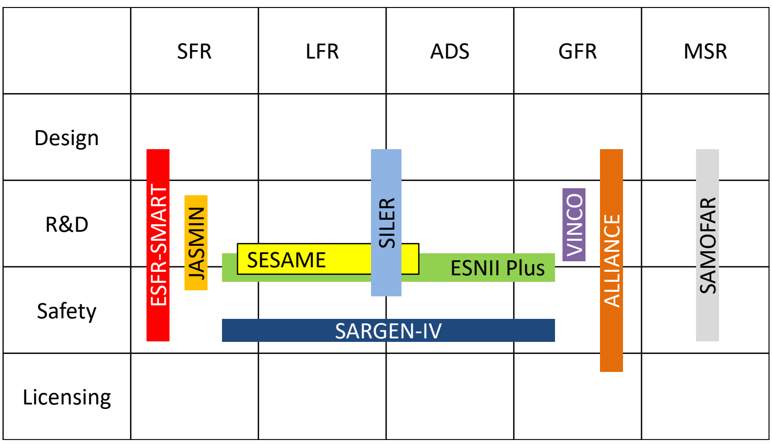


FIG. 2. Domains and advanced systems of interests of the considered EU project.

Table 2. R&D areas of the considered EU project.

	TH & CFD	Neutronics	Fuel	Seismic	Multiphysics
SILER				x	
ALLIANCE	x	x			
JASMIN	x	x			x
ESNII Plus	x	x	x	x	x
VINCO	x				
SESAME	x				
SAMOFAR	x	x			x
ESFR-SMART	x	x	x		x

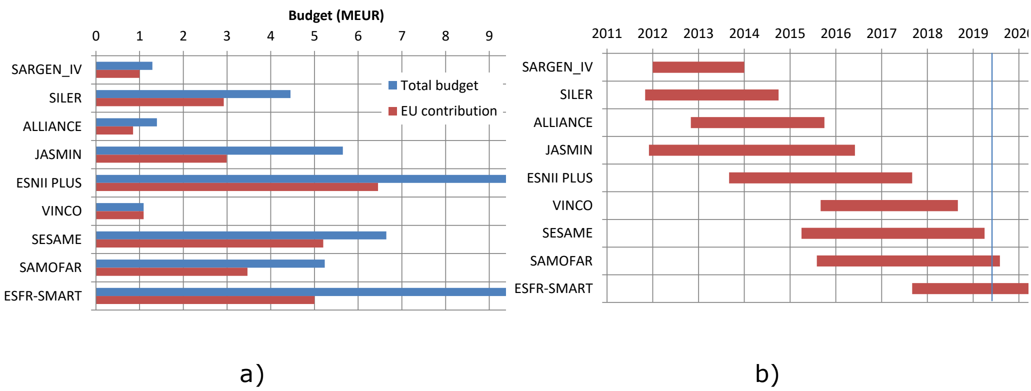


FIG. 3. Budget (a) and time span (b) of the considered EU project.

2. SARGEN_IV: Proposal for a harmonized European methodology for the safety assessment of innovative reactors with fast neutron spectrum planned to be built in Europe

2.1 Key objectives

The safety of innovative reactors needs to be addressed in a comprehensive and robust manner while demonstrating a level of safety acceptable for the general public. Having a European consensus on the methodology and safety criteria that will be used to assess innovative reactors becomes of prime importance with an impact on any further design activities.

With the goal of preparing the future assessment of these advanced reactor concepts, the European project SARGEN_IV gathered safety experts from 22 partners from 12 EU Member States: recognized European Technical Safety Organizations (TSOs), the Joint Research Centre of the EC, Designers and Vendors as well as from Research Institutes and Universities in order to:

- identify the critical safety features of the selected Generation-IV concepts, relying on the outcomes from existing projects from the 7th Framework Programme (FP7),
- develop and provide a tentative commonly agreed methodology for the safety assessment, relying on the outcomes of the investigations carried out within international organizations (such as IAEA, WENRA, OECD/NEA), on national practices presently in use and on practices proposed within other European Framework Programs projects,
- identify open issues in the safety area, mainly addressing and focusing on assessment relevant ones, detect and underline new fields for R&D in the safety area (addressing methodological, theoretical and experimental issues, as well) in order to provide a roadmap and preliminary deployment plan for the fast reactor safety-related R&D.

The project partners were convinced that fostering the harmonization of the various European safety approaches would have been very beneficial and would have streamlined Euratom contribution to Generation-IV International Forum in the safety field. It was also meant to improve relationship between safety assessment needs and research programmes efficiency in the development of new concepts.

A particular attention was addressed to take into account the lessons learned from the Fukushima-Daiichi nuclear accident that will impact significantly the research and development needed for demonstration of Generation-IV reactor safety.

2.2. Key results

WP2: identification of the major safety features

In the project, a review on the safety issues was performed for each ESNII concept: SFR, LFR, GFR and MYRRAH FASTEF. A list of the initiating events was also identified and categorised according to their occurrence frequency.

A conclusive deliverable [**Error! Reference source not found.**] gathered the main results for each of the three concepts and a focus was performed to identify phenomena able to affect more than one concept, i.e.

- for the coolant: sensitivity to impurities, coolant activity, retention of fissions products, toxicity, opacity,
- for the structural materials: corrosion, erosion, irradiation behaviour,
- issues in relation with fast reactors : sensitivity to blockage, power density, core compaction, reactivity void effects, handling hazards, failure of the core supporting structures,

- management of the three safety functions (reactivity control, decay heat removal, containment),
- capability to cool the core by natural circulation
- sensitivity to external events (flooding, earthquake),
- considerations on the Fukushima-Daiichi TEPCO events (extreme flooding, extreme earthquake, total loss of electric supply, accident management)
- categorisation of initiating event organised by challenges: challenge to clad integrity, challenge to reactor boundary, containment challenge

This work gave a useful guidance for the identification and the prioritisation of the R&D needs respective to the identified safety issues. In particular it was pointed out that efforts have to be performed to define the severe accident for each concept and to develop requirements for the containment in order to practically eliminate large and early releases.

Develop and provide a tentative commonly agreed methodology for the safety assessment

In the scope of the development and the licensing of the above mentioned ESNII prototypes in Europe, it appeared crucial to develop a tentative commonly agreed assessment methodology able to be applied to each of the four above mentioned concepts and based on the safety issues identified.

Firstly, it was performed a review of the safety methodologies proposed by international organizations and those issued from national practices and European consortia. This included:

- INPRO methodology proposed by IAEA and ISAM proposed by the GIF
- Experience feedback for safety assessment from national TSOs approaches (from Finland , France, Belgium, Spain, Germany)
- Safety approach proposed for European projects related to gas cooled, lead cooled and sodium cooled fast reactors
- Safety approach proposed by international organisations (IAEA, WENRA, NEA/MDEP)

2.3. Recommendations for the future

On the basis of the reviews mentioned above that led to numerous recommendations, the SARGEN_IV consortium prepared a proposal [**Error! Reference source not found.**] for the safety assessment practices targeting the Generation-IV prototypes to be built in Europe.

Some of the most important recommendations are as follows:

- The safety assessment should cover the whole nuclear plant (reactor, fresh and spent fuel storage);
- The entire life on the plant (from commissioning to decommissioning) should be addressed;
- Safety assessment should integrate the security/safeguards aspects;
- The consequences of chemical releases have to be taken into account in the design;

- The defence-in-depth (DiD) principle remains a fundamental principle for the safety of innovative reactors and an important topic is to define accurately the level 4 of DiD for each concept;
- Accident sequences that could lead to large or early releases have to be practically eliminated.

3. SILER: Seismic-Initiated Events Risk Mitigation in Lead-cooled Reactors

SILER is a Collaborative Project, partially funded by the European Commission in the 7th Framework Programme, aimed at studying the risk associated to seismic-initiated events in Generation-IV Heavy Liquid Metal reactors, and developing adequate protection measures. The attention of SILER is focused on the evaluation of the effects of earthquakes, with particular regards to beyond-design seismic events, and to the identification of mitigation strategies, acting both on structures and components design. Special efforts are devoted to the development of seismic isolation devices and related interface components.

Two reference designs, at the state of development available at the beginning of the project and coming from the 6th Framework Programme, have been considered: ELSY (European Lead Fast Reactor) for the Lead Fast Reactors (LFR), and MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications) for the Accelerator-Driven Systems (ADS).

3.1. Key objectives

One of the main goals of SILER was the development and experimental qualification of seismic isolators for lead-cooled reactors (but applicable to any other nuclear plant).

3.2. Key results

Two device typologies have been considered: High Damping Rubber Bearings (HDRBs) and Lead Rubber Bearings (LRBs). Both isolators have been designed (for ELSY and MYRRHA, respectively), manufactured and tested in different sizes, even to the full scale, which results to be greater than one meter, due to the huge mass of the reactor buildings. In particular, a prototype has been subjected to three-directional dynamic tests (at the Department of Structural Engineering of the San Diego University) under the real service loads up to failure, which occurred well beyond the design conditions.

The adoption of base isolation provides a great reduction of the acceleration and inertial forces in the structure, providing very important benefits to the components and the structure itself, but introduces significant relative displacements between the isolated and conventionally founded parts of the plant. Thus, a seismic gap of suitable width shall surround the entire isolated "island". Of course, it shall be adequately protected from bad weather (included floods) and other possible damages, and kept free during the whole life of the structure, in order to allow for relative movements in case of earthquake. Moreover, all the service networks and pipelines crossing the seismic gap shall be provided with suitable expansion joints. In SILER, both devices have been developed and successfully tested in full scale and in real operational conditions, even beyond the design limit (see FIG. 4, FIG. 5 and FIG. 6). It is worth noting that, due the severe seismic condition assumed in the design of nuclear plants, the relative displacement can reach 0.7-0.8 m in beyond-design situations.

In SILER, several critical components of ELSY and MYRRHA (like vessel, pumps, proton beam, etc.) have been numerically modelled and carefully analysed under severe seismic conditions, taking also into account the effects of the sloshing of the liquid lead and the soil-structure interaction.

Particular attention has been devoted to the cost-benefit analysis related to the adoption of seismic isolation, which resulted to be positive. Moreover, according to the indication of EC, the main results of the project have been disseminated through the organization of seminars, courses, workshops and the implementation of a web site (http://www.siler.eu).

3.3. Recommendations for the future

In particular, guidelines for design, manufacturing, qualification, installation and maintenance of seismic isolators for nuclear plants have been delivered. This document is particularly important, due to the lack of international rules regarding the seismic isolation of nuclear plants (at the time of the project at least).

More information about the SILER Project main results can be founded in references [**Error! Reference source not found.**, **Error! Reference source not found.**].

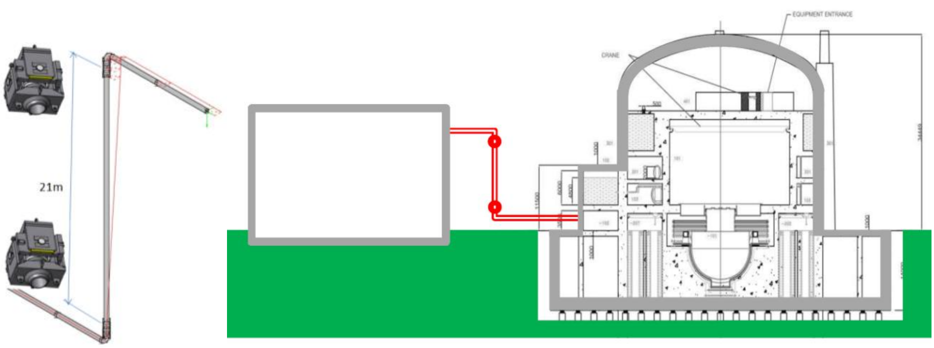


FIG. 4. Sketch of the pipeline connecting the seismically isolated reactor building of ELSY and the turbine, provided with two flexible joints to adjust the relative displacements.

FIG. 5. Full scale pipeline expansion joint during seismic tests at the ELSA laboratory of the JRC of Ispra.

FIG. 6. Three-directional dynamic test performed at SRMD on a full-scale (1350 mm diameter) HDRB. After partial damage, occurred close to 300% shear strain (almost three times the design value), the isolator was successfully subjected to a full cycle under the design load at the design conditions.

4. ALLIANCE: Preparation of ALLEGRO – Implementing Advanced Nuclear Fuel Cycle in Central Europe

Gas cooled fast reactors (GFR) represent one of the three European candidate fast reactor types, the two other being sodium cooled fast reactor (SFR) and lead cooled fast reactor (LFR). Technically, GFR is a realistic and promising complementary option thanks to its specific advantages connected with high temperatures. The GFR concept was mainly based on studies performed in France in the late 90-ies and was further developed within the EU 5th and 6th Framework Programmes respectively. It also included the development and safety assessment of a small experimental plant called at the time ETDR (Experimental Technology Demonstration Reactor). This plant was regarded as a necessary stepping-stone to a full-sized GFR in order to test the high-temperature fuel required by the latter. The concept was further analysed and refined by the EU FP7 GoFastR project: the ETDR has been renamed ALLEGRO (see **Error! Reference source not found.**) and a number of design changes were introduced, e.g. the power was raised from the original 50 MWth to 75 MWth. ALLEGRO would function not only as a demonstration reactor hosting GFR technological experiments, but also as a test pad of using the high temperature coolant of the reactor in a heat exchanger for generating process heat for industrial applications and a research facility which, thanks to the fast neutron spectrum, makes it attractive for fuel and material development and testing of some special devices or other research works.

The three respective nuclear research institutes of the Central European region (ÚJV, Řež, Czech Republic, MTA EK, Budapest, Hungary, and VÚJE, a.s., Trnava, Slovakia) agreed in 2010 to start a joint project aiming at the preparation of the basic documents in order to form the basis for a later decision on the construction and operation of the ALLEGRO gas cooled fast reactor in one of the countries. CEA, France, supports this effort by various means, especially by transferring the documents of the earlier design efforts (under appropriate Non-Disclosure Agreements) to the project participants. NCBJ, Świerk, Poland, joined the project in 2012, i.e. ALLEGRO is supported in all the four Visegrad-4 (V4) countries. The project ALLIANCE has been launched in 2012 by the nine member organizations (see

Table 1).

4.1. Key objective

The aim of the project ALLIANCE was to continue the elaboration of basic documents needed for high level decisions and licencing of ALLEGRO. The ALLIANCE project [**Error! Reference source not found.**, **Error! Reference source not found.**, **Error! Reference source not found.**] focused on the preparatory phase for developing the ALLEGRO gas cooled fast reactor demonstrator. The main nuclear parameters (like power density, burnup etc.) would be similar to those of the planned 2400 MWth power GFR. The core built up from the initial fuel type will be replaced by a core of ceramic fuel for the second half of ALLEGRO operation. Safety analysis performed within the previous EU GoFastR project covered the consequences of most initiating events and most of the ALLEGRO relevant issues were analysed. Safety principles of the ALLEGRO reactor will be based on the WENRA requirements and the study of GIF [**Error! Reference source not found.**], added to the actual national safety rules of the hosting country. Moreover, in formulating siting requirements and requirements concerning the design to reduce the impact of external hazards, the results of the European stress tests following the Fukushima events were applied. Nevertheless the current design of ALLEGRO does not fully satisfy these requirements. One of the main reasons is that the safety margin of the stainless steel cladded mixed oxide (MOX) fuel chosen for the initial ALLEGRO core of 75 MWth power is rather low and cannot provide the necessary protection against core melting after a Fukushima-type accident (though the margin is acceptably large concerning Design Basis Accidents, i.e. accidents which may occur with a very low but not negligible probability).

4.2. Key results

A new strategy for developing the ALLEGRO reactor was prepared, and accepted by the Partners in 2015. The main components of this strategy are: (a) to reduce ALLEGRO power from 75 MWth to 10 MWth and to find the optimum core configuration (switch from MOX to UO2); (b) to optimize nitrogen injection (launch time, duration) and the backup pressure in guard containment; (c) to increase main blowers inertia to avoid short term peak temperature for the loss of coolant accident + blackout case and/or to develop a design with a gas turbine in the secondary side coupled to the primary blowers (this is the solution also advised for GFR).

A new systematic Roadmap was prepared to cover all design, safety and experimental aspects of ALLEGRO development.

The ALLEGRO consortium is represented by V4G4 Centre for Excellence, a legal entity registered in Slovakia. The main goal of V4G4 is to establish R&D facilities to investigate fuel development issues, helium technology related problems, issues related to structural materials and to construct a non-nuclear 1:1 mock-up of ALLEGRO.

The Realisation Phase of the "ALLEGRO Project" will be started whenever the objectives of the Preparatory Phase are reached, approximately in 2025. The realisation phase will include the preparation of the basic design, licensing (site permit, construction license, etc.), construction, operation and decommissioning of the ALLEGRO reactor.

As ALLEGRO will be a result of a joint effort on the regional (or even European) level, an international consortium should be formed to finance the entire project. The desired and potentially possible governance structure applicable in the Realisation Phase was discussed within the ALLEGRO project almost from the very beginning. It was found that the existing EU structures (e.g. "ERIC – European Research Infrastructure Consortium") are not applicable as they are appropriate only for infrastructures used for basic research and they practically exclude the joint financing by governments and the industry. In case of nuclear development infrastructures the contribution from both sides is absolutely needed. The different governance models were discussed in detail in the project deliverables.

4.3. Recommendations for the future

The Design and Safety Roadmap was elaborated which consists of about 80 tasks in order to elaborate a new conceptual design with satisfactory safety features by 2025. A pre-conceptual design will be prepared and discussed on the European level by 2020. The Roadmap clearly fixes the achievements needed for the pre-conceptual design and the conceptual design by tasks. Leading and participating member organisations are declared for each task. The manpower needed and eventual investment costs are also estimated per task. The first version of the Research-Development-Qualification Roadmap is also prepared. It consists of those experimental tasks which are necessary to complete in order to ensure a sound basis for the design.

One of the main challenges of the ALLEGRO design is associated with final resolution of the emergency decay heat removal from the core. This problem is a key issue for feasibility and safety acceptance of the GFR. To continue with development of the ALLEGRO GFR demonstrator design, complex set of tools is necessary, allowing reliable simulation of both operation and safety relevant events, up to severe accidents.

5. JASMIN: Joint Advanced Severe accidents Modelling and Integration for Na-cooled fast neutron reactors

The project was launched in 2011 in support of both the ESNII roadmap and the Deployment Strategy of SNETP for the enhancement of Sodium-cooled Fast neutron Reactors (SFR) safety through the development of new capabilities to simulate innovative reactor designs [**Error! Reference source not found.**]. The project was focussed on the primary phase of SFR core disruptive accidents, considered as the overture to larger scale core destruction. However, the code integrated features, that represents a good opportunity for simulating in a single code what is generally simulated in separate codes, were also considered through the in-containment source term modelling.

5.1. Key objectives

The project aimed at enhancing the current capability of analysis of severe accidents in SFRs by developing a new European simulation code, ASTEC-Na from the existing ASTEC platform developed by IRSN and GRS for LWRs. It was motivated by the need for new simulation tools with updated models, extended modelling scope and flexible platforms in replacement of the current available codes for SFR safety studies developed in the 80’s.

Then, it was intended to provide ASTEC-Na with:

- Improved physical models (accounting for recent LWR and SFR research);
- A modern architecture and a high flexibility to ease its coupling with other tools and the accounting for innovative reactor designs;
- Extended capabilities to evaluate the consequences of unprotected accidents on materials relocation and fission products and aerosols behaviour, once released.

Most important activities consisted in the development of new models and in their verification upon experimental data and through code benchmarks.

5.2. Key results

ASTEC-Na model development

The three ASTEC-Na modules that focussed the modelling efforts were CESAR, ICARE-SFR and CPA*. The final in-vessel and ex-vessel modelling capabilities listing the models that were developed are displayed in FIG. 7. The ICARE module development particularly benefited from accurate fuel thermomechanical and fission gas models issued from SCANAIR (a simulation tool developed in IRSN for reactivity-initiated accident (RIA) in LWRs) for describing the pin behaviour during accidental transients which makes it very promising for assessing future SFR designs [**Error! Reference source not found.**]. A highly flexible point-kinetics model was also implemented with the possibility to use time-dependent reactivity coefficient provided by neutron physics codes [**Error! Reference source not found.**]. The in-containment source term modelling in CPA* was focused on the Na-particle generation from pool fires and their chemical ageing. Other source term issue (like fission product scrubbing in Na pools, etc.) was left out. Late incorporation of the FEUMIX module, simulating sodium pool & spray combustion, greatly enhance the code capabilities but still source term modelling in ASTEC-Na need to be extended to the missing models.

ASTEC-Na model verification and validation

The CESAR thermos-hydraulic module, where the models developed most, pointed out good performances (i.e. boiling onset) for the single phase where the quality of ASTEC-Na results were found similar to what exhibited by more mature codes. For two-phase thermal-hydraulics, the pressure drop calculated by the 5-equations model was generally too large and some deviations were found in the calculation of the two-phase front radial propagation inherent to the 2D axial-symmetric model. In ICARE, though the RIA model showed its capability to reproduce the dynamics of the physical phenomena (i.e. internal pressure built-up, gap closure, clad straining, etc.), some deviations from data trends during PCMI (Pellet-Clad-Mechanical-Interaction) (i.e. axial fuel expansion, clad deformation) were observed that could prevent from an adequate molten fuel pressurization and clad failure calculation. The mechanistically based approach for fission gas simulation (requiring data not necessary available within SFR conditions) prevent from a conclusive RIA model validation.

The point kinetics model was found reliable to calculate the power evolution in a pool-type SFR during transients till the flux shape is not excessively perturbed. The validity of the model up to hexcan failure that depend on the material relocation and thus on the transient might be overcome thanks to the ability of ASTEC-Na to use time-dependent reactivity coefficients but will require performing a lot of iterations (to have adequate coefficients for a time period, the state of the core during this time period has to be known).

The verification of in-containment source term modelling in CPA* was not fully conclusive as key phenomena remained described by heavily parametrized models. However, the deviations from data trends, in airborne concentration of aerosols and their chemical compositions, highlighted a need for further review and extension of the implemented models. Code benchmarking could not help as ASTEC-Na was at the forefront of in-containment source term modeling.

5.3. Recommendations for the future

The ASTEC-Na tool, though offering great opportunities was still far from being mature at the end of the project The SWOT analysis performed in analysing the code weaknesses and threats allowed to point out the priorities in future development of the missing models and, beyond ASTEC-Na, to make some key recommendations for any forthcoming development and validation of a safety analytical tool:

- Extend the validation of prototypic MOx fuel thermos-mechanical and fission gas models to the high temperature domain covered in SFR transients;
- Perform further analytical work on in-containment and in-vessel fission product behaviour to alleviate the scarcity of experimental data in the open literature;

As for ASTEC-Na, the development of an interface with a fuel irradiation and a neutron physics codes to minimize as far as possible the user work was strongly recommended and the continuation of the sensitivity studies on the RIA model key parameter warmly advised.

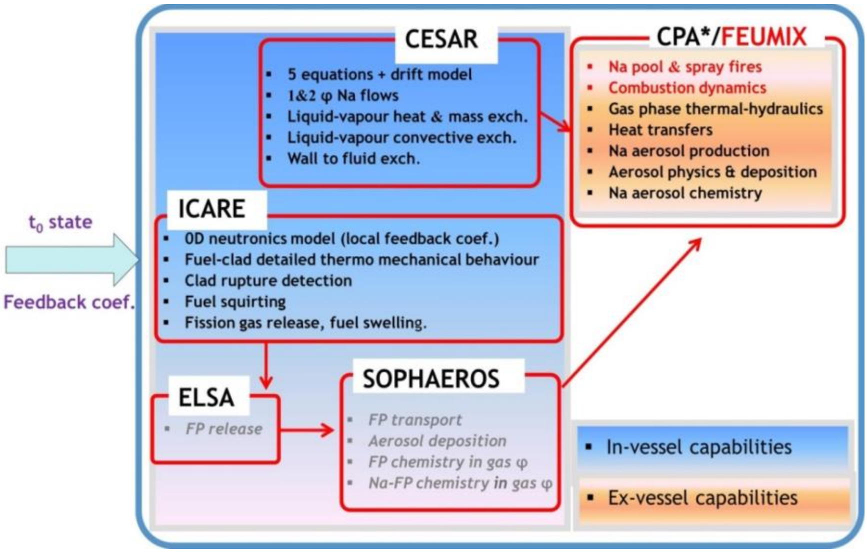


FIG. 7. ASTEC-Na calculation scheme and modelling capabilities.

6. ESNII Plus: Preparing ESNII for HORIZON 2020

6.1. Key objective

The aim of this four-year cross-cutting project was to develop a broad strategic approach to advanced fission systems in Europe in support of the European Sustainable Industrial Initiative (ESNII) within the SET-Plan. The project involved private and public stakeholders, including industry, research and academic communities (see

Table 1).

6.2. Key results

Organisation of ESNII to capitalise on opportunities in Horizon 2020 and beyond

Ways to coordinate the work of ESNII between EC and the national R&D programmes were analysed. Central to this coordination is establishing the funding mechanisms that can be used to gain maximum leverage for funding obtained from the EC's Framework Programmes and for the Member State programmes.

Future financial and legal models for ESNII

Three challenges were identified:

- Funding ESNII and SNETP. This is of the order of k€ per partner, obtained from member organisations combined with Euratom grants (FP7 and Horizon 2020).
- Funding the R&D carried out on ESNII systems. This is of the order of M€, and is obtained from Member State national programmes and Euratom grants (Horizon 2020).
- Funding design and construction of the ESNII demonstrators. This is of the order of G€ and must be obtained from Member State national programmes.

Strategic Roadmapping

The aim of the task was to facilitate and define areas for joint programming between national actors, Member States and the EU. This task hence served as a first benchmarking exercise of joint proposals with variable common objectives and partnerships for Horizon 2020 EU programmes. A Workshop was organised and the following topics were identified: MOX Fuel, Austenitic and Ferritic-Martensitic Materials, In-core Instrumentation and RCC-MRX code.

Support to facilities development

Functional specifications of the R&D facilities related to SFR, LFR and GFR were identified with particular attention to the specificities and the unresolved issues. The availability and capabilities of irradiation infrastructure in Europe were reviewed in order to support the material and fuel development.

Siting and licensing requirements for the new generation of fast reactors

The specific requirements for licensing Generation-IV reactors are currently not explicitly included in the existing legal framework at the national level, even if there are plans or intentions to modify the legislations to improve the nuclear safety and to address the new reactor generation development. In order to survey the requirements and recommendations that may be used in the process of licensing Generation-IV systems, by capturing and integrating the international experience, an overview on the existing standards and recommendations (WENRA, GIF, EUR, CORDEL, MDEP and IAEA documents), with the consideration of Fukushima lessons learnt was performed. The conclusions drawn could be found in [**Error! Reference source not found.**].

Prospective analysis of supply chain

Fast reactors, selected at European level as next generation Nuclear Energy Systems, pose undeniable challenges from a technological point of view. In order to support the foreseen deployment strategy, a survey of the existing supply chain has been thoroughly carried out in terms of its capabilities and potentialities with respect to Fast Reactors needs. The identified challenges of the EU nuclear industry with respect to Fast Reactors can be found in [**Error! Reference source not found.**].

Potential of small modular fast reactors

Although the "economy of scale" was privileged as soon as nuclear was considered for civil applications, exceptions are represented by installations in remote regions or by specific technologies fitting in the small to medium power range. Opportunities offered by SMR based on fast reactors technologies were analysed, with a particular focus on LFR and the EU context. Two main potential applications were identified: installations of SMRs having power in the order of 100 MWe for the compensation of renewables, or multi-units sites with a total power in the range 350-700 MWe for the replacement of fossil fuel power plants and the supply of process heat to industrial clusters.

Potential of cogeneration fast reactors

The additional opportunity of fast reactors designed for cogeneration applications (i.e., production of electricity and process heat) is made possible by the elevated temperatures characterizing the primary circuit of such reactors, compared to traditional LWRs. A state-of-the-art overview on the EU cogeneration market with emphasis on opportunities for fast reactors was complemented by technical recommendations and by a top down cost estimate for an LFR system in a cogeneration application.

Core Physics

Benchmarking activities of neutronic codes used in Europe and recommendations for their application to the different advanced concepts were performed. Main safety parameters of the three EU demonstrators were calculated with the main codes used in Europe. R&D needs to improve the core safety were identified.

Fuel

MOX fuel properties catalogue was updated through additional measurements performed during the project on samples previously irradiated in European reactors. The effect of burn-up on thermal conductivity was, for the first time, measured on MOX fuel for fast reactors with high Pu content.

Seismic behaviour

The work focused on the modelling and analysis of the behaviour of the demonstrators by implementing seismic isolators including experimental verifications proving their efficiency in accidental conditions.

Instrumentation

Instrumentation and measurement techniques relevant to safety and in service inspection and repair were developed related to fuel cladding failure detection, coolant chemistry, thermal hydraulics characterisation and in-service inspection and repair.

6.3. Recommendations for the future

- ESNII shall continue organizing the EU R&D on sustainable nuclear energy systems. Coordination with national member states programs needs to be encouraged.
- The facilities for developing experimental programs shall be preserved and stronger cooperation facilitated to avoid duplications and improve budget utilization.
- A regulatory framework for Generation-IV reactors has to be built by countries interested in Generation-IV systems deployment to develop and maintain the competences for licensing process. The documents of IAEA, WENRA, NEA and EUR may be used in the process of developing national Generation-IV systems licensing requirements.
- Concerning the industrial supply chain, further specifications on Generation-IV specific components will be needed to verify if there are suppliers for them.
- Possible contribution of fast neutron systems to implementation of SMRs in Europe should be further investigated.
- In the core physics area, R&D must be pursued to improve the safety.
- Measurements of MOX fuel properties using existing and future irradiation experiments, in particular those having an important impact on safety must be continued.
- Seismic devices and the corresponding modelling have to be encouraged for future projects of demonstrators.
- Competences in instrumentation must be preserved in some key European laboratories to support the safe operation of the nuclear installations.

7. VINCO: Visegrad Initiative for Nuclear COoperation

7.1. Key objective

Project VINCO (Visegrad Initiative for Nuclear COoperation) was Coordination and Support Action (CSA) carried out jointly by Visegrad countries (Czech Republic, Hungary, Slovakia and Poland) and France. Main objective of the VINCO project was to establish a cooperation network in Visegrad Group and France focused on studies of gas-cooled reactor technology, mainly Gas-cooled Fast Reactors (GFR). This Action complements already established V4G4 Centre of Excellence Association and represents the next stage of capacity building in nuclear technologies in Central European countries, focused mainly on ALLEGRO Project (see **Error! Reference source not found.**). Taking into account that development of a new nuclear technology becomes too complex and too costly for small and medium-sized countries the need of international cooperation becomes obvious. Visegrad countries decided thus to join their efforts and develop complementary specializations in participating countries, namely: reactor design and safety analyses in Slovakia, helium technology in Czech Republic, fuel studies in Hungary and material research in Poland. This group is completed by France, which started already studies on gas-cooled reactors, however, mainly due to current focus on sodium technology, had to slow down studies on GFRs. However, significant knowledge has been gathered earlier in French CEA, therefore its participation in further studies carried out in V4 countries is fully justified and beneficial for the project.

Main objectives of the VINCO project were thus:

- development of the principles of cooperation and rules of access to existing and planned infrastructure,
- identification of the specific objectives of the R&D activities in the cooperating countries,
- description and analysis of the existing research, training and educational equipment and capabilities,
- determination of the investment priorities in cooperating countries and
- setting up of joint research, educational and training projects.

A close cooperation with CEA, France ensured better description of the investments needed in Visegrad Region, tightening of pan-European cooperation and strengthening of the role of V4 countries, helping them to evolve from users to the suppliers of R&D capabilities in nuclear technologies. A major expected impact of the project would be setting up of a distributed regional research centre specialized in nuclear technologies needed to develop Generation-IV reactors and to improve safe operation of existing and planned Nuclear Power Plants in the region.

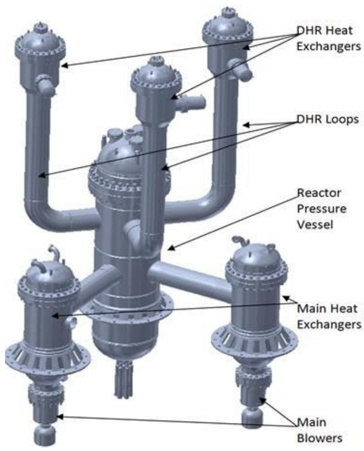


FIG. 8. Schematic drawing of the ALLEGRO Reactor (courtesy of Petr Darilek, VUJE).

7.2. Key results

Activities carried out in the frames of the VINCO project allowed to strengthen the links between the partners, establish running cooperation, especially in the field of simulation capabilities in participating institutions, initiate common educational and training actions and exchange the practices of experimental works in hot cell laboratories. Financial and legal framework analysis in V4 countries carried out within the project helped to identify the possible international cooperation schemes in V4 countries. Mutual learning and exchange of scientific staff between the laboratories took place, mainly in form of benchmark learning exercises on both, the neutronic and the thermo-hydraulic analyses and were devoted to the development of input models as well as the efficient use of various calculation tools utilized by different users. Several joint events were organized, such as School, workshops and exchange visits. An important part of the project was related to educational issues. Database of (nuclear) Educational Resources has been prepared and a brochure on Generation-IV technology prepared and printed. Finally, communication campaigns were organized to provide the information about nuclear technology for a broader public and establish contact with decision makers in the V4 Region.

7.3. Recommendations for the future

Recommendation for future actions constituted an important part of VINCO project activities. Main conclusion was that cooperation through the international agreement would bring advantages in the form of reaching of the critical mass required for such a project, clearly defined structure, competitions and responsibility. An obstacle can be politically and procedurally demanding scenario, as the wording of such agreement should be supported by a broad-political agreement of all countries. The ALLEGRO Education and Research Centre (ALLEGRO ERC) was evaluated as the most promising scheme of cooperation for the development of the GFR technology and generally for the development of any Generation-IV nuclear system technology after 2020. The Centre (possibly a part of ESFRI Roadmap) can integrate existing scientific and research resources of V4 countries, both human and technical, aiming the EU to keep up with other leading teams around the world in developing advanced nuclear power sources, with focus to GFR. The integrating aim of the ALLEGRO ERC is to prove feasibility and to provide sound basis for design of industrial scale nuclear GFR demonstrator ALLEGRO.

A long-term expected impact of the project is the strengthening of inter-regional cooperation of V4 countries in nuclear technologies and related educational activities by sharing available infrastructures, expertise, training and educational capabilities. Specialization and exchange of information should allow for the acquisition of the state-of-the-art equipment answering the common needs of European research institutions related to the development of Generation-IV of nuclear reactors.

After completion of the project we may state that the main lines of the expected project impact remain valid. Moreover, VINCO project helped us to identify new objectives for collaboration within V4 countries, namely development of High Temperature Gas-cooled Reactor (HTR) technology, a topic especially important in Poland. HTR reactors may produce steam at 550ºC, which is necessary for chemical industry and may constitute a necessary step in the implementation of more demanding GFR technology. These activities will be carried out in the frames of NOMATEN Centre of Excellence established in National Centre for Nuclear Research in close collaboration with strategic partners: CEA France and VTT Finland, which recently has been approved by the European Teaming for Excellence program constituting a new research quality in V4 countries.

8. SESAME: Thermal Hydraulics Simulations and Experiments for the Safety Assessment of Metal Cooled Reactors

8.1. Key objectives

The thermal-hydraulics is recognized as one of the key scientific subjects in the design and safety analysis of liquid metal cooled reactors [**Error! Reference**

source not found.]. SESAME project focusses on pre-normative, fundamental, safety-related, challenges for the four liquid-metal fast reactor systems (ASTRID, ALFRED, MYRRHA, and SEALER) presented in Introduction (see FIG. 1) with the following objectives:

- development and validation of advanced numerical approaches for the design and safety evaluation of advanced reactors;
- achievement of a new or extended validation base by creation of new reference data;
- establishment of best practice guidelines, Verification & Validation methodologies, and uncertainty quantification methods for liquid metal fast reactor thermal hydraulics.

The goal is to improve the safety of liquid metal fast reactors by making available new safety related experimental results and improved numerical approaches. These will allow system designers to improve the safety relevant equipment leading to enhanced safety standards and culture. Due to the fundamental and generic nature of SESAME, developments will be of relevance also for the safety assessment of contemporary LWRs.

8.2. Key results

Liquid metal heat transfer

A fundamental issue is the modelling of the turbulent heat transfer over the complete range from natural, mixed and convection to forced convection regimes. Current engineering tools apply statistical turbulence closures and adopt the concept of the turbulent Prandtl number based on the Reynolds analogy. This analogy is no more applicable for liquid metals, and robust engineering turbulence models are needed. Within the SESAME project, the main focus was the extension of the validation base for mixed and natural convection regimes and for geometrically complex cases, together with further development and implementation of selected promising models in widely used engineering codes.

Core thermal Hydraulics

Although experiments in liquid metal are being carried out in the European context on wire-wrapped fuel assemblies and to a lesser extent on fuel assemblies with grid spacers, the data to be retrieved from those experiments will be limited to pressure drops and the thermal field and will not include detailed information on the flow field. To derive reference data for the flow field in wire wrapped fuel assemblies, a combination of experimental data and reference high fidelity numerical simulations was set-up. Such need was not only recognized in Europe, but also in the US. A collaboration was established between the European and US partners allowing to maximize the benefits of both validation campaigns and to close the gap in the validation process of wire wrapped fuel assemblies.

Missing data for spacer-grid fuel assembly design were also produced by performing experiments in a liquid metal rod bundle. Such experiments were performed for grid spacers without blockages and with blockages and were accompanied by CFD simulations.

Pool Thermal Hydraulics

Although it is recognized that pool thermal-hydraulics as such is highly design-dependent, the development and validation of modelling approaches for pool thermal-hydraulics is not. In order to improve the validation base, liquid metal experiments were performed at different scales. Firstly, an experiment in the TALL-3D facility which include a small pool in which thermal stratification and mixing phenomena can be studied. Four large scale experiments have been performed in the CIRCE facility using the so-called ICE test section which has been instrumented such that relevant data for thermal stratification and flow patterns can be extracted. The ESCAPE facility, a scaled down mock-up of MYRRHA, is instrumented such that relevant data for thermal stratification and flow patterns can be extracted. In parallel, CFD approaches were developed for all facilities mentioned and validated using the experimental data. Finally, the validated CFD approaches were applied to the MYRRHA and ALFRED reactor design (see FIG. 9).

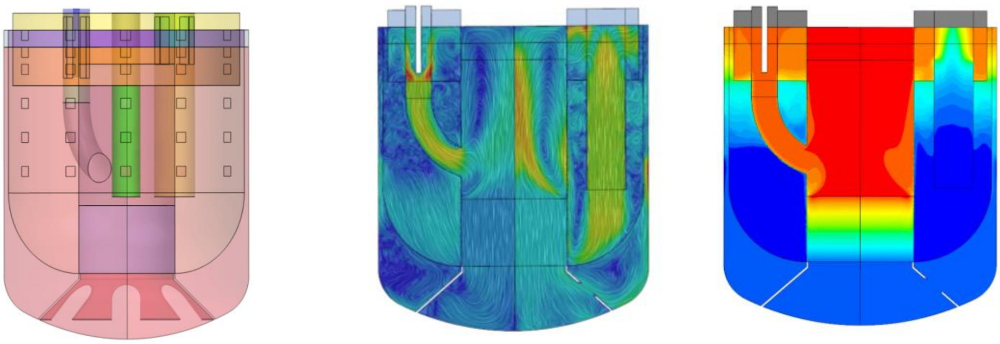


FIG. 9. CFD Model of ALFRED Primary Loop. (Courtesy of CRS4, SESAME Task 3.1.2)

System Thermal Hydraulics

Traditionally, the analysis of nuclear system behavior is performed using system thermal-hydraulics codes. Such analyses are validated using integral design specific experiments or reactor data from prototype, test, or demonstration reactors. In recent years, the traditional approach of using system thermal-hydraulic codes is supplemented with new multi-scale approaches in which system thermal hydraulics codes are coupled to detailed three dimensional CFD approaches. SESAME project aimed at extending the validation base by providing reference data at different levels. The validation data were provided in loop scale by experiments in the NACIE-UP facility, focused on the multi-scale coupling of the behaviour in the fuel assemblies and the loop system. Scaling up, the CIRCE facility in the so-called HERO configuration is used to provide experimental validation data. Real reactor data were provided from the Phénix reactor end of life tests. This data allowed validation of the three dimensional effects to a much larger extent than the natural circulation test data which were previously used. Finally, the approaches under development will be applied to the MYRRHA and ALFRED lead-cooled reactor designs.

Guidelines and Education

One of the main goals of the SESAME project is the establishment of Best Practice Guidelines, Verification & Validation methodologies, and Uncertainty Quantification methods. To this purpose work meetings have been organized in Stockholm (2016) in which the current practices and experiences of all partners and some invited experts from outside the project have been compared and discussed. With respect to education and training, a lecture series was organized in 2017 hosted by VKI in Belgium. During the lecture series, experts from the project disseminated their knowledge on experimental techniques and modelling approaches. The textbook [**Error! Reference source not found.**] was published as one of the main deliverables to the nuclear liquid metal community at large. Finally, an international workshop on nuclear liquid metal thermal hydraulics was hosted by NRG in Petten, with more than 70 lectures, and participants from the entire world.

8.3. Recommendations for the future

SESAME project improved the safety of liquid metal fast reactors not only in Europe but also globally by making available new safety related experimental results and improved numerical approaches. These outcomes will allow designers to improve the safety of their reactors, which will finally lead to an enhanced safety culture. For the future, it is recommended to keep the successful approach of SESAME in which experiments, modelling and simulations moved hand-in-hand. New projects, based on the outcomes of SESAME, would be implemented enlarging the community, strengthening the partnerships, improving the synergies, leading innovation, enhancing safety culture at the European and international level.

9. SAMOFAR: A Paradigm Shift in Reactor Safety with the Molten Salt Fast Reactor

The ultimate aim of nuclear energy research is to develop a nuclear reactor that is truly 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 a molten salt reactor 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.

9.1. Key objectives:

The grand technical objective of the SAMOFAR project is to prove the innovative safety concepts of the MSFR by advanced experimental and numerical techniques, and to deliver a breakthrough in nuclear safety and optimal waste management. This objective has been split in four sub-objectives:

- Delivering the experimental proof of concept of the unique safety features of the MSFR.
- Providing a safety assessment of the MSFR for both the reactor and the chemical plant.
- Updating the conceptual design of the MSFR.
- Creating momentum among key stakeholders.

Besides the Work Package (WP) on project management, the SAMOFAR project contains six specialized parts. WP1 deals with the integral safety assessment and the overall reactor design (see FIG. 10) including the chemical operation plant. WP2 determines experimentally all safety-related data of the fuel salt. WP3 investigates experimentally and numerically the natural circulation dynamics of the fuel salt in the primary vessel and emergency drain tanks, and the behaviour of the salt in the freeze plugs during a drain transient. WP4 assesses numerically the accident scenarios identified in WP1, which include the normal operation transients and the off-normal accident scenarios. WP5 assesses experimentally and numerically the safety aspects of the chemical extraction processes, and the interaction between the chemical plant and the reactor. WP6 covers the dissemination and exploitation of knowledge and results, e.g. by education and training of young scientists.

SAMOFAR is the latest MSR-related project in a successful series (MOST, ALISIA, EVOL) and started in August 2015. The SAMOFAR consortium consists of 11 partners from the EU, Switzerland and Mexico, each providing a specific own contribution. Besides the partners' contribution, also observers participate to the project.

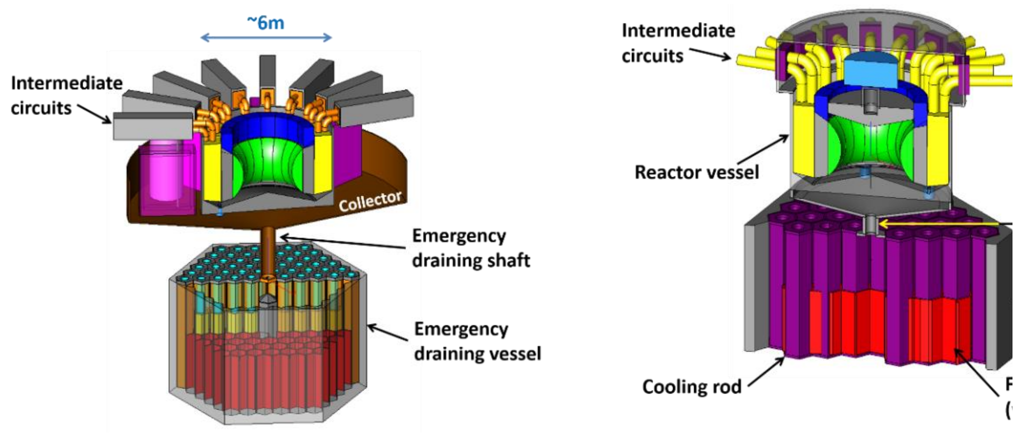


FIG. 10. Schematic design of the primary circuit of the MSFR showing the reactor vessel and emergency draining system for the fuel salt.

9.2. Key results

In WP1 the design of the MSFR including the emergency draining system has been updated and assessed by a panel of experts. A plant simulator has been developed and is now being used to define reactor control strategies and procedures for the various operation modes of the MSFR, such as full power operation, load-following, start-up and shut-down. A risk assessment methodology has been developed based on the Integrated Safety Assessment Methodology, which will lead to "built-in" safety at the early design stages. Other risk analysis methods have been applied to the MSFR and have led to the identification of postulated initiating events and a list of relevant design key-points.

Test calculations with the MELCOR and ASTEC severe accident codes showed that these codes can most probably be used, but that some data need to be added. A special setup has been constructed for experimental studies of actinides in molten fluorides and for the synthesis of actinide fluorides. Experimental studies on the vaporization behaviour of the fuel salt revealed the retention properties at high temperature. It turns out that CsF remains fully dissolved in the salt, but that CsI needs further investigation. A test facility has been made to measure viscosity of salts based on ultra-sound methods. Finally, the interaction of salt with water under the influence of gamma radiation has been investigated.

In WP3 the major experimental contributions in two large setups (DYNASTY and SWATH) have been prepared. For DYNASTY, numerical research has revealed flow instabilities in a natural circulation loop with a distributed heated salt. The DYNASTY facility is in operation to generate experimental data, which will be used for stability analysis and for the validation of numerical codes in WP4. The design and construction of the SWATH facility and the test sections in which the experiments will be carried out have been completed. SWATH uses a molten salt between 500°C and 700°C to perform thermal hydraulics measurements, including phase change phenomena and experiments on freeze plugs.

In WP4 transient calculations based on the scenarios identified in WP1 will be performed based on leading-edge multi-physics codes including uncertainty propagation. Verification and validation of these code systems has been done via code-to-code comparison and by using the experimental data generated in WP3.

In WP5 the fuel salt processing scheme has been updated, and thermochemical calculations have revealed the transfer coefficients. This data has been used to calculate the radionuclide inventory at each stage using new software, as well as the radioactivity, the decay heat production and the shielding requirements. The behaviour of uranium and iodine in the salt has been investigated experimentally.

In WP6 a summer school has been organized with focus on the scientific fundamentals of fluid fuel reactors. Almost 90 MSc/PhD students and young professionals participated. The SAMOFAR website (http://www.SAMOFAR.eu) acts as the portal to reach the public and for information exchange and for archiving. The youtube channel (http://samofar.eu/samofar-youtube-channel/) has been updated with lectures from the summer school and movies.

9.3. Recommendations for the future

The MSFR is a reactor design at low TR level with several points for improvement. To come to a realistic safety assessment of the reactor, a more detailed design is needed with better materials data (structural materials, fuel salt properties, etc), validated simulation models of the specific phenomena occurring in the

MSFR, and reliable data on the performance of components and processes. These topics are subject of the new SAMOSAFER proposal that focuses, among others, on safety requirements and risk identification of molten salt reactors including the chemical processing plant; measurement and calculation of the fuel salt retention properties; evaluation of nuclide mobility and the resulting inventory in each compartment of the reactor including the chemical processing plant; modelling and simulation of phenomena needed for the safe confinement of fuel salt; modelling of heat removal processes, including radiation heat and other phenomena; reactor operation and control to assess normal operation and emergency operation; education and training of students, and dissemination and exploitation of our results.

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

10.1. 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 level compared to traditional reactors. The ESFR-SMART project [**Error! Reference source not found.**] aims at enhancing further the safety of Generation-IV SFRs and in particular of the commercial-size European Sodium Fast Reactor (ESFR) in accordance with the ESNII roadmap and in close cooperation with the ASTRID program. The project aims at 5 specific objectives:

- Produce new experimental data in order to support calibration and validation of the computational tools for each defence-in-depth level.
- Test and qualify new instrumentations in order to support their utilization in the reactor protection system.
- Perform further calibration and validation of the computational tools for each defence-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.
- 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.
- 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.

Close interactions with the main European and international SFR stakeholders (GIF, ARDECo, ESNII and IAEA) via the Advisory Review Panel will enable reviews and recommendations on the project’s progress as well as dissemination of the new knowledge created by the project. By addressing the industry, policy makers and general public, the project is expected to make a meaningful impact on economics, EU policy and society.

10.2. Key results

The project is currently close of the end of the second year and the key results obtained at the first phase of the project are summarised below [**Error! Reference source not found.**].

Proposal of new safety measures

The key idea is to make a next step in developing the large-power (1500 MWe/3600 MWt) SFR concept, following up the "line" of the Superphenix 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.
- 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.

Evaluation of core performance

After the new core design was proposed the 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 Equilibrium Cycle were 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.
- 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.

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 proposed for the startup core of the Superphénix (SPX) Sodium Fast Reactor based on open publications.
- A computational exercise on sodium boiling modeling was organized based on a KNS-37 sodium loop experiment featuring sodium boiling in pin-bundle geometries.

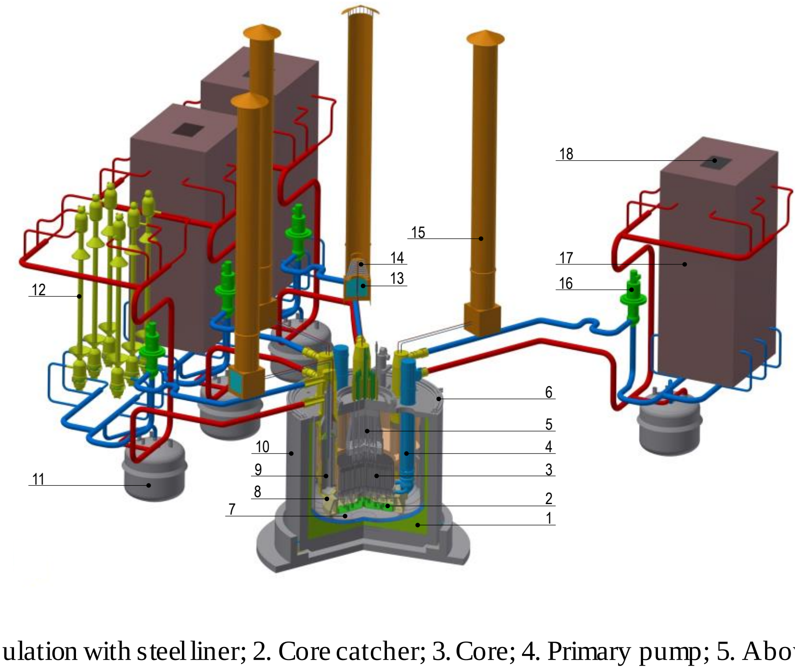
Experimental programs

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 test on chugging boiling regime (CHUG) was launched to support the computational activities on analysis of the ESFR behaviour under sodium boiling conditions.
– New test on corium jet impingement (HAnSOLO) was started using a water-ice system as a model of the corium-catcher system.
– Safety rules were formulated for designing a new high-temperature sodium facility.
– Eddy-current flow meters (ECFM) was qualified for a positioning above the fuel assemblies in order to detect possible blockages of the sodium flow

10.3. Recommendations for the future

Since the project is only at the second year no recommendations for the future are provided.



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. 11. General view of ESFR-SMART reactor.

Conclusion

The paper briefly presents nine Euratom projects started since late 2011 in support of the infrastructure and R&D of the seven fast reactor systems.

The **SARGEN_IV project** was the first opportunity to gather together various experts of fast reactors safety from TSOs, research institutes, utilities and universities. The project allowed very fruitful exchanges providing a synthesis on identification and ranking of the safety issues and the proposal for a harmonization of the safety assessment practices that could be used further for each of the concepts proposed by the ESNII. Beside showing how difficult is to have a detailed safety assessment when the design of the reactor is not well defined, the SARGEN_IV project contributed to the harmonisation of the different methodologies, crucial for developing a consistent assessment platform which could be used effectively in the decision-making process and to make the different innovative reactor types publicly acceptable in Europe.

The **SILER project** demonstrated that the technology for the seismic isolation of nuclear facilities already exists and that the main components like isolators (in particular High Damping Rubber Bearings and Lead Rubber Bearings) and flexible joints for pipelines (even the more critical ones) are reliable enough to guarantee the safety of the plant, even in the case of beyond design events. SILER also confirmed the significant advantages given by seismic isolation, not only in terms of reduction of the seismic actions on the structure and most critical components, but also from the economical point of view, thanks to the possibility of standardizing the design of the reactor building, making it substantially independent of the seismicity of the construction site. Some activities of SILER continued in the ENSII Plus Project (see Section 6), regarding the design of the seismic isolation systems of the ASTRID and ALFRED reactors.

The **ALLIANCE project** is helping to realise the vision of a next-generation GFR in one of four central European countries during the next decade. Outcomes will help meet EU energy and climate targets.

The **JASMIN project** has fostered a collaborative work on the integral Beyond Design Basis Accident (BDBA) ASTEC-Na code development and validation. The project, relied on the PIRTs produced within the previous CP-ESFR FP7 project, capitalized the large amount of knowledge produced since 40 years in this field in the ASTEC-Na code development by collecting and sharing some past experimental program results, and disseminated it to end-users. JASMIN end-products were the final version of the ASTEC-Na code and the associated validation experimental matrices. Both might be used in the future not only for R&D activities but also for industrial applications. Cross-cutting issues were also investigated and led to the conclusion that the sound bases of ASTEC-Na and the existing similarities with Pb-cooled and Pb-Bi reactors, turn it to be a good option to develop an ASTEC-LM (Liquid Metal) version.

The **ESNII Plus project** prepared the ESNII structuration and deployment strategy, to ensure efficient European coordinated research on Reactor Safety for the next generation of nuclear installations, linked with SNETP SRA priorities. To achieve the objectives of ESNII, the project coordinated and supported the preparatory phase of legal, administrative, financial and governance structuration, and ensured the review of the different advanced reactor solutions. At the same time, the project addressed the following technical cross-cutting areas:

- Core physics benchmarking activities of neutronic codes used in Europe and recommendations for their application to the different advanced concepts. Identification of R&D needs to improve the core safety.
- Fuel update of the MOX fuel properties catalogue through additional measurements performed during the project on samples previously irradiated in European reactors.
- Seismic behaviour, modelling and analysis of the behaviour of the demonstrators by implementing seismic isolators including experimental verifications.
- Instrumentation development of instrumentation and measurement techniques relevant to safety and in service inspection and repair.

The **VINCO project** addresses one of the most important problems of the society: to find energy for future generations. Obviously, such a problem cannot be resolved by a small, C&S action, however, VINCO contributes to its solving by building a research platform able to cope with one of the future concepts, gas-cooled nuclear reactors, in Visegrad countries.

Within the **SESAME project**, new analytical and simulation methods are being validated with reference data. Most of these reference data are based on experimental results and, when not feasible, are complemented or replaced by high fidelity simulation data (typically DNS or LES). As such, within these projects, experiments, high fidelity reference simulations and pragmatic engineering simulation will go hand-in-hand providing not only the international liquid metal fast reactor designers, but also the light water community with valuable new reference data and modelling approaches.

The progress in the **SAMOFAR project** till now, which is only very briefly summarized in this paper, contains significant results beyond current knowledge, both in the fields of safety assessment, Molten Salt Fast Reactor design, fuel salt data, experimental evaluation, numerical algorithms and modelling, and the synthesis of salts and coatings. Many results were published at scientific conferences, journals and other dissemination channels to increase the impact of the project. The inclusion of SAMOFAR related topics in the curricula of the university programs has contributed to the dissemination and to the education of students. The SAMOFAR project is scheduled to finish at July 31, 2019.

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 on-going and scheduled to finish in August 2021.

Acknowledgement

Projects has received funding from the Euratom research and training programme under grant agreements No. 295446, 295485, 323295, 295803, 605172, 662136, 654935, 661891, 754501.

References

[1] SARGEN_IV EC Project: Deliverable 2.5 Identification and ranking of the safety issues

[2] SARGEN_IV EC Project: Deliverable 3.5 Proposal for a harmonization of the safety assessments practices

[3] M. Forni, A. Poggianti, R. Scipinotti, A. Dusi, E. Manzoni, "Seismic isolation of lead-cooled reactors: The European project SILER", (2014), Nuclear Engineering and Technology, 46 (5), pp. 595-604.

[4] M. Forni, A. Poggianti, R. Scipinotti, A. Dusi, E. Manzoni, M. G. Castellano, "Seismic-Initiated event risk mitigation in LEad-cooled Reactors: MAIN RESULTS OF THE SILER PROJECT", SECED 2015 Conference: Earthquake Risk and Engineering towards a Resilient World, 9-10 July 2015, Cambridge, UK.

[5] A. Horvath, ALLIANCE - Preparation of ALLEGRO – Implementing Advanced Nuclear in Central Europe, FISA 2013, 8th European Conference on Euratom Research and Training in Reactor Systems, Vilnius, Lithuania, 14-17 October, 2013

[6] B. Hatala, P. Darilek, R. Zajac, M. Lackova, ALLEGRO project, Conference EUROSAFE 2015, Brussel, Belgium, November 2-3, 2015.

[7] J. Berka, T. Hlinčík, I. Víden, T. Hudský, J. Vít, The design and utilization of a high temperature helium loop and other facilities for the study of advanced gas-cooled reactors in the Czech Republic, Progress in Nuclear Energy 85 (2015) 156-163.

[8] GIF/RSWG/2007/002, Basis for the safety approach for design & assessment of Generation IV nuclear systems

[9] S. Perez-Martin, W. Pfrang, N. Girault, L. Cloarec, L. Laborde, M. Buck, V. Matuzas, A. Flores y Flores, P. Raison, A.L. Smith, N. Mozzani, F. Feria, L. Herranz, B. Farges, Development and assessment of ASTEC-Na fuel pin thermomechanical models performed in the European JASMIN project, Annals of Nuclear Energy, vol. 119, pp 454-473 (2018).

[10] V. Matuzas, L. Ammirabile L. Cloarec, D. Lemasson, S. Perez-Martin, A. Ponomarev, Extension of ASTEC-Na capabilities for simulating reactivity effects in Na-cooled fast reactors. Annals of Nuclear Energy, vol. 119, pp 440-453 (2018)

[11] M. Nitoi, J.-M. Carrere, Z. Hozer, L. Burgazzi, D. Gugiu, M. Farcasiu, M. Constantin. Siting and licensing requirements for GenIV demonstrators, ESNII Plus Deliverable D3.3.1, July 2017.

[12] M. Frignani et al. Status and perspectives of industrial supply chain for Fast Reactors. Proc. of International Conference on Fast Reactors and Related Fuel Cycles: Next Generation Nuclear Systems for Sustainable Development (FR17), 26-29 June 2017, Yekaterinburg, Russia.

[13] F. Roelofs, K. Van Tichelen, M. Tarantino "European Thermal-Hydraulic Progress for Sodium and Lead Fast Reactors", The 17th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-17), Xi'an, China, September 2017

[14] F. Roelofs (editor), Thermal Hydraulics Aspects of Liquid Metal Cooled Nuclear Reactors, Elsevier, ISBN: 9780081019818, https://www.elsevier.com/books/isbn/978-0-08-101980-1

[15] K. Mikityuk, E. Girardi, J. Krepel, E. Bubelis, E. Fridman, A. Rineiski, N. Girault, F. Payot, L. Buligins, G. Gerbeth, N. Chauvin, C. Latge, J. Guidez, "Horizon-2020 ESFR-SMART project on SFR safety: status after first 15 months", 27th International Conference on Nuclear Engineering ICONE27, May 19-24, 2019. Tsukuba International Congress Center, Tsukuba, Ibaraki, Japan.

STEPHANE BOURG

SUMMARY AND HIGHLIGHTS OF SACSESS AND GENIORS PROJECTS

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Abstract. Processes such as PUREX allow the recovery and reuse of the uranium and the plutonium of GEN II/GEN III reactors and are being adapted for the recycling of the uranium and the plutonium of GEN IV MOX fuels. However, it does not fix the sensitive issue of the long-term management of the high active nuclear waste (HAW). Indeed, only the recovery and the transmutation of the minor actinides can reduce this burden down to a few hundreds of years. In this context, and in the continuity of the FP7 EURATOM SACSESS project, GENIORS focuses on the reprocessing of MOX fuel containing minor actinides, taking into account safety issues under normal and mal-operation. By implementing a three-step approach (reinforcement of the scientific knowledge => process development and testing => system studies, safety and integration), GENIORS will provide more science-based strategies for nuclear fuel management in the EU.

1. Introduction

The civilian use of the nuclear energy if more and more discussed in terms of global and long-term environmental impact. Whereas different studies based on life cycle assessment demonstrate the low environmental impact of the nuclear electricity, ensuring its viability [1], its social acceptance remains weak if we want to consider it as fully sustainable. This social acceptance is mainly related to the long-term management of the nuclear waste, and in particular of the high active waste (HAW) [2].

In most of the countries having deployed the nuclear energy, the spent nuclear fuel coming out of the reactor after four/five years are directly stored and considered as the ultimate waste under dry or wet conditions. So far, their very long-term disposal is not fully assessed, and it will take more than 200,000 years before their relative radiotoxicity drop down to the one the natural uranium (Fig. 1 orange curve).

In some countries, like France, a mono recycling of the spent fuel is implemented, by recovering the uranium and the plutonium from the spent fuel, manufacturing uranium oxide fuel (UOX) with the re-enriched reprocessed uranium and mixed oxide fuel (MOX) with the plutonium mixed with depleted uranium from the stockpile. This reprocessing allows the saving of about 20% of uranium from the mine but also reduces the time to have a relative toxicity of the remaining ultimate waste that are conditioned under a glass form below the one of the natural uranium after 15,000 years. It also reduces the total volume of the HAW by a factor of 3.5 and the footprint of the deep geological repository by a factor of about 4 thanks to the reduced heat load of the waste allowing a higher density packing.

However, such a timeframe is still difficult to understand and apprehend for the public. Indeed, think about what our world was 15,000 years ago (Fig. 1 green curve).

To address this issue and bring back the timeframe of the nuclear waste in the human history perception, one option has been being developed for about 30 years: the partitioning and transmutation strategy (P&T). It consists in recovering not only the uranium and the plutonium from the spent fuel but also the minor actinides (neptunium, americium, curium) that drive then the long-term radiotoxicity of the waste. The partitioning is the chemical process step allowing the recovery the minor actinides from the spent fuel dissolution liquor, and the transmutation is the physical process step transforming these minor actinides into short life radionuclides in fast reactors or dedicated systems (ADS). With such an approach, the relative radiotoxicity would drop below the one of the natural uranium after only 300 years (Fig. 1 blue curve).

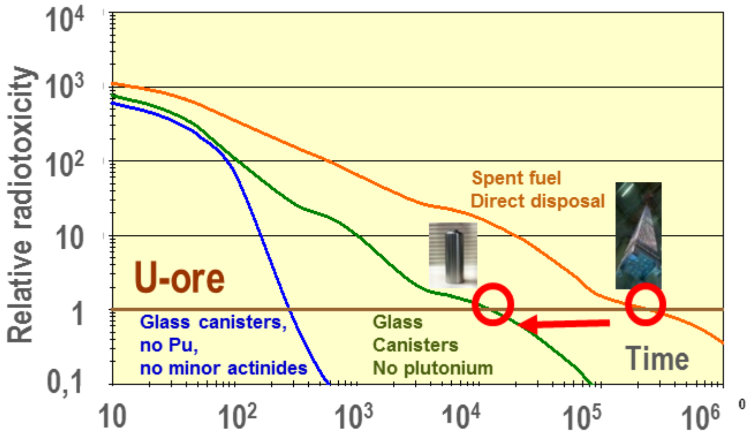

FIG. 1. Relative long-term radiotoxicity of the HAW according to their typology (credit CEA).

In fast reactors, the minor actinides would be either mixed together with the uranium and plutonium fuel (MOX, metallic, carbide or nitride fuel) (homogeneous recycling) or managed specifically in blanket fuel surrounding the U/Pu fuel (heterogeneous recycling). In ADS, the transmutation would be operated in dedicated targets (heterogeneous recycling) (Fig. 2)

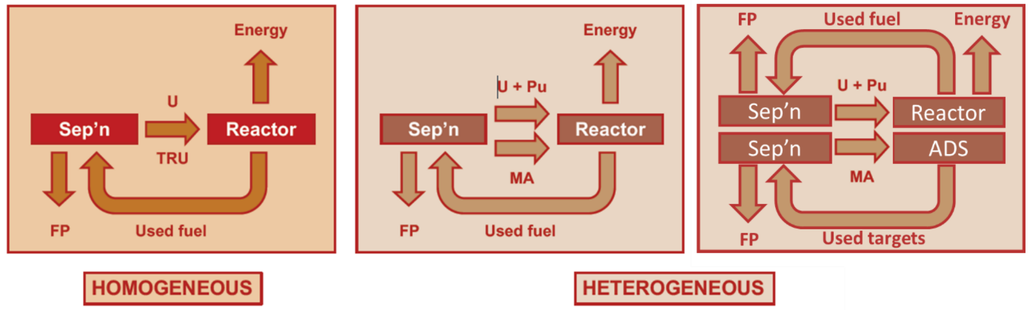

FIG. 2. P&T strategies.

For more than 25 years, the international nuclear chemistry community has been developing different options to allow this transmutation, and particularly in Europe, under the lead of the French atomic energy and alternative energies commission (CEA). The first European project was implemented under the third framework program and is still continuing. After a wide phase of screening both in terms of general concepts and chemical systems, a few promising reference options have been selected and are now further developed. The work is now focusing on gaining a better understanding of the chemical systems under normal and mal-operation taking through a global safety approach. Upscaling is also estimated through modelling and system studies. After a summary of the background of these studies, the work done over the last 6 years within the FP7 project SACSESS and the H2020 project GENIORS on the promising reference processes will be developed.

2. Background

The first European project dealing with the partitioning of the minor actinides started in 1994 (High-Level Liquid Waste Partitioning by Means of Completely Incinerable Extractants: EUR18038). Gathering CEA (France) and University of Reading (UK), it focused on the recovery of actinide cations An(III) and lanthanide cations Ln(III) from the PUREX raffinate using diamide family molecules (Fig. 3 right) and to the separation of An(III) and Ln(III) using TPTZ family molecules (2,4,6-Tris(2-pyridyl)-s-triazine) (Fig. 3 centre).

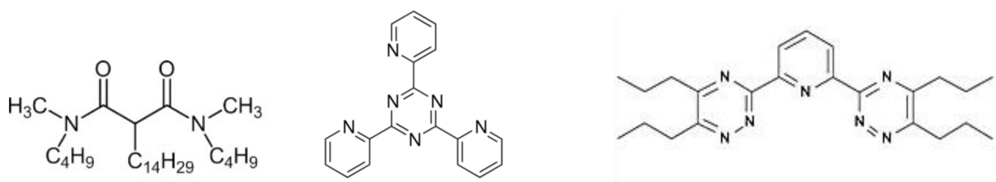

FIG. 3. Diamide (DMDBTDMA), TPTZ and BTP (nPr-BTP) molecules.

The work continued under the FP4 NEWPART part project and FP5 PARTNEW project, where a new molecule family was developed: the Bis Triazinyl Pyridine

BTP replacing the TPTZ and derivatives (Fig. 3 right). The screening of new continued widely in the FP6 EUROPART project with the synthesis, characterisation and the assessment of extraction properties of more than 100 new ligands from the various families. At the end very few of them showed better properties than the previous ones, but some derivatives of the BTBPs (Bis-triazine bi-pyridine) (Fig. 4 left) and mainly the TODGA (fig. 4 right), firstly tested in Japan (N,N,N′,N′-tetraoctyl diglycolamide).

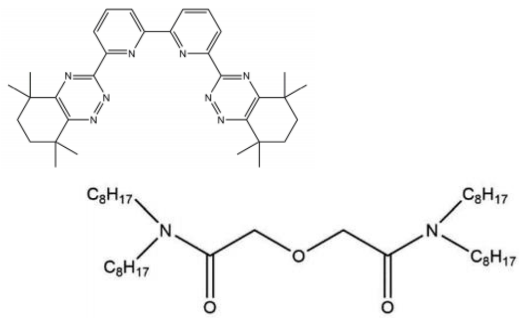

FIG. 4. CyMe4-BTBP and TODGA molecules.

In the same timeframe, worldwide, numerous options have also been developed (SACSESS Book http://www.sacsess.eu/Docs/SACSESS.PDF) [3]. They are summarized on Fig. 5. So far, no one them have been implemented up to the industrial scale but some of them seems more promising and are still under study. Within the FP7 ACSEPT, the first schemes of the European reference processes were proposed: an innovative SANEX based on TODGA allowing the recovery of Am and Cm directly from the PUREX raffinate and the EURO-GANEX, also based on TODGA. A hot-test was performed on both flowsheet, at CEA for the i-SANEX and at ITU for the EURO-GANEX.

In 2011, the Fukushima accident brought back the nuclear safety on the front scene and in this frame, the SACSESS process, follow-up of ACSEPT, designed in 2012 and entered into force in March 2013 presented a very different approach than the previous project, using the safety consideration as the driver of the R&D needs. This strategy was kept for designing the GENIORS project in 2016.

3. SACSESS

SACSESS started in March 2013 and ended in June 2016, with a consortium of 26 partners, a total budget of 10.5 M€ and a EU grant of 5.55 M€. The concept of SACSESS was the improvement of the reference partition processes driven by a safety approach and a technological roadmapping to identify the gap of knowledge and the R&D needs for the further developing the reference processes (Fig. 6).

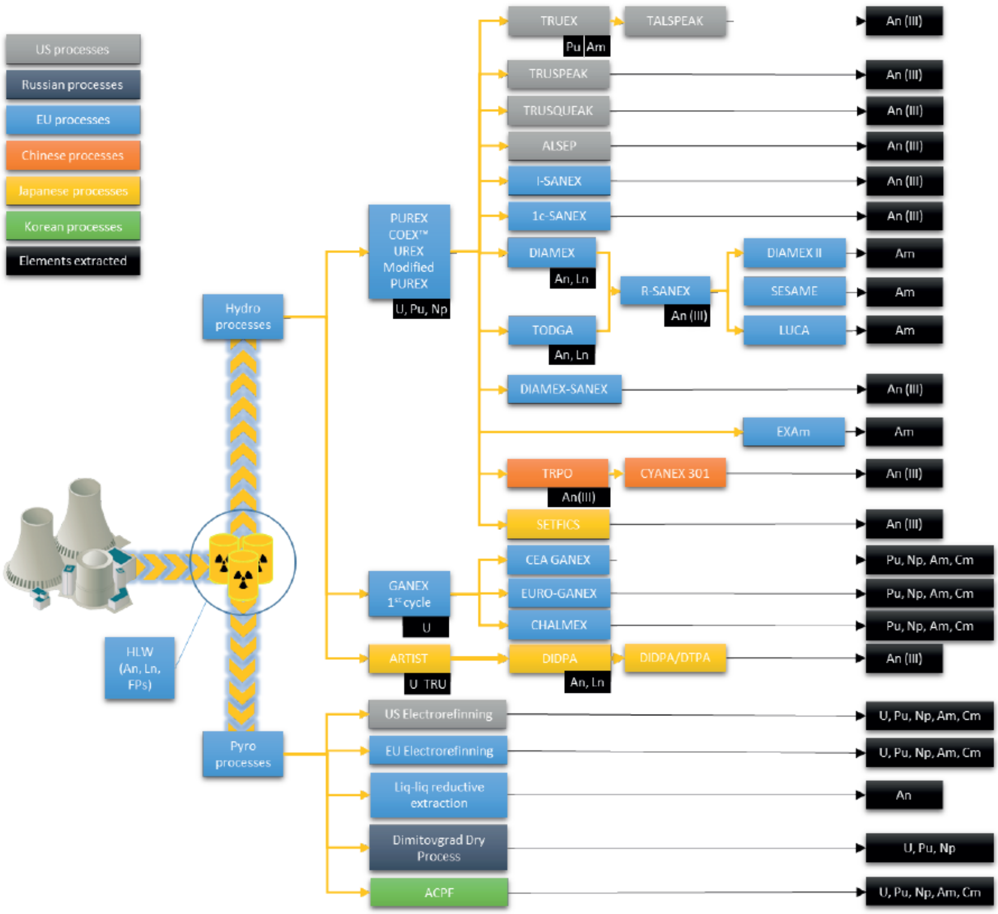

FIG. 5. *Schematics of the different process options proposed worldwide the advanced reprocessing of spent nuclear fuel.*

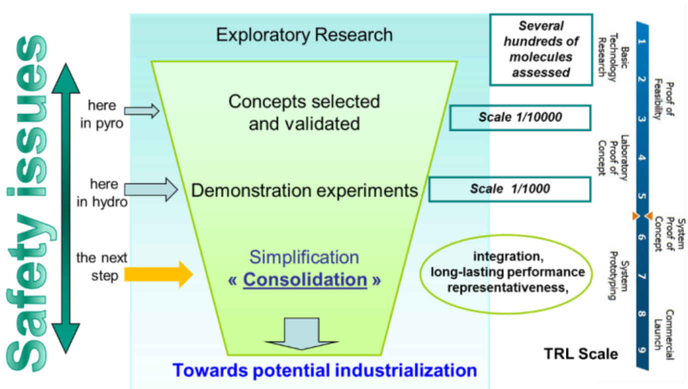

FIG. 6. *The SACSESS concept.*

3.1. The reference processes

The first reference process is the innovative SANEX process (i-SANEX) –Fig. 7). Based on TODGA for the An/Ln extraction, it requires HEDTA in the feed as masking agent and DTPA and malonic acid in the stripping solution for selectively extracting the actinides.

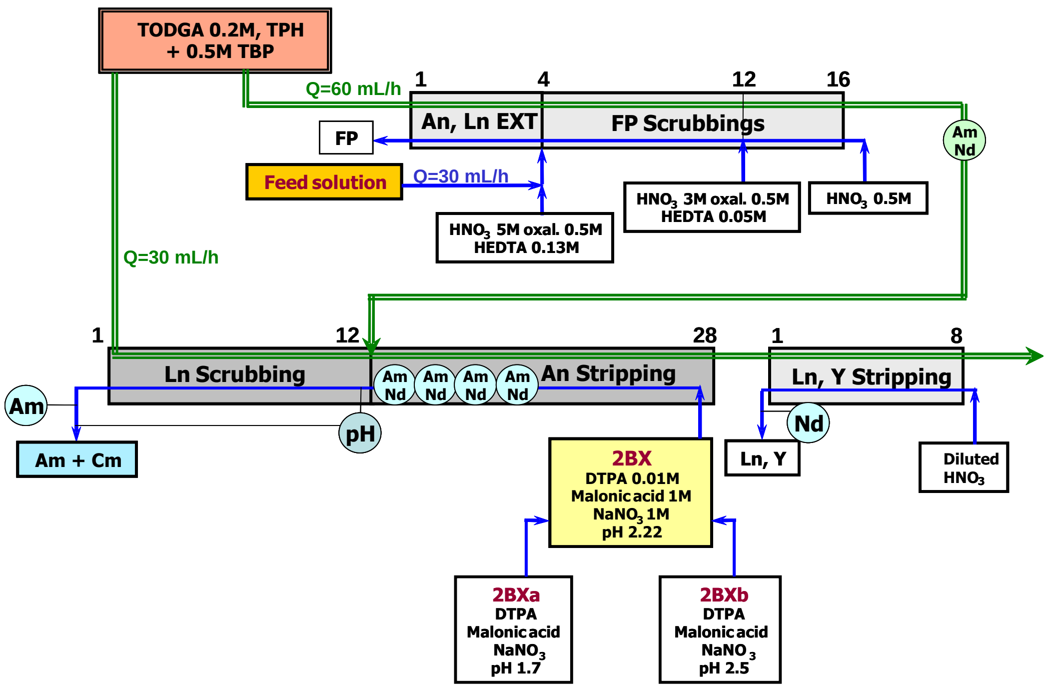

FIG. 7. The reference i-SANEX flowsheet.

The second reference process is the EURO-GANEX process (Fig. 8). The TODGA is also used at the extraction, together with DMDOHEMA to reduce the third phase formation risk and increase the Pu loading. CDTA is used as masking agent in the feed and the stripping is made thanks to an innovative molecule: the sulfonated BTP.

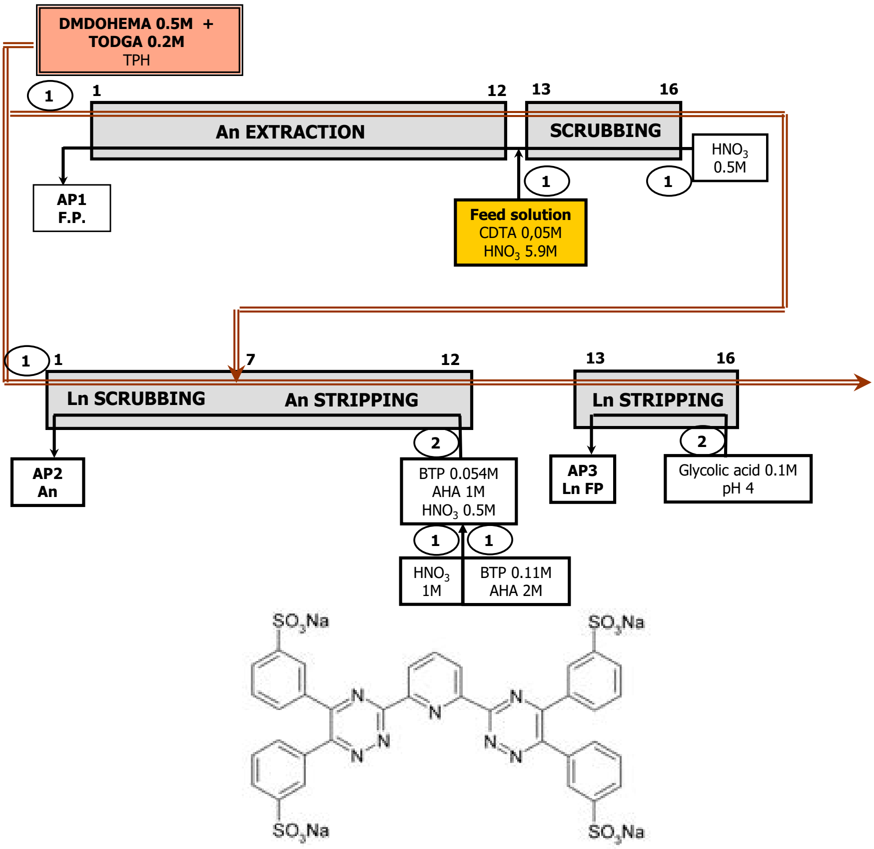

FIG. 8. The reference EURO-GANEX process.

In addition to the i-SANEX and EURO-GANEX processes, it was decided to study also an option allowing the recovery of the americium alone from the PUREX raffinate (Fig. 9). Actually, the Americium is the main contributor to the long-term radiotoxicity, once the plutonium removed, the curium is very difficult to manage once concentrated, would highly impact the design of the separation and fuel fabrication workshops, and has a half-life of 18 years allowing it to decrease during the interim repository stage of the waste management, making its impact negligible at the disposal. This process is based on an innovative molecule, the TPAEN as selective americium stripping agent whereas the extraction is very similar to the one of the i-SANEX process.

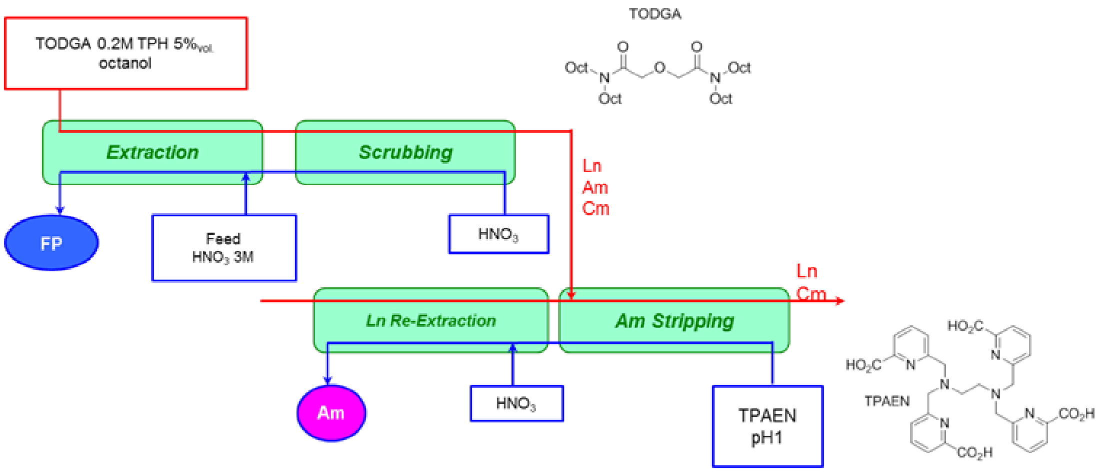

FIG. 9. The reference EURO-EXAM process.

3.2. Safety driven R&D

Through intereactive workhsops, the differnet process flowsheet were analysed through a safety methodology (HAZOP) (Fig. 10). This confirmed that more R&D was needed on chemical issues:

– Chemical and radiolytic stability
– Impact of degradation products / downstream effects
– Solvent clean-up

But also, on process issues:

– Loading /3rd phase formation
– Kinetics
– Losses

In parallel, the need for more modelling at different scales, more simulation and more online analysis was pointed out.

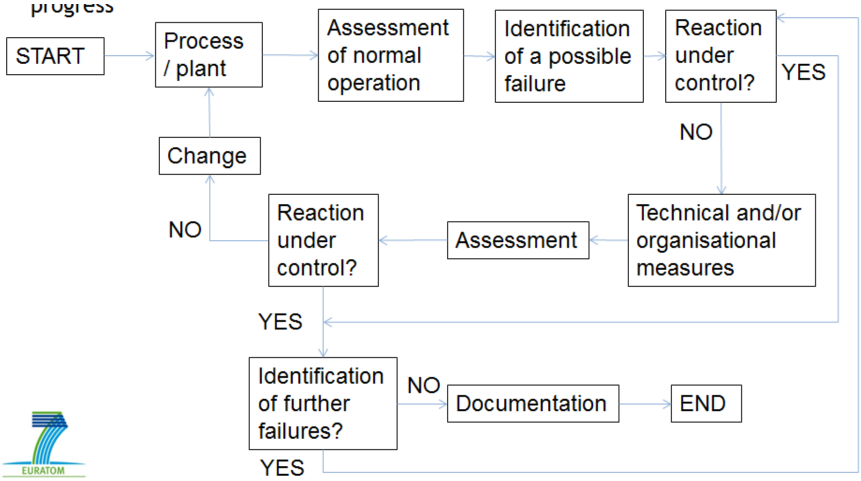

Fig 10. The HAZOP safety methodology.

These different topics were addressed in SACSESS, in particular the radiolytic stability issues.

The behaviour upon static gamma irradiation of TODGA, Me-TODGA, CyMe4-BTBP and $CyMe_4$-BTPhen extracting agents as well as of some diluents used to prepare organic phases was studied in detail. Also, aqueous solutions containing SO_3- Ph-BTP or PyTri-diol were irradiated. The main TODGA degradation products were identified and synthesised as pure components. These products' extraction behaviour was studied to assess whether their build-up would impair the extractive properties of TODGA solvents.

Irradiation of $CyMe_4$-BTBP and $CyMe_4$-BTPhen diluted in 1-octanol forms a primary degradation product which was identified as an octanol adduct. This explains why $CyMe_4$-BTBP and $CyMe_4$-BTPhen solvents keep their extractive properties even if the $CyMe_4$-BTBP or $CyMe_4$-BTPhen concentration decreases upon irradiation. The compounds are not destroyed but form an adduct with similar properties.

Static irradiation of SO_3-Ph-BTP solutions showed the molecule to be significantly more sensitive towards radiolydic degradation than are e.g. TODGA or $CyMe_4$-BTBP. However, a dynamic irradiation test in the irradiation loop setup at Idaho National Laboratory did not result in a deterioration of its properties.

Hydrogen generation rates (G-values) have also been determined from nitric acid and TODGA / kerosene phases under alpha-irradiation (from plutonium and americium ions) and compared to gamma irradiation. This is an important safety-related issue in the design of any future industrial scale process.

3.3. Technology driven R&D

Studies within SACSESS have also started the key task of integrating the novel separation processes with the other parts of the overall reprocessing and recycling plant. Specifically, the effects of the aqueous phase complexing agents such as DTPA and HEDTA on the downstream product finishing process is studied. Assuming the oxalate co-precipitation process as the baseline finishing process, initial studies have considered the effects of the complexing agents on residual metal ion solubility post-oxalate precipitation. Methods of decomposing the complexants have been tested, either before oxalate precipitation or in the oxalate mother liquor before acid recycling.

A gap analysis was also conducted on the different options to identify the maturity level of the different steps (Fig. 11). The output of this work was used to design the GENIORS project.

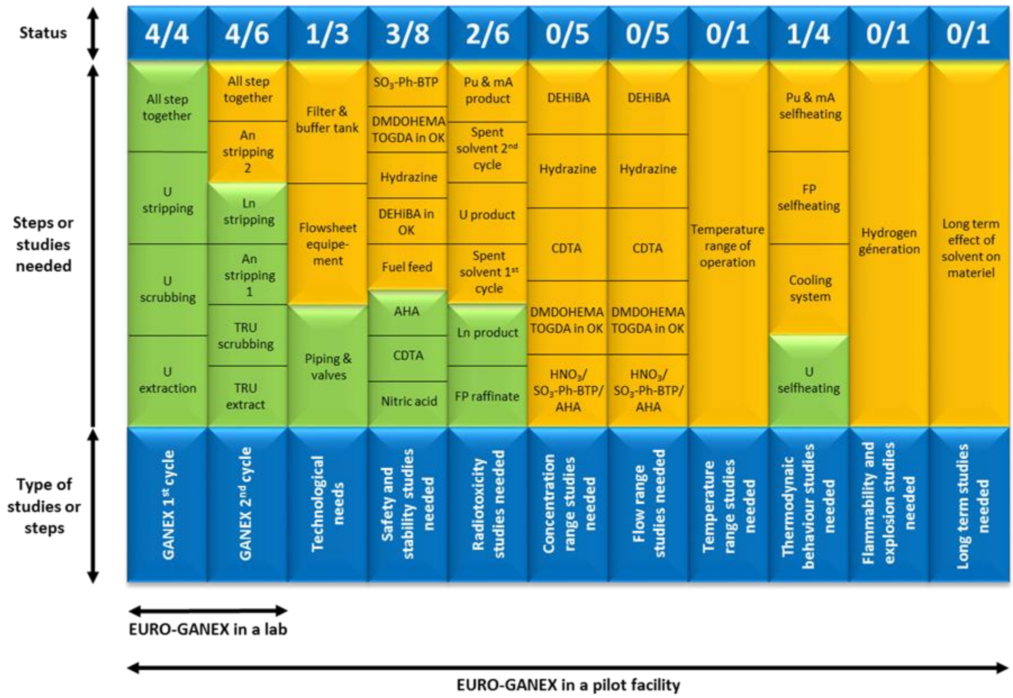

FIG. 11. Maturity level of the EURO-GANEX process.

3.4. The EURO-EXAM process

The lab scale data on the properties and performances of the new TPAEN led to the definition of a process flowsheet which was tested under spiked conditions at Juelich. This allowed us to highlight drawbacks that were not so impacting at the lab-scale, in particular, the quality of the TPAEN (depending on some impurities) and the very sensitive effect of the temperature which highly impact the performances. Following these tests, it has been decided to look for another chemical system.

4. GENIORS

GENIORS started in June 2017 with 24 partners, a total budget of 7.5 M€ and an EU grant of 5M€.

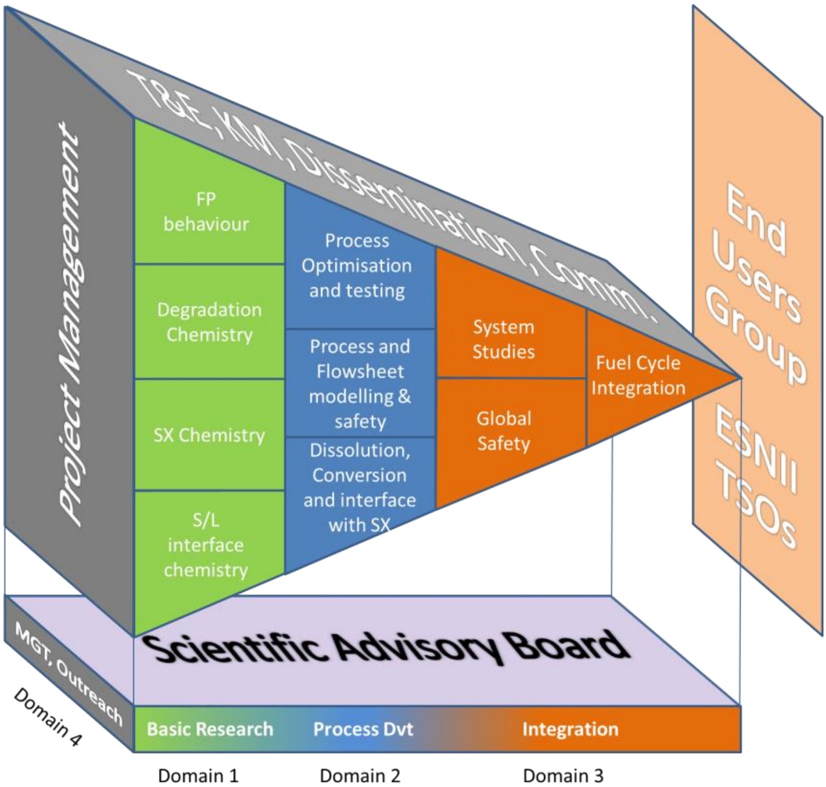

FIG. 12. Organisation of GENIORS.

4.1. Concept and ambition

Based on the progress made in SACSESS it has been decided to continue the safety and technology driven work, with an increase emphasis on the deep understanding of the mechanisms (Fig. 12). The ambition of GENIORS (Fig. 13) is to proceed by down-selection to keep at the end only the routes on which no weakness has been identified. In order to continue improving the reference flowsheets, four main drivers have been identified: the behaviour of problematic fission products, the radiolytic stability of the chemical systems and the impact of the degradation products including gaseous species, the process related issues (kinetics, loading, third phase) and the interface of the separation processes with the dissolution and the conversion.

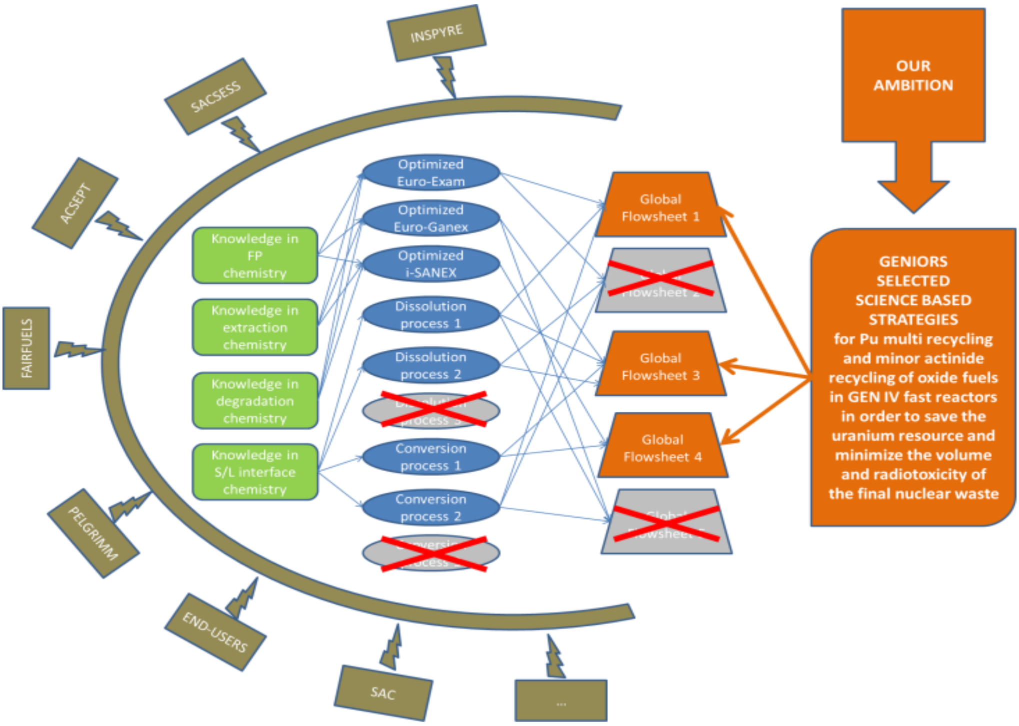

FIG. 13. The ambition of GENIORS.

4.2. Main R&D studies

Following the progress and drawbacks/limitations identified in SACSESS, some key points are today under study in GENIORS.

In particular, the problem of plutonium loading and third phase formation risk in EURO-GANEX initiated an optimisation study on the TODGA. It has allowed the selection of a promising modified diglycolamide with which the use of DMDOHEMA is not needed anymore. The process is simpler. The full assessment of this new molecules is undergoing.

The interface between the separation and conversion processes highlighted that sulphur atom of the sulfonated BTP could be an issue. A new molecule (pitridiol, PTD) following the CHON principle, was selected and is under study.

Based on these new achievements, it has been decided to reconsider the i-SANEX flowsheet and simplify it but also to take benefit of this for redefining the EURO-EXAM flowsheet, without TPAEN.

An innovative back-up option is still developed: the CHALMEX process based on the use of the CyMe4-BTBP in a fluorinated diluent (FS13). This process would allow a direct extraction of the TRUs from the dissolution liquor.

4.3. System and safety studies

The aim of this work is to propose the vision of an emerging process towards industrialisation, with a concept design of a plant and its safety review. The methodology is based on interactive brainstorming workshops, in particular combined with the training and education activities of GENIORS. The first one was organised in October 2018 in Antwerp.

5. CONCLUSIONS

Thanks to the European collaboration, new reference separation processes have been defined, which have excellent performances, at the level of the ones obtained at the CEA with the historic DIAMEX, SANEX, GANEX and EXAM processes. The science-based approach, driven by safety and technological considerations allows the work to be focused on the main issues. Based on this complementary information, and a better understanding of the mechanism, it will be possible to confirm the choices and reduce the number of options and keep only the most relevant, in a global vision.

REFERENCES

[1] C. Poinssot et al., Energy 2014, 6, 199–211
[2] C. Poinssot et al., PiNE 2016, 92, 234–241
[3] P. Joly and E. Boo, SACSESS roadmap — actinide separation processes; 2015.

HAMID AÏT ABDERRAHIM

PARTITIONING & TRANSMUTATION CONTRIBUTION OF MYRRHA TO AN EU STRATEGY FOR HLW MANAGEMENT AND MAIN ACHIEVEMENTS OF MYRRHA RELATED FP7 AND H2020 PROJECTS: MYRTE, MARISA, MAXSIMA, SEARCH, MAX, FREYA, ARCAS

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Abstract. Today, nuclear power produces 11 percent of the world's electricity. Nuclear power plants produce virtually no greenhouse gases or air pollutants during their operation. Emissions over their entire life cycle are very low. Nuclear energy's potential is essential to achieving a deeply decarbonized energy future in many regions of the world as of today and for decades to come, the main value of nuclear energy lies in its potential contribution to decarbonizing the power sector. Nuclear energy's future role, however, is highly uncertain for several reasons: chiefly, escalating costs and, the persistence of historical challenges such as spent fuel and radioactive waste management. Advanced nuclear fuel recycling technologies can enable full use of natural energy resources while minimizing proliferation concerns as well as the volume and longevity of nuclear waste. Partitioning and Transmutation (P&T) has been pointed out in numerous studies as the strategy that can relax constraints on geological disposal, e.g. by reducing the waste radiotoxicity and the footprint of the underground facility. Therefore, a special effort has been made to investigate the potential role of P&T and the related options for waste management all along the fuel cycle. Transmutation based on critical or sub-critical fast spectrum transmuters should be evaluated in order to assess its technical and economic feasibility and capacity, which could ease deep geological disposal implementation.

1. Introduction

Utilization of nuclear energy from fission reaction of uranium (U) and plutonium (Pu) produces high level radioactive waste (HLW) including minor actinides and fission products. For example, the EU presently relies on nuclear energy for ~30 % of its electric power production from Generation II and III nuclear fission reactors leading to the annual production of 2500 t/y of used fuel, containing about 25 t of plutonium, and about 100 t of HLW containing 3.5 t of MAs, namely neptunium (Np), americium (Am) and curium (Cm), and 3 t of long-lived fission products (LLFPs). These MA and LLFP stocks need to be managed in an appropriate way. The used fuel reprocessing followed by the geological disposal (closed fuel cycle) or the direct geological disposal (open fuel cycle) are today the envisaged solutions, depending on national fuel cycle options and waste management policies. The required time scale for geological disposal exceeds our accumulated technological knowledge and this remains the main concern of the general public. Partitioning and Transmutation (P&T) has been pointed out in numerous studies [1] [2] [3] [4] [5] [6] [7] [8] [9] as the strategy that can relax constraints on geological disposal and reduce the monitoring period to technological and manageable time scales (few hundreds of years). Therefore, a special effort has been made to integrate P&T in advanced fuel cycles and advanced options for HLW management. Transmutation based on critical or sub-critical fast spectrum transmuters should be evaluated in order to assess the technical and economic feasibility of this waste management option, which could ease the development of a deep geological disposal.

2. Status today

In most cases and various countries in EU such as France, UK, Belgium, Germany, Spain, Sweden, Italy as well as Japan, USA, Russia, South Korea, R&D and/or demonstration/validation/qualification programmes and infrastructures related to the advanced options for HLW management through P&T and ADS development already exist for more than four decades IAEA-LMFNS [10] OECD/NEA DataBase for WPFC or Experimental Facilities [11] [12]. In 2005, the research community on P&T within the EU in collaboration with the DG Research & Innovation of the European Commission started structuring its research towards a more integrated approach. This resulted in a European strategy based on the so-called four building blocks at engineering level for P&T as summarized below:

- Demonstration of the capability to process a sizable amount of spent fuel from commercial LWRs in order to separate plutonium (Pu), uranium (U) and minor actinides (MA) from Pu based spent fuels,
- Demonstration of the capability to fabricate at a semi-industrial level the dedicated fuel sub-assembly to be loaded in a dedicated transmuter,
- Design and construction of one or more dedicated transmuters,
- Provision of a specific installation for processing of the dedicated fuel unloaded from the transmuter, which can be of a different type than the one used to process the original spent fuel unloaded from the commercial power plants, together with the fabrication of new dedicated fuel.

The four building blocks illustrated in Table 1 must be consistently developed in parallel. This approach is applicable in NI2050 [13] and will result in the identification of the costs and the benefits of P&T for closing the fuel cycle and solving the SNF legacy.

Table 1. P&T building blocks.

P&T building blocks	Description	Name & Location
1 Advanced Partitioning	▪ Demonstrate capability to process a sizable amount of **spent fuel** from commercial Light Water Reactors to **separate** plutonium, uranium and minor actinides	
2 MA Fuel production	▪ Demonstrate the capability **to fabricate** at a semi-industrial level the **MA dedicated fuel** needed to load in a dedicated transmuter	
3 Transmutation	▪ **Design and construct one or more dedicated transmuters**	▪ **MYRRHA (BE)**
4 MA Fuel reprocessing	▪ Specific installation to process fuel unloaded from transmuter ▪ Not necessarily the acqueous reprocessing but **pyroreprocessing & electrorefining**	

The Belgian Government decision on September 7, 2018, to build in Mol the new large research infrastructure MYRRHA is a first sign of the realization of the building block 3 here above. Belgium allocated budget of 558 M€ for the period 2019 – 2038 that would allow to build the phase one of MYRRHA consisting in a linear accelerator up to 100 MeV coupled to a Proton Target facility (called MINERVA) and that will be operational around 2026. The same decision foresees the financing of the further development of the upgrade of the linac towards 600 MeV (phase 2) and of the MYRRHA sub-critical reactor (phase 3) including the support R&D and licensing work.

2.1. Advanced Partitioning

Recycling of plutonium in the nuclear fuel cycle has been established on an industrial scale, leading for example to the use of MOX fuel in power reactors. Once Pu has been removed, the main contributor to the radiotoxicity and heat load of the remaining material is Americium. In the past decade a number of options have been developed and improved to separate Am from the PUREX rafinate. The first process of this kind, called EXAM, was designed at CEA in the 2010's. It was based on the previous DIAMEX-SANEX process that aimed at co-extraction of Am and Curium. The key development was the creation of the suited molecule on which the selective stripping of Am is based. The first test molecule TEDGA (tetraethyldiglycolamide) was in a second phase replaced by TPEAN. Although this molecule showed enhanced selectivity on a lab scale, spiked tests of the EURO-EXAM process were not sufficiently successful to elevate TPEAN as the new reference molecule.

2.2. MA Fuel production

Minor actinide fuel production has been established on a lab scale where it has been shown that the production of targets and small full segments is feasible.

2.3. Transmutation

In the field of transmutation, a distinction needs to be made between the behaviour under irradiation of MA fuel, i.e. the study of the transmutation process itself on the one hand and the development of the transmuter itself on the other hand. Transmutation studies have been carried out in the past using fast sodium cooled critical reactors and dedicated positions in material test reactors. Both homogeneous transmutation, with MA diluted at a low content (< 5%) in the standard driver fuel $(U,Pu)O_2$ or by heterogeneous recycling with MA concentrated (10%-15%) in UO_2 based fuels into the radial blankets (outer part of the core) have been tested. As mentioned above, the transmutation tests have been performed in test reactors that were not designed for transmutation. Although in the development of the new GenIV fast spectrum critical reactors such as ALFRED and ASTRID, transmutation is envisaged, the track towards the development of a dedicated transmuter on an industrial scale runs via the MYRRHA project. A conceptual design for an ADS based transmuter, EFIT, has been developed in the FP6 IP-EUROTRANS. EFIT is a 400 MWth Accelerator Driven System driven by a LINAC delivering 800 MeV protons at a maximal current of 20 mA (typical operation would require 13 mA). The system is a pool-type reactor and the core is cooled by pure lead. The fuel types considered are Inert Matrix Fuels (IMFs) such as CERCER (Ceramic-Ceramic) and CERMET (Ceramic-Metal).

2.4. MA Fuel processing

As the final building block in the Partitioning & Transmutation strategy, one has to consider the reprocessing of the dedicated transmutation fuel. The irradiation times required for an efficient transmutation are rather long and it is uncertain if a single cladding could withstand these harsh conditions. It might also be necessary to adjust the plutonium content of the fuel to compensate for the loss in reactivity (some plutonium will be burned). As with the reprocessing of LWR fuel, also here the technologies can be separated in two groups: the aqueous technologies and the pyro technologies. These innovative fuels pose heavy challenges for the aqueous processes as they will contain significant amounts of plutonium and minor actinides that will pose problems for the stability of the chemicals (both solvents and extractants) used in the processes. The technologically most simple option is just to increase (significantly) the cooling-down period. However, this will have strong negative consequences on the time-scales needed to perform the irradiations. Advanced PUREX and GANEX processes are under development, but only still at laboratory scale. Since pyroprocessing does not rely on solvents and extractants, it will suffer less from the high radiation output of these innovative fuels. However, all technologies from the pyro family are still only available at lab scale.

3. How to improve/accelerate through cooperation

Based on the works performed in the SACSESS and GENIORS projects, a new process concept (AMSEL), relying on promising new molecule families developed for the GANEX and i-SANEX processes were proposed. The next steps in the development is the validation of this newly proposed flowsheet. The basic idea of the AMSEL process is to selectively strip Am from an organic solvent containing Am, Cm and lanthanide fission products. For this purpose the behaviour of both Am and fission product behaviour needs to be investigated. For the latter it is important to investigate whether they will follow the Am in the process. In addition the radiolytic stability of the system needs to be studied. Besides the research aiming at collecting and generating basic data, effort needs to be put in the development of the process itself including proper modelling and flow sheeting and the experimental validation of the process.

The main objectives in the field of transmutation studies are focussed on the behaviour of ^{241}Am in the transmutation process since it is the dominant contributor to the radiotoxicity of the nuclear waste after the removal of Pu. An important step forward is to bring robustness, accuracy and predictability to Fuel Performance Codes (FPCs) Which are the cornerstone of fuel behaviour evaluation and safety analyses. In the context of transmutation, the specific focus is on investigating Am-bearing fuel safety-related behaviour. For this purpose, tree steps need to be taken. Firstly one needs to Extend the validation database of models and simulation codes through the generation of data related to the production and behaviour under irradiation of helium, fission gases and fission products and to the specific thermo-chemical properties of fuels containing Am. Secondly we must Improve the prediction capabilities of FPCs by developing and implementing more reliable mechanistic models, and by moving towards coupling of FPCs with neutronics / thermal-hydraulics codes, for the simulation of normal, off-normal and accidental conditions. Finally, we have to identify the experimental needs for code validation in off-normal situations, leading to the pre-design of a simulation-based transient irradiation tests that can be performed in a dedicated transmuter.. Here a collaboration between the different groups active in transmutation studies in Europe should be encouraged.

In the development of the transmuter, MYRRHA has come to a stage where the licensing process is aimed to be completed by 2026 and the redaction of the required documents including the preliminary safety assessment report (PSAR) should be completed by 2024. As a result, research supporting this effort by delivering input for the PSAR is required to make significant steps forward. Particularly, efforts should be focussed on the safety of the driver fuel and the fuel assembly and core arrangement in off normal conditions including transients, fuel blockages and fuel assembly deformations. The primary system safety should be focussed on the coolability of the system under all circumstances including the investigation of heat transfer and natural circulation in a pool configuration. In addition, sufficient effort needs to be put in the assessment of radiological release from the system, in particular in accident scenarios.

4. Contribution of MYRRHA to the EU strategy towards industrialization of P&T

It is clear that due to the sheer size and cost of an installation like EFIT, one should work on smaller prototypical systems, for all the four building blocks in the European strategy. Moreover, the ADOPT frame work [6] also indicated that a demonstrator facility operating at a power of 50-100 MWth should be constructed as a stepping stone towards EFIT. MYRRHA, as a small-scale Accelerator Driven System that can provide fast neutrons for irradiation purposes, is put forward by SCK•CEN and recognized by the European Commission as a likely demonstrator. MYRRHA as an ADS Demo has the important objectives to:

- Demonstrate the Accelerator Driven System technology
  - Demonstrate the reliability of the proton accelerator
  - Demonstrate the coupling of a proton accelerator and sub-critical core at sufficient power
  - Demonstrate the heavy liquid metal technology
- Demonstrate the feasibility of transmutation in such a system by being able to load sample-sized and pin-sized innovative ADS fuel materials for transmutation research
- Provide representative irradiation conditions in support of
  - Material qualification programs for EFIT
  - Innovative ADS fuel qualification programs for EFIT

MYRRHA has other objectives (radioisotope production, for one) of course, but they are not of relevance for this report.

To design and construct MYRRHA, a series of R&D programs have been launched in the field of accelerator technology, heavy-liquid metal technology and reactor physics (the coupling of an accelerator to a subcritical core). SCK•CEN has established HLM labs for corrosion, for thermal-hydraulic experiments, lead and lead-bismuth chemistry, for component testing etc. All this research and development are essential for MYRRHA but contribute on a larger scale to the design and development of the larger EFIT facility.

5. FP7 and H2020 MYRRHA related projects and their main achievements

Since the establishment of the four building blocks strategy the fostering of the R&D programme within the DG RTD programme for P&T and waste management via the closed fuel cycle, became more evident and led to booking very important results to the programme and the R&D community driving this research. In the next paragraphs of this chapter we are illustrating this progress by summarizing seven projects of FP7 and H2020 related to the subject as well as their main achievements.

MYRTE (MYRRHA Research and Transmutation Endeavour)

The goal of MYRTE is to perform the necessary research in order to demonstrate the feasibility of transmutation of high-level waste at industrial scale through the development of the MYRRHA research facility. Within MYRRHA as a large research facility, the demonstration of the technological performance of transmutation will be combined with the use for the production of radio-isotopes and as a material testing for nuclear fission and fusion applications. Numerical studies and experimental facilities are foreseen to reach this goal.

H2020 MYRTE - main achievements

The MYRRHA Linac has to deliver a high-power proton beam with very high reliability and with minimum beam losses. The emphasis within MYRTE is on the injector which is considered to be the most critical part. The proton source and the low energy beam transport section have been put into operation successfully. The constructions of the first accelerating structure, the 4-Rod Radio Frequency Quadrupole (RFQ) has been completed and pre-conditioning has been performed successfully. To feed the RFQ a 192 kW continuous wave Radio Frequency (RF) amplifier has been developed. To control the RF phases and amplitudes of the injector cavities a Low-Level RF control system is required. The design of the digital system is finished, and the system is ready to be used for the RFQ high power RF and beam tests. The control system for the RFQ is ready for first tests. Several diagnostics devices have been designed and prototypes have been realized. A reliability model of LINAC-4 at CERN has been developed and is under validation with data from operation. Prototypes of the Drift Tube Linac-cavities have been performed successfully. As result, all cavities exceeded the MYRRHA specifications.

In the thermal Hydraulics work package, experiments and simulations go hand in hand. The flow induced vibration experiments have been finished successfully. Two independent approaches implemented in different code platforms have been developed to simulate flow induced vibrations and have already been applied to determine preliminary modal characteristics of a MYRRHA rod bundle.

Volatile radioactive nuclides will be formed in the coolant of the MYRRHA reactor. Therefore, it is important to study chemical reactions that govern the potential release of these nuclides from the coolant to the gaseous environment. The main outcome of previous projects was that volatile species of nuclides form in presence of moisture and when oxide layers are present on the liquid metal. Currently, evaporation experiments are performed to study systematically the influence of moisture and oxygen content in the gas and the oxygen concentration in the liquid metal. These experiments are supported by theoretical studies. Also, the deposition of volatile molecules on surfaces of different materials is studied, with the purpose of finding materials that can be used to remove them from the gas phase. Very encouraging results have been obtained so far. These studies are performed on the most important fission products.

Thanks to the sub-criticality of the reactor, the fuel composition is more flexible for ADS than for a critical reactor, allowing a larger amount of minor actinides in the fuel. However, these advantages hold as long as the reactor remains subcritical. Thus, on-line reactivity monitoring is essential. Several methods of sub-criticality determination including both planned to be applied for ADS and reference ones were used and compared in MYRTE. The positions and deposit of the detectors used for the sub-criticality measurements are of high importance. This subject was thoroughly investigated. The experiments dedicated to the safety issues such as coolant and moderator voiding were completed. The calculations are in acceptable agreement with the experiments.

A specific work package in MYRTE is investigating topics issues related to the safe use of $(U,Am)O_{2-x}$ fuel as basis for transmutation of Am. Samples of sub-stoichiometric $(U,Am)O_{2-x}$ have been prepared, and their thermal diffusivity was measured in the temperature range between 500 K and 1600 K. Fuel to liquid lead bismuth metal interaction tests have been performed on representative $(U,Am)O_{2-x}$ samples in contact with LBE at 500°C for 50 h under oxidizing and non-oxidizing conditions. The samples were characterized afterwards and no significant changes or interaction products were found.

MARISA (MYRRHA Research Infrastructure Support Action)

The FP7 project MARISA reviewed advanced fuel cycles and approaches for the long-term management of radioactive waste considered in the EU and nations worldwide. Work performed as part of MARISA confirmed the foremost role of MYRRHA in developing and demonstrating the concept of P&T with the long-term objective of industrial deployment. Furthermore, research capabilities offered by MYRRHA will allow for integrating diverse national and international research programmes on Partitioning & Transmutation.

FP7 MARISA - main achievements

The main achievements of MARISA have been the confirmation of positioning of MYRRHA as an International Open Users Facility in the European and global research landscape; MYRRHA legal structure, articles of association, intergovernmental agreements, governing rules, procedures for in-kind contributions and IPR defined; MYRRHA management principles developed, management instruments implemented and access framework for User Groups and Communities detailed; MYRRHA financing mechanisms and instruments defined; MYRRHA Environmental Impact Assessment Report development initiated; Technical integration MYRRHA primary system design, accelerator and Balance of Plant accomplished.

MAXSIMA (Methodology, Analysis and Experiments for the safety in MYRRHA Assessment)

The goal of MAXSIMA is to contribute to the "safety in MYRRHA" assessment.

FP7 MAXSIMA - main achievements

Neutronic and shielding analysis as well as transient analyses using system codes in support of the MYRRHA safety studies have been carried out. The following main topics of the MYRRHA safety analysis have been studied in specific tasks of the MAXSIMA project:

- Design of the MYRRHA core (and required shielding studies) using 3-D methods
- Study of a complete list of accidental events and analysis of input data uncertainty propagation in the safety-relevant output parameters
- Analysis of a number of severe accident scenarios potentially leading to core disruption.

  Also, the safety aspects of the fuel assemblies and the control and safety rods of the reactor core have been analysed. In the fuel assembly, the cooling of a partially blocked fuel rod bundle was experimentally investigated. A second experiment was carried out to validate the correct movement of buoyancy driven control. Both experiments were numerical supported by CFD simulations. See FIG. 12 for the control rod qualification.

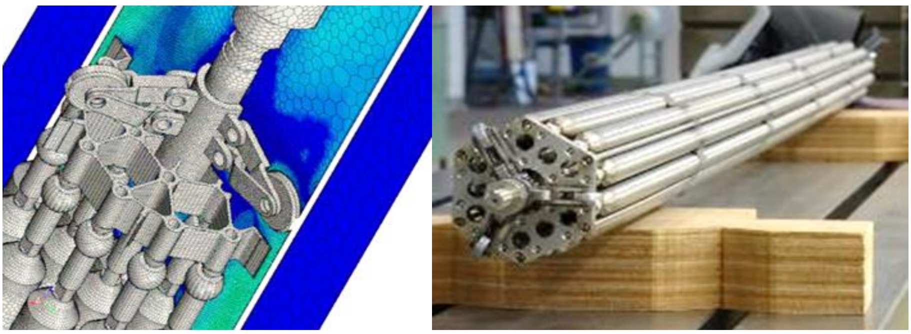

FIG. 12 MYRRHA Control Rod Qualification.

To demonstrate the safety level of a steam generator in the primary pool, a large scale experiment has been designed, constructed and successfully carried out. The goal of the experiment was to characterize the Steam Generator Tube Rupture (SGTR) event in a configuration relevant for MYRRHA. In parallel numerical tools have been verified and validated to support the design phase as well as the safety assessment of such solutions. Post-test analysis was able to predict pressure and temperature time trends in agreement with experimental data, providing a contribution to code validation for water-LBE interaction scenario in a large pool facility.

The TRIGA Annular Core Pulsing Reactor (ACPR) at INR-Pitesti was used as a testing facility for transient test experiments. Fuel test segments (UO_2, DIN 1.4970 cladded) were designed and fabricated by SCK•CEN and were transported to INR-Pitesti (Romania). The objective of the tests is to establish the failure threshold, expressed in deposited energy in the fuel, for fast transients. All transient test results of the UO_2 tests were reported, design for MOX fuel fabrication and the MOX fuels fabrication test results were issued. It is intended to carry out transient test experiments in a follow-up project. See FIG. 13.

FIG. 13 MYRRHA Fuel Transient testing in TRIGA ACPR of ICN in Pitesti.

An enhanced innovative passive safety system for Decay Heat Removal (DHR) of heavy liquid metal cooled reactors was developed. For such reactors the systems dedicated to heat removal should also guarantee that the primary coolant is not brought to the so-called freezing or solidification condition. Simulations have been carried out by computational tools (RELAP5 and TRACE) showing that the system is able to fulfil the expectations.

The records of the publications and dissemination activities can be summarised as follows: 10 journal papers, more than 80 contributions to national/international conferences/workshops and 20 contributions to lecture series/summer schools.

SEARCH (Safe exploitation related chemistry for HLM reactors)

In accordance with the ESNII roadmap MYRRHA will be the first HLM cooled nuclear system to be deployed in Europe. The SEARCH project aimed to support the licensing process of MYRRHA by investigating the safe chemical behaviour of the fuel and coolant in the reactor. The control of the oxygen content and the management of impurities in the melt will be studied. A second critical issue in the safety assessment of a nuclear system is the compatibility of the fuel with the coolant after fuel pin leakage or a core melt. The full analyses of these scenarios using validated codes require more experimental data on "basic" properties of the interactions between the materials involved. For that, the heat transfer coefficients of a wire-spaced fuel bundle and the basic chemical behaviour of a mixture of fuel, coolant and clad materials range will be studied at relevant temperatures. The compatibility experiments will be done with UO2, PuO2 and unirradiated MOX fuel, addressing the energy release, solubility in the coolant and fuel-coolant-clad compound formation. Fuel dispersion in the coolant will be simulated by a suitable numerical approach, aiming to address the migration of the fuel and the possibility to have criticality problems due to fuel accumulation. The prevention of risks to the general public will be studied by looking into the escape of radioactive materials including fission products and heavy volatile elements as Po and Hg into the environment. The kinetics and efficiency of methods to capture these elements in the cover gas system will be examined. The evaporation of Po and Hg from LBE will be measured to obtain a full data set for licensing. Issues related to Po management will be also addressed by an ab initio theoretical approach, predicting its solubility in LBE, the interaction with noble metals to select possible getters and studying formation of Po-compounds.

FP7 SEARCH - main achievements

The main achievements of SEARCH project have been the following. Firstly, heat transfer test of a wire-spaced fuel bundle mock up in in forced and natural convection were performed. Here, a heat transfer correlation was established that can be used for further analyses of the reactor design. Secondly, significant steps were taken in the development of impurity and oxygen control techniques and methods were taken. The impurity source terms from corrosion and spallation were determined and mechanical and cold trap filtering tests were performed. The project also showed the compatibility of homogenous and sintered MOX fuel with LBE at 500°C and 800°C. In these tests the pellet integrity was maintained completely and no compound from chemical interactions between the lead bismuth coolant and the MOX fuel were found.

The project also built CFD and Simmer models for fuel dispersion studies where particle transport studies, accumulation zones were determined. Finally, the project measured the release of Hg and Po from LBE where in the case of Hg it studied the ideal behaviour while in the case of Po it studied the dependence on the covergas and LBE oxygen content. We found that volatile molecules are formed with water vapour but also that the Po compounds for a stable deposition on steel below 300°C.

During the project, two workshops & one lecture series was organized.

MAX (MYRRHA Accelerator eXperiment)

The present FP7 proposal MAX is subsequent to the recommendations of the Strategic Research Agenda of SNETP for ADS development in Europe. It is aimed to pursue the R&D required for a high-power proton accelerator as specified by the MYRRHA project. There is especially a strong focus on all the aspects that pertain to the reliability and availability of this accelerator.

This R&D effort builds on the large body of results and the clear conclusions that have been obtained during the consecutive FP5 project PDS-XADS and FP6 project EUROTRANS.

FP7 MAX - main achievements

With respect to the EUROTRANS outputs, a very significant progress has been made on the path towards the accelerator for MYRRHA. From the very start, MAX has been organized around the actual needs of the MYRRHA Linac and thereby has been able to focus on the specific requirements of this machine. This has led to a number of achievements that are all fundamental in view of the reliability goal.

- A fully reliability-oriented overall consolidated concept of the accelerator.
- A set of benchmarked modelling tools allowing for start-to-end beam simulations.
- An operational reliability model based on the SNS experience.
- An adequate and realistic injector design.
- A detailed engineering design of a few critical elements.

Specific experiments, matched to particular aspects of an ADS-accelerator, have also supported some of these achievements or provide valuable information for future and further developments.

- Cooling performance tests of the 4-rod RFQ model cavity in real CW RF operation.
- Investigation of the behaviour of a low-β elliptical superconducting (SC) cavity in accelerator-like conditions (2K, high RF power).
- Assessment of a SC cavity fault-recovery scenario using a digital low level RF feedback system and featuring an adaptive tuner controller.
- RF test of a superconducting CH cavity at 4K and 2K in vertical cryostat.
- Performance of a 704 MHz solid state RF amplifier module and associated power combiner.

A particularly strong achievement of the results generated by the MAX programme is the global level of confidence, in the concept on the one hand, and in the feasibility of its components on the other hand. This level of confidence is coherent with the fact that MAX has now brought to the first major milestone on the road towards the realisation of the MYRRHA Linac, this milestone being labelled "ready for prototyping". It is the starting point of a new set of mandatory R&D activities where the emphasis should lie on experimental optimisation.

FREYA (Fast Reactor experiments for hYbrid Applications))

Building up on the former activities accomplished in the previous FPs, namely MUSE in FP5 and EUROTRANS in FP6, it is proposed in the FREYA project to extend the investigations of the subcritical configurations for validation of the methodology for on-line reactivity monitoring of ADS systems. The investigations will be related to the different subcriticality levels for the nominal operation mode of ADS. In order to investigate the robustness of several proposed measurement techniques with regard to the reflector effect, it is foreseen to perform experiments with different reflector materials. To complete the validation of the methodology for subcriticality monitoring, the robustness of the reactivity indicators with regard to a change in vertical position of the neutron source will be investigated in view of possible variations of the height of the spallation source in a real ADS. On the other hand, given the objectives for MYRRHA/FASTEF as studied within FP7 CDT to be operated as a subcritical facility and a critical facility, an experimental programme in support of the design and licensing of both operation modes is needed. Although the experimental programme with regard to the critical mode operation of MYRRHA/FASTEF can generate useful information for the validation of reactor codes for LFR development, a dedicated effort for the validation of reactor codes for LFR developments is envisaged by the LFR community.

FP7 FREYA - main achievements

The main achievements of FREYA project can be summarized as follows:

Several VENUS-F fast reactor cores were coupled to an GENEPI-3C accelerator that delivers a deuteron beam. GENEPI-3C provides an external neutron source to the VENUS-F reactor through T(d,n)4He fusion reactions. Different sub-criticality levels of the VENUS-F fast core for the nominal operation mode of ADS (k-eff varied 0.95-0.99) as well as a deeper subcritical level of 0.90 (core loading) were studied. The applicability of the different sub-criticality measurement techniques was investigated. FREYA experimental programme with regard to the LFR as well as for the critical mode operation of MYRRHA for the licensing of these designs so as for the validation of reactor codes has been accomplished. Six workshops were held as well as a one week dissemination lab-session.

ARCAS (ADS and fast Reactor CompArison Study)

The objective of the proposal is based on the outcome of PATEROS CA to assess more in depth the regional approach to P&T implementation. It will respond to one of the key-topics put forward by the Strategic Research Agenda of SNETP. The project intends to look at the economical aspects of the most realistic scenario for P&T with the hypothesis: limit the MA bearing fuel transport and limit the MA bearing fuel handling in and between all places such as at the reactor, at the fuel fabrication and at the reprocessing plant. We would like to assess the cost associated to implementing ADS's or dedicated Fast Reactors as minor actinide burning facilities. The idea is to start from two fixed hypotheses: (1) we work in double-strata approach and look only at the second ("burning" stratum); (2) we assume a certain influx of minor actinide mass per year that needs to be burned. These two hypotheses will allow the project to avoid extensive scenario studies.

The economic impact will be evaluated for investment cost, associated fuel cycle and operational cost but not the needed R&D cost. A crucial parameter to be established for both reactor systems is the maximal minor actinide (MA) content in a core loading. This maximal MA value is determined by operational safety criteria to be adhered by the dedicated burner. An evaluation of a number of safety parameters for the systems will give an upper boundary for the minor actinide mass present in the core.

In order to not diversify the work, the project should define a generic and representative system for the ADS approach and the FR approach. For the ADS, one can benefit from the work done in the FP6-EUROTRANS on the EFIT design. For the FR, one could use an SFR or LFR as a starting point. However, the design should be optimized to the task of a dedicated burner. Concerning the FR two options could be envisaged for the core lay-out: driver fuel with blanket or homogeneous mixture.

FP6 ARCAS - main achievements

ARCAS project main achievements have been: Establishing a reference minor actinide stream for a European region eligible for transmutation; study of homogeneous and heterogeneous transmutation in sodium-cooled Fast Reactor from FP7-CP-ESFR; study of homogeneous transmutation in lead-cooled Accelerator Driven System EFIT from FP6-IP-EUROTRANS; state-of-the-art report on transmutation fuel fabrication and reprocessing, including Technological Readiness Levels; scenario studies, including economic assessment, of transmutation in a regional European frame work.

FP7 Conclusions

In this paper we tried to summarize the importance of the EURATOM Framework Programme acting as a trigger to foster the national efforts together with the DG RTD framework programme for reaching serious progress in a demanding R&D programme in terms of diversity of needed skills and competencies, various experimental unique facilities and laboratories as well as in financial means needed for such an endeavour aiming to industrializing a full concept of closing the fuel cycle in a European regional approach with different national policies towards nuclear energy.

The enormous work sitting behind these projects would not have been possible without the long standing support including financial one from the EURATOM DG RTD frame work programmes since the FP5 and continued in FP6, FP7 and H2020 for which the authors on behalf of the community they represent are very thankful.

References

[1] OECD/NEA, "Accelerator-Driven Systems (ADS) and Fast Reactors (FR) in Advanced Nuclear Fuel Cycles: a Comparative Study," OECD/NEA, 2002

[2] OECD/NEA, "Potential benefits and impacts of Advanced Nuclear Fuel Cycles with Actinide Partitioning and Transmutation," OECD/NEA, 2011.

[3] OECD/NEA, "Impact of Advanced Nuclear Fuel Cycle Options on Waste Management Policies", 2006.

[4] OECD/NEA, "Advanced Nuclear Fuel Cycles and Radioactive Waste Management", OECD/NEA, 2006.

[5] H. Oigawa, T. Yokoo, K. Nishihara, Y. Morita, T. Ikeda and N. Takai, "Parametric survey for benefit of partitioning and transmutation technology in terms of high-level radioactive waste disposal", Journal of Nuclear Science and Technology, vol. 44, no. 3, pp. 398-404, 2007.

[6] Aït Abderrahim, H., ADOPT Final Report - Recommendations for the EC for Further Activities in P&T and ADS Development. ADOPT Thematic Network (FIKW-CT-2001-20178), 2005.
[7] M. Salvatores, V. Meyer, V. Romanello, A. Boucher and A. Schwenk-Ferrero, "PATEROS D2.2: Results of the scenario studies”, 2008.
[8] Venneri, F. & Bowman, C. & Jameson, R.A.. Accelerator-Driven Transmutation of Waste (ATW), A New Method for Reducing the Long-Term Radioactivity of Commercial Nuclear Waste. 1993.
[9] CEA. Bilan des recherches conduites sur la séparation-transmutation des éléments radioactifs à vie longue et sur le développement de réacteurs nucléaires de nouvelle génération. CEA, 2012.
[10] “Experimental Facilities in Support of Liquid Metal Cooled Fast Neutron Systems. A Compendium”. https://nucleus.iaea.org/sites/lmfns/Pages/default.aspx, retrieved 2019-09-13.
[11] OECD/NEA, State-of-the-Art Report on the Progress of Nuclear Fuel Cycle Chemistry, OECD/NEA, 2018
[12] OECD/NEA, Review of Operating and Forthcoming Experimental Facilities Opened to International R&D Co-operation in the Field of Advanced Fuel Cycles, OECD/NEA, 2019
[13] Nuclear Innovation 2050 (NI2050), https://www.oecd-nea.org/ndd/ni2050/, retrieved 2019-09-13.

LORENZO MALERBA

ADVANCES ON GENIV STRUCTURAL AND FUEL MATERIALS AND CROSS-CUTTING ACTIVITIES BETWEEN FISSION AND FUSION

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Abstract. This paper describes six projects, most of which are part of the research portfolio of the EERA JPNM, devoted to qualification, modelling and development of structural and fuel materials for advanced and innovative nuclear systems, with also two examples of projects addressing issues of cross-cutting interest through fusion and fission. The main conclusion is that the benefit of the coordination under the umbrella of, in this case, the EERA JPNM, is clearly felt in terms of better alignment of national programmes and subsequent leveraging of institutional funding, to integrate Euratom support. Likewise, the benefit of addressing specific issues of common interest for fusion and fission is not only beneficial because of cross-fertilisation, but also because it allows more rational use of human and infrastructural resources, avoiding duplications.

1. Introduction

The sustainability of nuclear fission energy will be ensured when Generation IV (GenIV) systems are deployed. These can (i) produce more fuel than they consume, guaranteeing low-carbon energy production for centuries through recycling, without additional mining, in a circular economy; (ii) offer ~50% higher thermal efficiency and increased standards of passive safety than current reactors, thereby becoming both societally and economically attractive; and (iii) reduce significantly the volume and radiotoxicity (decay time < 1000 years) of nuclear waste. However, materials will be exposed to high levels of temperature and irradiation, with some in contact with potentially aggressive non-aqueous coolants, targeting a 60 year operation reactor design; likewise, fuel and fuel elements will need to ensure that high burnups are reached, including the possibility of burning minor actinides. Thus, the development, screening and qualification of suitably performing and affordable structural and fuel materials are crucial to make GenIV reactors an industrial and commercial reality, with positive impacts on economy, safety, waste, and thus sustainability of nuclear energy.

Thermo-nuclear fusion represents in the longer term a virtually inexhaustible source of energy with potentially very high standards of sustainability, efficiency and safety, thanks to the wide availability on earth of deuterium and lithium (from which tritium is self-produced by nuclear reaction in the reactor itself), the inert nature of the reaction products, the high density of energy that the reaction can provide and the inherent safety of the system. The main wastes in fusion are activated structural materials. These are moreover expected to withstand unprecedentedly harsh conditions in terms of thermal shocks, radiation dose, and also exposure to high temperature and contact with coolants/tritium breeders, the compatibility with which needs in some instances to be demonstrated. Despite the differences between GenIV fission and fusion, because of the extreme conditions expected in both systems several materials issues are in common. On the other hand, the main safety issue for fusion is represented by tritium management in terms of need to reduce inventory and avoid release. Solutions to this problem bear commonalities with fission.

In this framework of structural and fuel materials for GenIV and fission/fusion cross-cutting issues, the present paper will describe six projects, four of which are ongoing as part of H2020 and roughly half way through, namely GEMMA [1], INSPYRE [2], M4F [3] and TRANSAT [4], while the remaining two, MatISSE [5] and PELGRIMM [6], are now concluded and were part of FP7. Of these six projects, four (GEMMA, INSPYRE, M4F and MatISSE) are integrating part of the research portfolio of the Joint Programme on Nuclear Materials of the European Energy Research Alliance (EERA-JPNM) [7,8], which will also be described.

2. The Joint Programme on Nuclear Materials of the European Energy Research Alliance (EERA JPNM)

EERA [7] was created in 2007 as the initiative of a number of European public research centres in order to join forces and coordinate efforts towards a low carbon energy economy in Europe. Since 2014 it is an international non-profit association (EERA AISBL). Currently, it brings together more than 250 organisations and coordinates the work of around 50,000 researchers from 30 countries, being Europe's largest energy research community.

EERA's official mission is to help streamline regional, national and European efforts, in order to deliver scientific and technical results from basic research to the demonstration phase (TRLs 2 to 5) and ensure efficient transfer to industry and market. EERA is the research pillar of the European Union's Strategic Energy Technology Plan (SET-Plan) [9].

EERA's members work together in, currently, 17 research joint programmes (JPs). These pursue research goals along shared agendas covering the whole range of low-carbon energy technologies, including social and economic aspects of the energy transition and addressing also the systemic nature of the transition to a zero-carbon society.

The EERA JPNM is one of the 17 EERA JPs, one of the two dealing with materials and the only one dealing with nuclear energy related activities. As such, the EERA JPNM acts as bridge and link, in research terms, between nuclear energy and other low carbon energy sources and systems. The reason for the focus on materials is the pivotal importance that these have in view of safety and sustainability of nuclear energy, as well as innovation in the energy field in general.

The objective of the EERA JPNM is to improve safety and sustainability of nuclear energy by focusing on materials aspects. This has two implications:

- Better knowledge of materials behaviour under operating conditions, to select the most suited materials and define safe design rules, especially allowing for radiation and temperature effects, while caring for compatibility with coolants.
- Development of advanced materials with superior capabilities, either through improved and advanced fabrication and processing methods, or adoption of new types of materials, in terms of resistance to high temperature, irradiation and aggressive environments.

Three grand challenges (GC) have been accordingly identified (JPNM Vision Paper [10]):

- GC1: Elaborate design correlations, assessment and test procedures for the structural and fuel materials that have been selected for the demonstrators under the service conditions expected.
- GC2: Develop physical models coupled to advanced microstructural characterization to achieve high-level understanding and predictive capability
- GC3: Develop innovative materials solutions and fabrication processes of industrial application to achieve superior materials properties, to increase safety and improve efficiency and economy.

A Strategic Research Agenda (SRA) [11] identifies the research lines to be pursued in the EU to ensure that suitable structural and fuel materials are available for the design, licensing, construction and safe long-term operation of GenIV nuclear systems, including an analysis of corollary aspects such as infrastructures, education and training, interaction with industry and international cooperation.

Currently, more than 50 organisations collaborate under the coordination of the EERA JPNM, by contributing to at least one of the six subprogrammes in which its activities are organized, devoted to qualification, modeling and development of structural and fuel materials.

One of the main instruments of implementation of the SRA of the EERA JPNM, in terms of alignment of research actions between the different organisations involved, are the so-called pilot projects. These are small projects of 3-4 year duration focused on precise topics that result from the convergence of research interests and lines of organisations from different member states. The Euratom-funded projects launched under the umbrella of the EERA JPNM, which are described in this paper, are the result of juxtaposing a number of JPNM pilot projects under a consistent framework. As such, these projects should not be looked as separate entities, but rather as different contributions towards the goals set out by the EERA JPNM SRA.

3. PELlets versus GRanulates: Irradiation, Manufacturing & Modelling (PELGRIMM)

Call: FP7-Fission 2011- R&D activities in support of the implementation of the SRA of SNE-TP
Grant agreement number: 295664
Starting date: 01/01/2012
Duration: 66 months
Budget: 7.2 M€ (3 M€ of contribution from Euratom)
Participants: 12 (AREVA, CEA, EDF, ENEA, ENEN, JRC, KIT, KTH, LGI, NRG, PSI, SCK-CEN)
Coordinator: F. DELAGE, CEA

PELGRIMM investigated Minor Actinides (MA) bearing fuels, shaped as pellets and beads, for GenIV–Sodium Fast Reactor (SFR) systems. Both MA transmutation options were considered, namely: MA homogeneous recycle in driver fuels and MA heterogeneous recycle on UO_2 fuels located in radial core blankets. The consortium included research laboratories, universities and industries, sharing their progress and achievements, and leveraging their skills, both experimental and in modeling and simulation, on the following topics: fuel fabrication and characterization, including behaviour under irradiation, of both pellet and sphere-packed loaded core design fuel, extended to safety performance pre-assessment from normal operating conditions to transients and severe accidents, to keep the link between fuel investigations and key issues of core physics.

Innovative irradiation tests and Post-Irradiation Examinations (PIE) performed within the project have largely contributed to improve the knowledge on Am-bearing fuel behavior under irradiation for both concepts: MA-Driver Fuels MADF) i.e. $(U,Pu,MA)O_2$ and MA-Bearing Blanket fuels (MABB)i.e. $(U,MA)O_2$, in spherepac and pellet forms. Regarding the MADF concept, The PIEs of the semi-integral SPHERE irradiation showed that, for comparable irradiation conditions the behaviour of different shaped fuels were rather similar. The main difference lies in the presence of fuel-clad mechanical interaction for pelletized fuels, apparently absent for sphere-packed fuels. The MABB concept got over a key step of its qualification program with the PIE of the first separate-effect irradiation MARIOS and the first semi-integral irradiation MARINE. MARIOS PIE showed the $(U,Am)O_2$ discs (i.e. MABB fuel) to be in relatively good shape after irradiation in the temperature range of 1000°C-1300°C. Irrespective of fuel porosity and irradiation temperature, no significant swelling was measured (only tailored porosity disks were slightly densified), and all helium produced during irradiation was released, whereas the released fractions of Kr and Xe were strongly temperature dependent.

Alternative routes of MA-bearing fuel fabrication processes were investigated to seek for improvements (simplification, robustness, lower secondary waste streams…). The Am-bearing fuel for MARINE, both pellet and spherepac types, were synthesized by infiltration of americium nitrate solutions in porous UO2 precursor beads prepared by sol-gel gelation. In addition, a variant of the sol-gel process, based on micro-wave internal gelation was developed and a new dedicated facility is now available. In parallel, the adaptation of the WAR process to the synthesis of (U, Am)O_2 beads and pellets provided promising results and high densified pellets were prepared. By demonstrating the feasibility of these different fuel synthesis routes, PELGRIMM opened the path to new possibilities for Am-bearing fuel developments. Moreover, the capabilities of fuel performance codes were improved thanks to the implementation of more mechanistic models, new numerical methods, more reliable properties laws, etc. The outcome of the benchmarks performed are encouraging: first attempts to simulate the fuel behaviour during SPHERE, SUPERFACT and MARIOS irradiations provided in most cases, preliminary calculated results consistent with PIE results.

In parallel, an optimized core loaded with (U,Pu,Am)O_2 spherepac driver fuels was realized and the corresponding safety performance assessment successfully performed. Two relevant accidental situations were analyzed: Unprotected Loss Of Flow accident (ULOF) and Unprotected Transient Over-Power accident (UTOP). Based on preliminary studies, the implementation of spherepac fuel would not cause any specific design or safety issue, if introduced in an SFR. Therefore, thanks to PELGRIMM a long step forward has been taken [12] in the long term process of the MA-bearing fuel qualification, initiated within the European projects ACSEPT (2008-2012), F-BRIDGE (2008-2012), CP-ESFR (2008-2013) and FAIRFUELS (2009-2015). Besides, links within PELGRIMM and ASGARD FP-7 projects implemented in parallel have led to bridge the fuel development to the fuel cycle back-end.

4. Materials' Innovation for Safe and Sustainable Nuclear in Europe (MatISSE)

Call: FP7-Fission-2013
Grant agreement number: 604862
Starting date: 01/11/2013
Duration: 48 months
Budget: 8.6 M€ (4.7 M€ of contribution from Euratom)
Participants: 29 (CEA, ENEA, CNRS, CIEMAT, CENTRO SVILUPPO MATE, CV REZ, CNR, EDF, HZDR, JRC, KIT, KU LEUVEN, KTH, LGI, U. Stuttgart, NNL, NRG, PSI, POLITO, ICN, SCK·CEN, UOXF, U. Alicante, VTT, U. Birmingham, Coventry U., U. Manchester, Open U., KAERI) – 13 countries
Coordinator: P.F. Giroux, CEA

The **MatISSE project** was fully embedded in the EERA JPNM, aimed at building a European integrated research programme on materials innovation for a safe and sustainable nuclear. The selected scientific and technical work was directed to progress in the fields of conventional and advanced nuclear materials, including capability to forecast their behaviour in operation, with emphasis on fuel and structural elements for advanced nuclear systems, reflecting the subprogramme structure of the JPNM at the time of the launch of the project.

In addition, MatISSE included a Coordination and Support Action, focused on allowing the evolution of the JPNM towards a more structured and solid way of working, including (i) networking with public authorities, (ii) harmonisation of best practices and implementation of communication tools and (iii) a common research strategy, appropriate organisation, knowledge management and the organisation of project calls.

The R&D activities of MatISSE were selected as being relevant for the European Sustainable Nuclear Industrial Initiative (ESNII), applying both experimental and theoretical approaches and organized in seven work packages (WP), each one with specific objectives (WP6 and WP7 were dedicated to dissemination, communication, E&T and management).

WP1 was dedicated to coordination and support to the JPNM. The efforts made in the different tasks of this WP resulted in various good achievements (e.g. description of work document, vision paper, SRA, pilot projects, cross-cutting workshops, memorandum of understanding with SNETP, E&T scheme, JPNM website) and hence further developed the JPNM as IRP.

WP2 was organized in two research areas, one devoted to the modelling of the microstructural embrittling features in irradiated ferrite/martensite (F/M) alloys and their effect on radiation-induced hardening (MEFISTO), the other to the modelling of irradiation creep starting from its microstructural origin in the same materials (MOIRA). Attention was focused on studying the nature, origin and effect of microstructural evolution under irradiation on the induced hardening. Developed atomistic models and dislocation dynamics models lead to determine the effect of the different microstructural features on radiation hardening and resulted in the prediction of the mechanical properties of different steels after irradiation.

WP3 had as objective the characterization of ceramic composites for GFRs and LFRs. This WP focused on the manufacturing and assessment of full ceramic SiC/SiC, sandwich type SiC/SiC (with internal tantalum liner) clad sections and MAX phase-based cermets. Investigations of mechanical, leak tightness and thermal properties of SiC/SiC composites were performed and encouraging results on SiC/SiC and sandwich clad compatibility with impure flowing He were obtained.

WP4 focused on characterization of ODS alloys for LFR and SFR cladding. A comprehensive and consistent description of the microstructures and mechanical properties of the ODS alloys extruded bars and tubes was performed, leading to a better understanding of the properties of these materials. 14Cr ODS tube showed a higher resistance than the 9Cr ODS tube during internal pressure creep tests.

WP5 consisted of four tasks addressing topics that had been identified by the ESNII reactor designers: (i) develop models and conduct mechanical tests for creep-fatigue of F/M and austenitic steels with emphasis on cyclic softening and crack propagation; (ii) evaluate the compatibility of some specific designed coatings for claddings and surface alloys for structural materials with Pb alloys as the working fluids; (iii) investigate fuel-cladding interactions for fuel pin of advanced nuclear systems, providing guidelines to include fuel-cladding interaction in the design; (iv) investigate the mechanisms of crack initiation and propagation under constant and cyclic load conditions for F/M steels and austenitic steels in lead based alloys.

5. GenIV Materials Maturity (GEMMA)

Call: WP-2016-2017-NFRP-5: Materials research for Generation-IV reactors
Grant agreement number: 755269
Starting date: 01/06/2017
Duration: 48 months
Budget: 6.6 M€ (4 M€ of contribution from Euratom)
Participants: 23 (ENEA, SCK-CEN, KAERI, NCBJ, PoliMI, WT, KTH, SINTEC, CIEMAT, KIT, AALTO University, UKAEA, CV-Rez, IIT, SANDVIK, EDF, CNR, CNRS, NOTTINGHAM University, CEA, JRC, RATEN, UTBM) – 12 countries
Coordinator: P.Agostini, ENEA

The GEMMA project addresses research, development, qualification and standardization of austenitic steels for GENIV reactors and technologies, including their protection and welding, this being one of the main research lines identified in the EERA JPNM SRA.

Through a wide use of experimental techniques, the project intends to:

- Qualify existing materials for the hostile conditions that are envisaged in GENIV systems;
- Perform screening for the selection of new materials, expected to be more resistant to the typical conditions encountered in GEN IV applications;
- Develop protective coatings to mitigate the effect of corrosion in GEN IV reactors;
- Improve and validate predictive models of material damage through dedicated experiments and forthcoming model refinement.

Presently, the materials to be qualified, including corrosion-protected materials and welded joints of various kinds, have been developed and distributed to the partners to allow the qualification to start. The base materials are slabs and plates of AISI 316L and 15-15 Ti steels, in both the MYRRHA and ALFRED variants. The welds were produced by TIG and SAW techniques, which were optimized in the project itself. Protections from corrosion were applied using innovative GESA (Gepulste Elektronen Strahl Anlage) methods and both PLD (Pulsed Laser Deposition) and Detonation Gun coatings; protected specimens will be subjected to mechanical and corrosion tests.

Effort was devoted to develop and test Alumina Forming Austenitics (AFA) steels. The most promising ones, in terms of corrosion resistance, were selected through accurate screening of properties, among over twenty different chemical compositions, in particular different aluminum, chromium and reactive element contents, with the contribution of an important European steel-maker. This indusrial involvement will enable a rapid shift to large-scale production for the most promising material and subsequent access to market.

Concerning welds, in addition to conventional testing a careful assessment of post-weld residual stresses was carried out on a welded slab that accurately reproduces the welds of the main vessel of ASTRID by high resolution neutron diffractometry, a technique that accurately assess detects even the smallest deformations of the crystalline lattice. This experiment is also aimed to validate stress models developed by GEMMA partners. It should be noted that the neutron diffraction of large welded pieces constitutes a novel application and permits a precise and volumetrically distributed evaluation of the tensional state within the joint. In parallel, thermodynamic and kinetic models for Fe-Ni-Cr model alloys under irradiation were developed; experimental studies of elemental diffusion phenomena on multi-layered samples, produced in the Project, will be used for model validation.

6. Investigations Supporting MOX Fuel Licensing in ESNII Prototype Reactors (INSPYRE)

Call: WP-2016-2017-NFRP-5 – Materials research for Gen-IV reactors
Grant agreement number: 754329
Starting date: 01/09/2017
Duration: 48 months
Budget: 9.37 M€ (4 M€ Euratom contribution)
Participants: 14 (CEA, JRC, ENEA, NNL, NRG, PSI, SCK.CEN, EDF, CNRS, U. Aalto, KTH, Polimi, TU Delft, LGI) – 8 countries
Coordinator: M. Bertolus, CEA

Fuel is at the heart of all nuclear reactor systems. Mastering the understanding of its behaviour is challenging due to the complex coupled phenomena (physical, chemical, radiation, thermal and mechanical) induced by fission. All occur in steep temperature gradients and have consequences at a multitude of dimensions from the nanometre to the metre (e.g. fission gas bubble precipitation, fission product migration and interaction, grain restructuring, cracking, and elemental radial migration). Fuel performance predictions for licensing under normal operation and accidental conditions have relied traditionally upon extensive integral irradiation testing (full length pins and assemblies) to generate empirical laws. Though successfully deployed for the four fast reactors operated in Europe thus far, they are not easily extrapolated to other conditions (high Pu content, low temperature operation, coolant interactions, etc.) prevalent for the licensing of first MOX cores for all four reactor systems of the European Sustainable Nuclear Industrial Initiative (ESNII).

Leveraging the knowledge from past integral irradiation testing programmes is essential to overcome the challenges of timely cost effective licensing of ESNII reactor MOX first cores. The solution lies in a basic science approach to develop the intricate models underpinning the empirically derived performance laws, so that they can be extended into other operational regimes. A first proof of principle of this approach was made in the F-BRIDGE project (2008-2012) [13]. Since then, however, the ESNII prototypes have evolved and are at advanced stages of definition, and the real needs and challenges of the reactor designers are articulated firmly. It is now that this harnessing of basic and applied science can truly bring significant advances to the licensing of fuel under normal and off normal conditions by resolving operational and safety issues.

INSPYRE is the unique path forward to cost effective nuclear fuel licensing, through a thorough understanding of fuel performance issues. The goals of INSPYRE focussed almost exclusively on MOX fuel are:

- To utilise out of pile separate effect investigations to underpin basic phenomena with soundly based physical models, both to extract more information form PIE on irradiated fuels, and to provide input as models within fuel performance codes.
- To perform additional PIE on selected samples to yield currently scarce data.
- To extend the reliability regime of traditionally deduced empirical laws governing various aspects of nuclear fuel under irradiation, using a combination of separate effect experiments, physical modelling and simulation, and integral neutron irradiation tests.
- To enhance the efficacy of operational fuel performance codes and improve their reliability in normal and off-normal situations.

INSPYRE is composed of 7 technical WPs:

- WP7 implements all new models and data in the codes, benchmarks and validates them for application under conditions relevant to the ESNII prototypes.
- WP is directly supported by WP5 and WP6. The latter focuses on the improved models to extend the reliability regime of empirical laws using results obtained in INSPYRE and in other projects. The former combines separate effects, basic research and advanced PIE studies to underpin mechanisms of fast reactor fuel behaviour
- Four more fundamental WPs underpin the programme by tackling issues such as: margin to fuel melting; atom transport and fission product behaviour; evolution of mechanical properties under irradiation; fuel thermochemistry and fuel-cladding interaction. These WP perform basic research investigations combining separate effect experiments, characterization of neutron-irradiated fuels, and multiscale and thermodynamic modelling.

By efficiently leveraging relevant past knowledge and by combining PIE and basic science approaches, within a well-balanced consortium of universities, research and industrial centres, all collaborating within the EERA JPNM, INSPYRE will impact crucially on the extension of the applicability of fuel performance codes, thereby enabling the reduction of the need for integral irradiation test and thus accelerating the licensing procedures, while improving safety standards.

7. Multiscale Modelling for Fusion and Fission Materials (M4F)

Call: WP-2016-2017-NFRP-13 – Fission/fusion cross-cutting research in the area of multiscale materials modelling
Grant agreement number: 755039
Starting date: 01/09/2017
Duration: 48 months
Budget: 6.5 M€ (4 M€ of contribution from Euratom)
Participants: 20 (CIEMAT, CCFE, CEA, Coventry U., CNRS, CVR, ENEA, HZDR, IZF, KIT, KTH, NCBJ, PSI, SCK-CEN, SINTEC, U. Aalto, U. Alicante, U.P. Catalunya, U. Helsinki, and METU/in-kind) – 13 countries
Coordinator: L. Malerba, CIEMAT

The main goal of the M4F project is to bring together the fusion and fission materials communities working on the prediction of microstructural-induced radiation damage and deformation mechanisms of irradiated ferritic/martensitic (F/M) steels, which are candidate structural materials in both GenIV fission and fusion reactors. The M4F project is multidisciplinary in nature and integrates models and experiments at different scales to foster the understanding of the complex physical phenomena associated with the formation and evolution of irradiation induced defects and their role on the macroscopic mechanical properties, particularly deformation behaviour.

Specifically, the project focuses on three interrelated issues, each of them requiring intense model development and dedicated experimental support:

- Describe as accurately as possible, through computational physical models, the microstructure evolution under neutron irradiation of F/M steels, taking into account simultaneously (i) the influence of the magnetic properties of the Fe-Cr system and the redistribution of Cr under irradiation (segregation and precipitation), (ii) the effect of C and (iii) the role of minor solutes such as Mn, Ni, Si, P. The models should allow the density, size distribution and chemical composition of the radiation-induced features that produce hardening to be predicted, at least up to a few dpa.
- Taking into account the microstructure induced by irradiation, develop meso-scale and continuum scale models, to describe plastic flow localization (i.e. localized deformation with loss of elongation in a tensile test) in F/M steels, at the level of single grain and then in polycrystals, through the elaboration of suitable homogenization methods and physically-based constitutive equations. The models should eventually allow the role of slip localization after irradiation on the mechanical behaviour of loaded components to be quantitatively assessed, so that design criteria can be derived.
- Develop a methodology to design and perform ion irradiation experiments as "surrogate" of neutron irradiation, with control on the potential artifacts that can be encountered in this type of irradiation, and to extract information not only on microstructural changes but also on the corresponding mechanical response, by means of nanoindentation. This requires on the one hand to develop microstructure evolution modeling tools with features suitable to simulate ion irradiation, particularly to account for damage gradients along the full ion penetration path and the closeness of a free surface; and, on the other, to establish best practice guidelines and possibly standards to perform nanoindentation measurements, being aware of which type of properties can be realistically deduced from them.

A side objective is to promote interaction and exchange between the fission and fusion materials scientific communities, in order to foster collaboration and to create the framework for future cross-cutting projects.

The project is accordingly structured in three domains (DM): DM1 – irradiated microstructure; DM2 - plastic deformation; DM3 – management (including data management, dissemination and fission/fusion interaction). Currently, all the experimental matrices have been established and the experiments, including irradiations, are in due course. Significant advances have been made in the development of all models, although for the moment the results of their application are limited.

8. TRANSversal Actions for Tritium (TRANSAT)

Call: WP-2016-2017-NFRP-14 – Cross-cutting support to improved knowledge on tritium management in fission and fusion facilities
Grant agreement number: 754586
Starting date: 01/09/2017
Duration: 48 months
Budget: 4 M€ (full contribution from Euratom)
Participants: 18 (CEA, CIEMAT, DH PHE, ENEA, IFIN HH, IIT, INFPR, IRSN, JSI, KIT, SCK-CEN, UKAEA, AMU, CORIA/URN, UNIPV, UOP, RATEN, LGI) – 8 countries
Coordinator: C. Grisolia, CEA

This multi-disciplinary project [14], will contribute to improving the knowledge on tritium management in fission and fusion facilities, addressing the challenges related to tritium release mitigation strategies and waste management improvement, and refining knowledge in the fields of radiotoxicity, radiobiology, and dosimetry.

Tritium sources are generally limited and kept as low as reasonable during the conception phase of a reactor. The amount of boron and lithium formed in tritium sources due to interaction with neutrons is limited in fission reactors to the lowest level possible. The fusion community is likewise continuously improving the fusion burnup and tritium breeding system to decrease the tritium recirculation and consequently its absorption by vessel walls or the tritium plant. However, it is not possible to go under a certain limit due to operational constraints or safety reasons, so it is necessary to work on tritium capture and permeation limitation between and through the circuits. TRANSAT thus focuses on the technologies needed to reduce tritium permeation between and through circuits by, for example, developing new materials with reduced tritium diffusion capability or using in situ operational effluents treatment. Furthermore, to better mitigate tritium permeation during the conceptual phase of reactors or devices, modelling tools for tritium inventory and tritium permeation fluxes estimation in fusion and fission devices are compared and benchmarked to improve the level of confidence in their estimation. Technological solutions for the development of on-request tritium production systems will also be evaluated.

Another important cross-cutting issue concerns tritiated waste management. Tritium, as an isotope of hydrogen, is easily absorbed in any material. This later leads to tritium release, the intensity and kinetic of which is related to the tritium inventory and its profile in the batch under consideration. As a result, the storage strategy of tritium contaminated waste is complex and directly related to different critical issues, e.g.:

– Measurement of tritium in the sample, not only on the surface. Non-destructive techniques have limited precision while destructive methods depend on the sampling strategy that is not satisfying due to possible inhomogeneity. Neither of them provides tritium profile information, so innovative measurements are developed to assess both tritium inventory and profile.

- Possible mitigation strategy against tritium release above the acceptance criteria of the storage facility: tritiated waste treatment (thermal treatment, incineration …), improved confining drum, confining matrices … These methods can be either combined or used separately. As part of waste management strategy and considering that detritiation processes are already covered by the H2020/ Power Plant Physics & Technology program (WP Safety and Environment), TRANSAT focuses on improving new concepts for confining drums.

In parallel, investigations are proposed to improve knowledge in the field of radiobiology, dosimetry, radio-toxicology, geno-toxicology, eco-toxicology and environmental fate in case of contamination by tritiated products (release as tritium gas or tritiated water, transformation into organically bound tritium, OBT). The radio-toxicological consequences of tritiated water or OBT contamination in animals or cells have been observed only at high tritium concentrations. Epidemiological studies showed that doses related to tritium were not specifically assessed in workers exposed to tritium. Consequently, these studies provide a poor indication of the health risks associated with tritium exposure and more data are needed. Also, during the decommissioning of nuclear facilities, operations are intended to remove or eliminate tritiated material, while fine airborne dust, namely aerosols are generated. The consequence of the release of such tritiated particles in terms of radio-toxicology and ecotoxicology are thus studied. The outcomes of this project will help radiation protection authorities, IAEA and other nuclear safety advisory organisms to assess more precisely the radiobiology, dosimetry, geno-toxicology and eco-toxicology of tritiated micron and sub-microns particles

9. Summary and conclusions

The EERA JPNM provides a consistent framework under which activities related with the qualification, modeling and development of structural and fuel materials for advanced and innovative nuclear systems, towards full nuclear energy sustainability, are coordinated. Substantial contributions from institutional funding effectively integrate the Euratom support: in all projects under this umbrella, including those belonging to H2020, the total budget significantly exceeds the Euratom contribution, thanks to the fact that these projects are the result of an alignment between national programmes that preceded their launch, i.e. they are based on JPNM pilot projects that are suitably combined to fit the calls. Even though PELGRIMM preceded the inclusion of fuel activities in the JPNM, it follows similar philosophy in terms of approach and topics. All this provides a strong basis to build, in the near future, an efficient European Joint Programme (EJP) on nuclear materials, within which Members States and European Commission earmark funding specifically devoted to this crucial topic. Materials are indeed key for all nuclear reactor generation safety, economy and sustainability, including fusion systems, and also offer the possibility of establishing links with other low-carbon energy technologies, particularly within EERA. Because of the harsh operating conditions and strict safety rules it has to comply with, the expertise on materials for the nuclear field can indeed produce spin-offs applicable to other energy systems where extreme operating conditions are faced.

The projects described in this paper also provide a couple of successful examples of cross-cutting actions between fission and fusion. These certainly represent a formula to be pursued more intensively in the future, because of the mutual benefit that cross-fertilization always brings, and especially because this formula, applied to properly identified topics, ensures that an optimal use of human and infrastructural resources is made, without costly duplications.

References

[1] http://www.eera-jpnm.eu/gemma/?q=jpnm&sq=sub6
[2] http://www.eera-jpnm.eu/inspyre/
[3] http://www.h2020-m4f.eu/
[4] http://transat-h2020.eu/
[5] http://www.fp7-matisse.eu/
[6] https://cordis.europa.eu/project/rcn/101413/factsheet/en
[7] https://www.eera-set.eu/
[8] http://www.eera-jpnm.eu/
[9] https://ec.europa.eu/energy/en/topics/technology-and-innovation/strategic-energy-technology-plan
[10] https://www.eera-set.eu/vision-paper-of-jp-nuclear-materials/
[11] http://www.eera-jpnm.eu/?q=jpnm&sq=nboard
[12] A. Gallais-During, F. Delage et al., "Outcomes of the PELGRIMM project: progress in the development of Am-bearing fuel under pelletized and spherepac forms", Journal of Nuclear Materials, 512 (2018) 214-226.
[13] https://cordis.europa.eu/publication/rcn/16699_en.html
[14] K. Liger, C. Grisolia, I Cristescu, C. Moreno, V. Malard, D. Coomb and S. Markelj, "Overview of the TRANSAT (TRANSversal Actions for Tritium) project", Fusion Engineering and Design 136 (2018) 168–172.

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NUCLEAR COGENERATION WITH HIGH TEMPERATURE REACTORS

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Abstract. Clean energy production is a challenge, which was so far addressed mainly in the electric power sector. More energy is needed in the form of heat for both district heating and industry. Nuclear power is the only technology fulfilling all 3 sustainability dimensions, namely economy, security of supply and environment. In this context, the European Nuclear Cogeneration Industrial Initiative (NC2I) has launched the projects NC2I-R and GEMINI+ aiming to prepare the deployment of High Temperature Gas-cooled Reactors (HTGR) for this purpose.

1. Clean energy needs beyond electricity

1.1. Current and future energy production

Clean energy production is a high European priority and it is widely recognized as a growing need in the world. So far, most of the effort was concentrated on electric power because the solution is rather straightforward. Electricity, however, accounts for 18% of the total energy consumption only (Fig. 1). Other applications, namely heat and transport, are today based almost 100% on fossil fuel with high emissions, mainly natural gas, oil and coal.

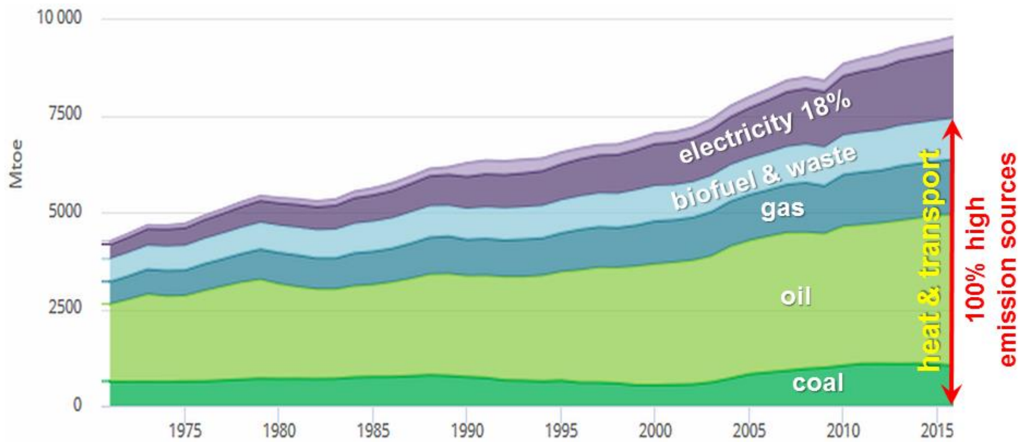


FIG. 1. World energy consumption by source [0].

In Europe, electricity represents 24% of the energy consumption, while heating and cooling for residential and industrial uses accounts for 50% [0]. Almost 100% of derived heat is obtained from combustion. This implies that an effective

European energy policy has to address this sector with high priority, although it is merely invisible to the general public. The expected political and socio-economic benefit is very significant.

So called "renewable energy sources" cannot provide sufficient solution for heat production. Wind turbines and solar panels produce electricity and using it to generate heat would be a waste of energy and would be very expensive, especially for industrial purposes. The only exceptions are solar thermal power stations, focusing solar radiation by mirrors, but they can be effectively used only in regions with high insolation and a high fraction of direct (as opposed to diffuse) sunlight.

The only option able to address all three virtues of the "sustainability triangle", namely economy, security of supply and environment, is nuclear energy. It is widely used today for electricity production. In Europe, industrial nuclear power plants produce currently 26% of all electricity and 52% of electric energy from non-combustible sources. However, out of all industrial and district heat only 0.2% comes from nuclear reactors.

1.2. High temperature industrial heat

About 95% of the process heat market in most industrialized countries is characterized by high energy intensity and high temperature (Fig. 2). This fact, coupled with the strong dominance of fossil fuels in heat production, results in high emissions, not only of CO_2, but also of fine dust, heavy metals, NO_x, SO_3 and others. Consequently, many issues concerning public health, environment, energy security, geopolitics, socio-economics etc. are at stake. As long as no commercially viable alternative exists, fossil fuels remain the sole option for the many high temperature processes that power our industry.

In Europe, about 89 GWth, ie. 50% of the process heat market is found in the temperature range up to 550°C (today mainly in the chemical industry, in the future possibly in steelmaking, hydrogen production, etc.) [0,0]. Therefore, to advance broader applications of nuclear cogeneration in the industrial processes that require heat supply at high temperature, international technology developments are focusing on nuclear reactor types designed to deliver this high temperature heat.

Various reactor concepts can be considered, e.g. the well-known Generation IV International Forum concepts, including modular High Temperature Reactors (HTR) and their long-term evolution towards very high temperatures (VHTR), Super-Critical Water Reactors (SCWR), Molten Salt Reactors (MSR) and different Fast neutron Reactor concepts cooled by either Sodium (SFR), Lead (LFR) or Gas (GFR). However, for near-term solutions delivering process steam up to 550°C, the HTR is currently the only option [0] and the only one that covers the largest range of temperature. Moreover, modular HTR designs feature unique simplicity owing to their intrinsic passive safety concept which makes expensive redundant and active engineered safety systems superfluous. This is a clear advantage for siting in proximity to industrial end users and for competitiveness, which are prerequisites for any industrial deployment.

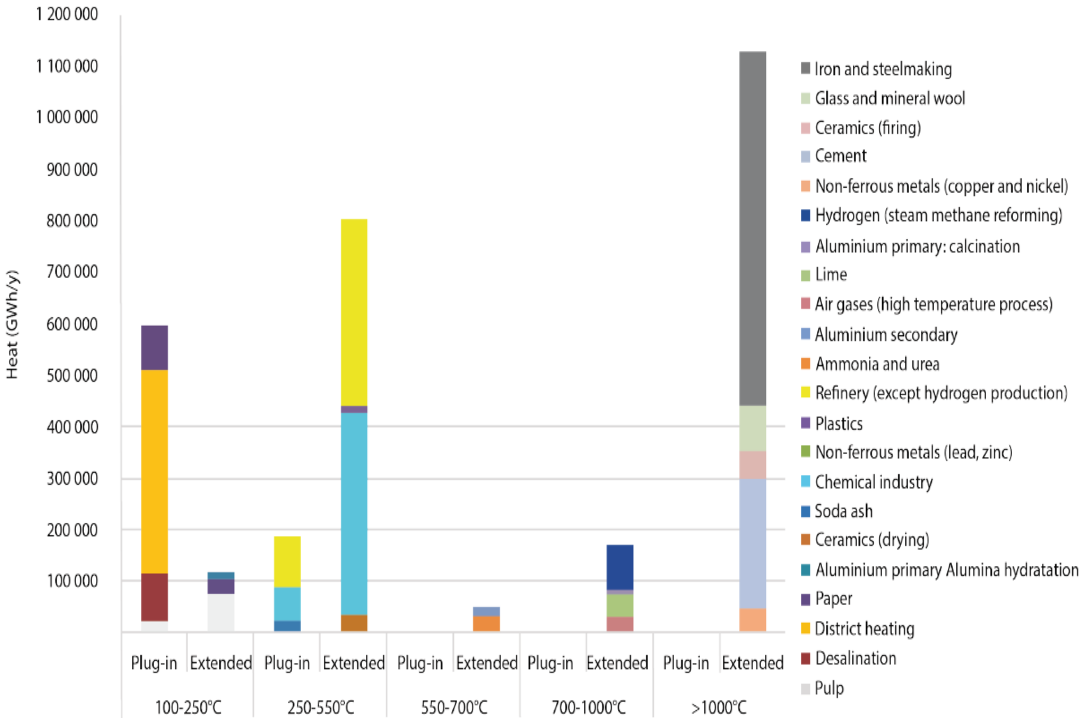


FIG. 2. Distribution of the heat market by temperature class and sector [3].

1.3. Nuclear Cogeneration Industrial Initiative

The challenges described above are in the focus of the European Nuclear Cogeneration Industrial Initiative (NC2I) [0]. The organisation has been created as one of three pillars of the Sustainable Nuclear Energy Technology Platform (SNETP) [0]. In line with the objectives and timing foreseen by the Strategic Energy Technology Plan (SET-Plan) issued by the European Commission, NC2I proposes an effective nuclear technology for reaching the SET Plan targets. Its mission stems from the assessment of energy needs of European economy and is focusing on realizing its mission: "*Contribute to clean and competitive energy beyond electricity by facilitating deployment of nuclear cogeneration plants*".

NC2I thus strives to provide a non-electricity nuclear contribution to the de-carbonisation of industrial energy, which is required, as mentioned before, mainly as high temperature process heat. Considering the relatively short-term deployment objectives, among the different nuclear technologies that can be used to operate reactors at higher temperatures than present LWRs, NC2I gives highest priority to HTGR, because:

– It is the most mature technology (750 reactor-years operational experience), capable to be deployed before 2050,

- It can fully address, without further development, the needs of a large class of processes receiving heat or steam as a reactant from steam networks (typically around 550°C); these are mainly the processes of chemical and petrochemical industries. Plugging into existing infrastructure of steam networks, HTGR plants could substitute present fossil fuel fired boilers and cogeneration plants which may then serve as back-ups for the case of outages.
- It has the potential for addressing in the longer-term other types of applications presently not connected to steam networks, in particular bulk hydrogen production and other applications at temperatures higher than 550°C.

NC2I proposes, therefore, as a first step, a deployment of HTGR systems of these "plug-in" applications on existing steam networks.

Although, HTGR technology is mature for such applications, the economic competitiveness of nuclear steam production, as well as its flexibility and reliability to adapt to industrial needs is yet to be demonstrated. Moreover, even if modern modular HTGR technology, which offers a very high safety level, has already been licensed (HTTR in Japan, HTR-10 and HTR-PM in China, not to speak of the preliminary safety reviews of MHTGR in the US and the HTR-Modul in Germany), a nuclear reactor has not been licensed yet for coupling with high temperature industrial processes. Any large deployment of HTGR for industrial process heat supply calls for prior demonstration at industrial scale of such a coupled system. NC2I is paving the way to this demonstration in Europe.

In order to realise this goal, NC2I has launched two EU projects "NC2I-R" and "GEMINI+". These projects are co-financed by the Euratom FP7 and Horizon 2020 Framework Programs, respectively.

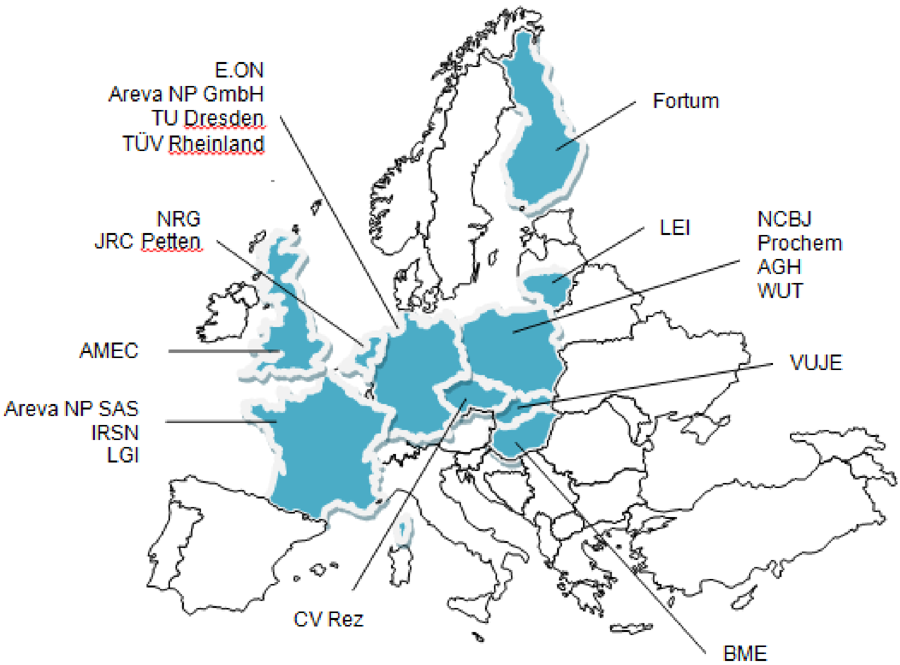
2. The project NC2I-R

2.1. Overview

The **NC2I-R project** was run from 2013 to 2015 by a consortium of 20 partners (Fig. 3). Building on an earlier project called EUROPAIRS [0], NC2I-R has drawn an inventory of all infrastructures and competences considered crucial for the establishment of new nuclear cogeneration, both at the scale of demonstration and of industrial deployment. This stock-taking spanned in particular the EU, but also reached out to selected countries overseas where use of nuclear cogeneration was/is industrial practice or planned for the future.

A second large activity investigated the requirements regarding the licensing process, safety demonstration and R&D needs of a nuclear co-generation system. Technology state-of-the-art and previous experience gained from licensing of existing and past nuclear cogeneration facilities in Europe and overseas were gathered and reviewed which led to a roadmap for licensing a new installation in Europe.

Demonstration and deployment options for nuclear cogeneration were identified and modeled to evaluate and rank them according to industrial and/or policy-driven interests. More detailed economics analyses were performed including sensitivity studies. These included factors influencing the economics & financing, and conditions of economic viability. General specifications for a demonstrator program including siting were defined, and the most promising chemical industry sites in Europe were mapped.



FiIG. 3. NC2I-R partners. NorthWest University from South Africa also participated.

2.2. Feedback from past and planned nuclear cogeneration installations

A total of 36 projects could be identified and contact persons be found using the international network of the NC2I-R consortium. From those, 23 from 10 countries have provided feedback on a variety of applications. The most common were:

– district heating (HU, CH, CZ, SK, S, ROC, FIN, RU)
– seawater desalination (KZ, JA)
– process steam for paper and pulp (N, CH)
– salt refining (D)
– process steam for reforming of gas and coal (D)
– (petro-)chemical (D, CAN)
– nuclear processes (UK, CAN)

Five main reasons were found to trigger plans for nuclear cogeneration installations:

- Security of supply,
- Conducting R&D on industrial nuclear cogeneration,
- Reducing carbon and other emissions,
- Economic benefit,
- Increasing the efficiency of an existing NPP.

While each nuclear cogeneration project is different, the following stakeholders, or at least some of them were involved from the beginning of the project:

- Manufacturer of the plant;
- Operator;
- Utility;
- End-user (industry, municipality);
- Plant owner;
- Political representatives at different levels.

Concerning technical aspects, in most of the projects, the cogeneration installation was included in the original design and did not require a revamp/upgrade of the NPP. The great majority of the commissioned projects did not encounter unexpected difficulties. However, the NPP Ågesta in Sweden had to face problems related to the FOAK character of the heat source. Paks in Hungary had technical problems related to the conventional heat transport system. All projects require back-up power to cover O&M outages. Fossil fuel boilers are used for back-up, and the back-up capacity is minimized by planning outages during summer when no domestic heating is required.

Reliable financial information on the nuclear projects was very difficult to obtain. The CAPEX ranges from a few dozens of million € for a capacity of several 100 MW to more than 1,000 million € for the Loviisa 3 project, using a reactor with a planned electric capacity between 1,200 MWe and 1,700 MWe and a thermal capacity between 2,800 MWth and 4,600 MWth.

The investment was either made by the government (Halden in Norway, Paks in Hungary), or absorbed within a utility budget - most of the time owned partly by the government - (Slovenske Elektrarne for Bohunice in Slovakia, Refuna AG for Beznau in Switzerland; Refuna is an 80-20 public-private partnership).

The levelized cost of energy (LCOE) was also difficult to obtain. The Loviisa 3 project in Finland, estimated that the energy produced by the NPP would have been 7 €/MWh cheaper than in a biofuel-fired scenario, and 18-26 €/MWh cheaper than in a scenario where the primary fuel was coal, a statement which obviously depends on the cost assumptions made for biofuel and coal. For Paks in Hungary, the initial levelized cost of delivered electricity was (11 HUF1985/kWh) in 1985, at today's exchange rate equivalent to 0.0358 €2013/kWh, a little useful value 30 years later. The initial levelized cost of delivered heat was 2.9 €/GJ (894 HUF/GJ).

2.3. Safety and licensing

Safety oriented work in NC2I-R aimed at providing input to both designers and regulators about the licensing, safety requirements and R&D needed to establish the safety demonstration of a nuclear co-generation system. The experience gained through the licensing of existing and past nuclear facilities with co-generation capabilities was collected and reviewed. Based on this feedback and taking into account recent trends for safety assessment of new installations, we proposed specific safety requirements associated with co-generation.

To effectively support the licensing of an HTR-based co-generation demonstrator and prototype, work in NC2I-R led to the recommendation that the following activities be conducted in addition to the standard licensing procedure:

- In the pre-application phase, early discussion of the safety features specific for HTR (e.g. passive decay heat removal, use of "vented containment") with the regulator of the host country with the aim to ensure their recognition in the licensing process;
- Demonstration that co-generation or process heat application issues are covered by the licensing procedure;
- Gap analysis for further R&D needs

Specific requirements have been outlined which need some more attention for an HTR co-generation application in the areas of:

- Safety Distances between reactor (possibly reduced Emergency Planning Zone) and heat consuming processes,
- Radionuclide release limits,
- Thermal hydraulic feedback/transients.

2.4. Deployment scenarios

In Europe, the economically most attractive near-term opportunities lie in the integration of HTR for powering a large chemical site where process steam is an almost ubiquitous commodity. The integration of a nuclear energy supplier as an Integrated Energy Manager would mean that the number of interfaces on the supplier site of a chemical park would be reduced thus enabling the end-users to concentrate on their core business.

Following this economic assessment, the next task was to localize and characterize chemical and petrochemical sites in Europe which could represent a potential market for deployment of nuclear cogeneration with HTR. The main processes compatible with HTR capabilities are:

- refinery: steam for fractional distillation,
- petrochemicals: reaction enthalpy,
- industrial sites: steam as commodity,
- paper and pulp: steam for boiling and drying.

Mapping of industrial sites was conducted in a manner allowing to describe the heat market and to characterize industrial sites across Europe. In total, 132 sites were located, 57 of them provided data related to their needs. The majority of sites (20) from where we could collect information use less than 100 MWth. In the category 100-500 MWth, 8 sites were located. There were 9 sites with a heat demand of about 500 MWth and one above 1000 MWth. The electrical power demand is distributed in a somewhat more uniform manner. The smallest demand – up to 50 MWe was reported by 20 sites. Each of the next categories, respectively 51-100 MWe, 101-200 MWe and 201-400 MWe, reported between 4 and 6 sites each.

The analyses performed as part of the NC2I-R project allowed to clearly understand the market, possible deployment sites and the expected energy policy and sustainability impact for near-term steam applications.

3. The GEMINI + project

3.1. Overview

Based on earlier work in Europe and internationally, the GEMINI+ project (2017 – 2020) is supporting the demonstration of nuclear cogeneration and is focusing on a particular technology and application of nuclear high temperature cogeneration. GEMINI+ is currently working on a conceptual design for a high temperature nuclear cogeneration system for supply of process steam to industry, a framework for the licensing of such system, and a business plan for a full-scale demonstration.

Among 24 EU partners representing 9 countries one can find 7 research organisation, 2 universities, 2 TSO's, 9 nuclear industries and 3 end-user industries. In the US, the NGNP Industry Alliance (NIA) has a similar objective and approach as NC2I [0]. In 2014, the twin organisations - NC2I and NIA - decided to join their efforts for demonstration of industrial high temperature nuclear cogeneration and launched the GEMINI initiative meant at coordinating technical development, endeavouring to converge as much as possible in the choice of technologies and design options, as well as actions towards European and US stakeholders for strengthening political support and funding. This GEMINI initiative was soon joined by JAEA (Japan) and KAERI (South Korea) in the GEMINI+ project consortium.

Since about the same time, the Polish government has shown interest to develop HTGR technology for providing heat to its industry. Therefore, this country appears to be presently the best candidate for hosting a nuclear cogeneration demonstration in Europe. NC2I therefore decided to focus its efforts on the support of Polish initiatives in this matter. As a first step, NC2I proposed the project GEMINI+ in the frame of the Euratom Framework Programme Horizon 2020 with the objectives of defining:

- The main design options of a demonstration plant addressing the needs of Polish industry,
- A licensing framework adapted to the specific aspects of industrial nuclear cogeneration with modular HTGR systems.

3.2. Project description

GEMINI+ is structured in Work Packages.

WP1 is developing a basis for the licensing framework for a modular HTGR:

- coupled with industrial process heat applications through a steam network,
- with a safety design fully relying on the intrinsic safety features of modular HTGR.

WP2 is elaborating the main design options of a HTGR system complying with the requirements of WP1 and of end user applications. It is supported by studies on economic optimisation including an assessment of the benefit that can be drawn from the use of modular construction methods presently developed for Small Modular Reactors, on integration into the energy market, and on decommissioning and waste management constraints on the design. Strong interactions between WP1 and WP2 are ensuring the compliance of the design with the safety requirements formulated in WP1.

Though WP2 will essentially select proven design options for getting a demonstration of industrial cogeneration as soon as possible, the project should not miss innovations that appeared in different sectors of technology after the basis of modular HTGR designs been established. It will be checked that integrating such innovations in the design would result in benefits in terms of safety, economic competitiveness and/or flexibility for various end-user applications, without bringing about significant additional risk and delay in the demonstration project. This is the task of WP3, which scrutinizes innovation in different fields (materials, instrumentation, industrial processes, integration in energy networks, etc.) and assess their suitability for the specific GEMINI+ design.

The project is also addressing the conditions of implementation for a demonstration project in Poland. This will be done in WP4 based on a selected industrial site in this country. The siting of the nuclear cogeneration plant and its compliance with the requirements for the considered applications on this site is being assessed. Three other prerequisites are being addressed:

- The availability of a reliable supply chain for the components,
- Possibilities to bridge in due time the residual technology gaps that will be identified by the project, in order to be able to guarantee the performance of the system, to justify its safety and to manufacture its components.
- A business plan for defining and scheduling the funding needs of the demonstration project and identifying and using funding options.

Finally, WP5 endeavours to provide a favourable environment to the demonstration project by:

- further developing the international partnership;
- soliciting advice and support from industry via a Business Advisory Group;
- supporting competence building of a Polish team on HTGR technology;

– creating a knowledge management basis and repository for all available documentation on HTGR technology, in particular the documentation created or recovered in the frame of previous European projects.

3.3. System requirements

In Poland, system requirements have been consolidated through a Polish national project "HTR-PL" and through the work of an official Polish HTR Committee gathering industry (end users and engineering companies), nuclear research and funding organisations, appointed by the Ministry of Energy. This Committee published in 2017 its final report with an assessment of the potential for deployment of HTGR industrial cogeneration in Poland [0] and a synthesis of Polish end-user needs. The common denominator of the Polish industrial needs is the following:

– Energy should be supplied only in the form of superheated steam delivered to existing steam networks presently fed by fossil fuel fired boilers. If the site requires electricity supply, it is already generated on most of the cases by existing turbo-generators connected to the steam network, and this organisation should not be disturbed by the substitution of conventional boilers by nuclear plants (Fig. 4).
– The steam networks are fed with steam at 540 °C, 13.8 MPa.
– The common denominator of the steam needs of the Polish sites is 230 t/h, which corresponds to a power delivered to the end-users of 165 MWth.

On the other hand, industry is expecting the cost of the steam delivered by the nuclear plant to be attractive, i.e. not higher than the cost of steam delivered by fossil fuel-fired boilers.

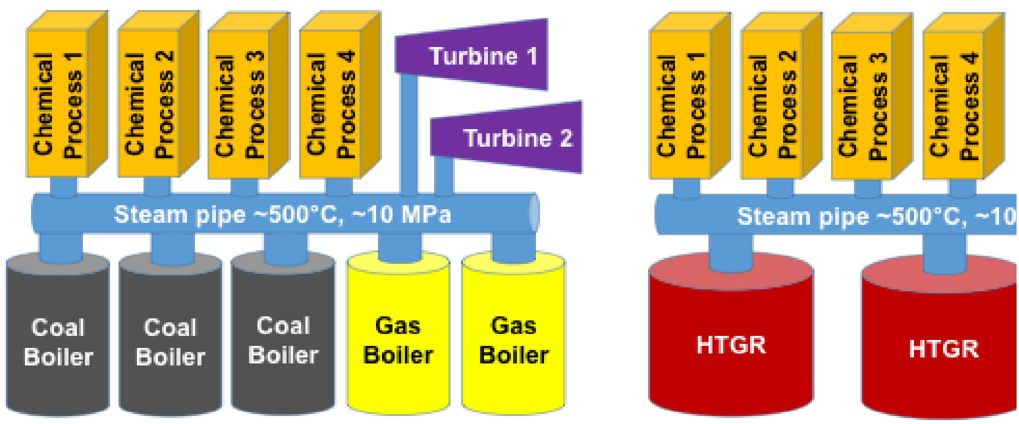


FIG. 4. Replacement of fossil boilers by HTGR.

3.4. Conceptual design of the reactor

The first design option is a block type core because NC2I, NIA, JAEA and KAERI have experience with this type of design: TRISO coated particles are embedded, mixed with matrix graphite and pressed to small cylinders, the "compacts"; these are stacked into vertical channels of prismatic graphite blocks that in turn are piled up to form the core. The heat is removed by helium gas blowing through additional vertical cooling channels across these blocks. GEMINI+ uses the same compact and block design as the 625 MWth SC-HTGR developed by Framatome Inc.

The design power of the GEMINI+ reactor will be reduced from the SC-HTGR power to meet the requirements of the Polish and most other European end users, as it appeared in a survey performed by the project NC2I-R. For the lower power selected for the Polish industry, the core will be cylindrical and not annular like the SC-HTGR core, which makes it more compact and minimizes the dimensions of the reactor pressure vessel in order to make the fully assembled vessel transportable. Two possible core configurations, presented in Fig. 5 are considered, and are being assessed in terms of vessel lifetime (acceptable integrated fast neutron fluence), maximum fuel temperature in accident conditions, feasibility of reactivity control and transportability of the vessel.

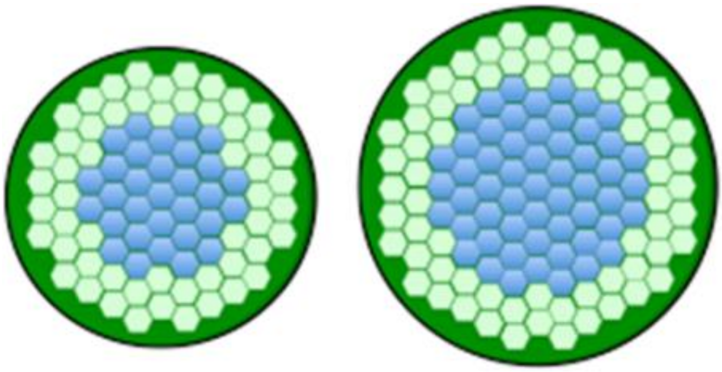


FIG. 5. HTGR core.

A sufficient number of barriers between the nuclear fuel and the non-nuclear steam network is required to exclude radio-contamination of the steam product. Therefore, the process steam for the end user is not produced in a steam generator interfacing with the primary circuit, but instead, a secondary circuit is employed. Different heat transfer fluid options have been examined and steam was selected as the best proven technology. It is produced in a steam generator and then condensed in a reboiler, at the interface with the industrial steam network (Fig. 6).

Even if the modular HTGR does not require electric power supply to be kept in safe conditions, keeping the reactor available to supply steam to the steam network requires continuing reactor operation even in case of loss of external power supply. A small turbo-generator located in the secondary circuit will therefore generate the power required for the house load of the nuclear plant, and the thermal power required to produce the steam branched off to the internal turbine is estimated to be about 15 to 20 MWth. The thermal power of the reactor should therefore be 180-185 MWth.

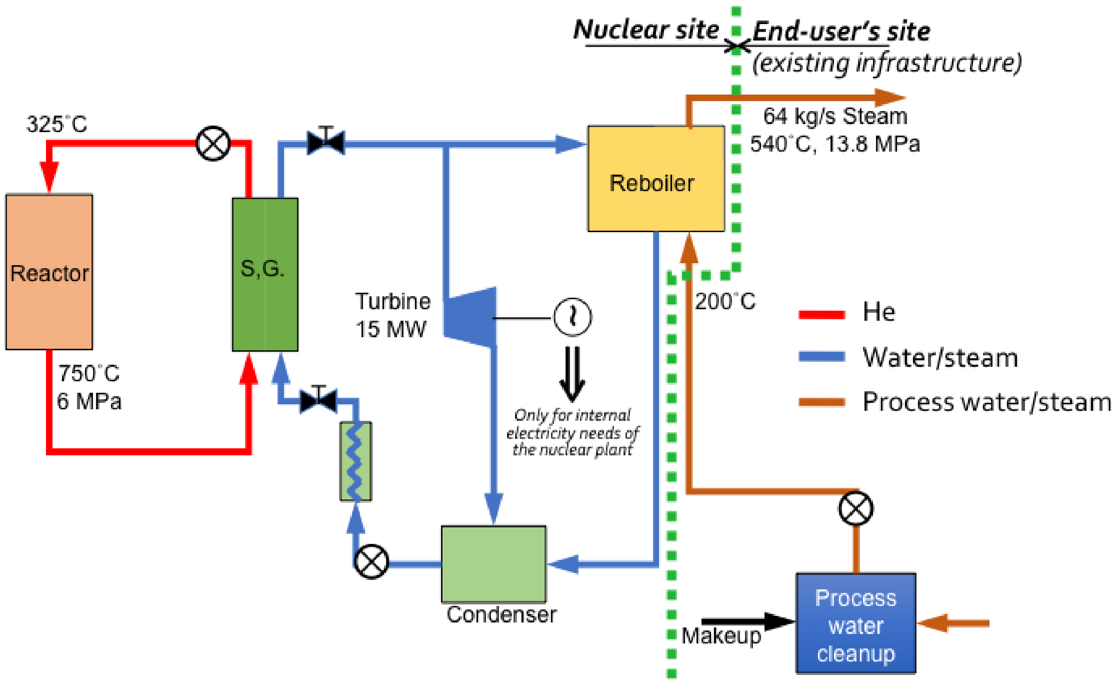


FIG. 6. General configuration of the nuclear plant with 185 MWth HTR.

4. Conclusion

HTR technology has been recognised by several countries and international organisations as the most promising technology to provide heat for industrial processes, including hydrogen production. The projects "NC2I-R" and "Gemini+" prepare the way for practical deployment of this technology. Now is the time to begin the reactor design and prepare the site for the first construction. Several companies in Poland are interested and they have got a green light from the minister of energy to initiate the project. The first commercial HTR is expected to produce energy by 2030-2032, while by 2050 High Temperature Reactors should be used widely.

References

[1] International Energy Agency, "World Energy Outlook 2018", www.iea.org/weo. Annotations on the figure by the paper authors.

[2] All data for energy in EU28 for 2015: http://ec.europa.eu/eurostat and http://heatroadmap.eu/

[3] A. Bredimas, Market study on energy usage in European heat intensive industries, EUROPAIRS project, FP7, Deliverable 131, 27/05/2011

[4] A. Bredimas, Results of a European industrial heat market analysis as a pre-requisite to evaluating the HTR market in Europe and elsewhere, Nuclear Engineering and Design, Vol. 271, p. 41-45 (May 2014).
[5] Advances in Nuclear Power Process Heat Applications – IAEA-TECDOC-1682 (May 2012).
[6] NC2I Vision Paper, June 2018, www.nc2i.eu.
[7] The Sustainable Nuclear Energy Technology Platform. A vision report, 2007, www.snetp.eu.
[8] C. Angulo et al., EUROPAIRS: The European Project on Coupling of High Temperature Reactors with Industrial Processes, Nuclear Engineering and Design 251, 30-37 (2012).
[9] www.ngnpalliance.org
[10] Possibilities for deployment of high-temperature nuclear reactors in Poland, Ministry of Energy, Warsaw, 2017. www.tiny.cc/htr-pl

ENRIQUE GONZALEZ

NUCLEAR DATA RESEARCH SUPPORTED BY EURATOM: CHANDA, ERINDA AND EUFRAT

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Abstract. Nuclear data and associated tools are critical elements of the nuclear energy industry and research, playing an essential role in the simulation of nuclear systems, safety and performance calculations and interpretation of the reactor instrumentation. Nuclear Data improvement requires a combination of many different know-hows that are distributed over many small and medium sized institutions along Europe. The Euratom programs have facilitated the setup of paneuropean collaborations getting together the required experience inside the projects CHANDA, ERINDA and the JRC action EUFRAT. The paper describes the holistic and inclusive approach of these projects that have also worked together to coordinate the European nuclear data research capabilities to improve the facilities, detectors, models and evaluation, validation and simulation tools. It also shows examples of success histories and summary of results of these projects and of their impact on the EU nuclear safety and industry, together with an outlook to the future.

1. Introduction

Nuclear data and associated tools are a critical element of the nuclear energy industry and research. They play an essential role in the simulation of nuclear systems or devices for nuclear energy and non-energy applications, for the calculation of safety and performance parameters of existing and future reactors and other nuclear facilities, for the innovation of the design of those nuclear facilities and the innovation on radioactive devices and use of radioactive materials in non-energy applications, and for the interpretation of measurements in these facilities and systems.

Nuclear Data, ND, is often not visible for applications that rely on the huge data sets of nuclear cross sections, emission probabilities, branching ratios, atomic masses, life times, energy levels, fission yields and many other nuclear data. However, with the present computing power and the development of the simulation codes, in many cases the limiting factor for the accuracy and prediction capabilities of these simulation codes comes from the accuracy of the relevant nuclear data and their uncertainties. Indeed, no matter how sophisticated the tool is, no simulation, calculation or interpretation of measurements can be better than the limit imposed by the nuclear data they use.

For these reasons, there are continuous request of new or better nuclear data, coming from new levels of safety, new safety criteria and scenarios, new reactor designs or new applications or new modes of operations of present reactors, innovative solutions for waste management and from pending requests, not feasible in the past, that can be addressed with the present R&D on nuclear data and tools. These requests are regularly evaluated and maintained in high priority request lists, in the framework of international initiatives and international organism like IAEA and NEA/OECD.

In order to have nuclear data available to applications several steps are needed in what is known as the nuclear data cycle. Nuclear data are typically deduced from differential (microscopic) measurements (a more or less direct measurement of the reaction of interest separated from other effects). This requires preparation of a high purity sample of the nuclide to measure, often radioactive and scarce, as well as the availability of sophisticated detection systems and controllable sources of neutrons and other radiations (often based on particle accelerators). Then the data are analyzed and the results are provided to international databases. Putting together results of several measurements and using nuclear theories, the data are further analyzed, and finally assembled into what is known as "evaluated nuclear data libraries". These evaluated data are then validated by comparing their predictions to integral experiments (complex systems, typically experimental reactors). From the differences between predictions and integral experiments, we can deduce corrections to the basic nuclear data and develop better evaluated libraries. This validation process can also reveal a possible need for additional differential measurements or evaluations, repeating the process until the required accuracy is achieved.

As a consequence, producing high quality data requires a combination of many different know-hows (target production, detectors, neutron sources, analysis, evaluation, nuclear theory, nuclear reactors, simulation codes, and others). In addition, it is important to realize that the necessary expert know-how is widely distributed within many research teams, particularly in Europe, and that most of these teams specialize only on one or few components of the nuclear data cycle. Therefore, in order to provide the nuclear data needed, it is important to prepare a very well structured wide and well synchronized collaboration between the key EU expert institutions.

The EURATOM framework program has been instrumental during the FP7 and before, to nucleate pan-European collaborations of laboratories that on one side have developed competitive projects to develop the tools and perform measurements, evaluation and validation of new or improved nuclear data like CHANDA. It has also facilitated the setup of frameworks for easy and efficient transnational access to experimental facilities needed for those activities, like the competitive proposal ERINDA and the direct JRC action EUFRAT.

1.1. ERINDA

The **ERINDA project** 0 **(European Research Infrastructures for Nuclear Data Applications)** has coordinated the European efforts to exploit up-to-date neutron beam technology for novel research on advanced concepts for nuclear fission reactors and the transmutation of radioactive waste. For the development of these transmutation systems and for improved nuclear safety accurate nuclear data haven been obtained in the ERINDA project. The strategic objectives of ERINDA were:

- to provide transnational access for nuclear data measurements at the consortium's facilities;
- experiments should account for nuclear data requests of highest priority and scientific value;
- improve simulation methods to predict the running conditions of innovative reactor systems and the transmutation of nuclear waste;
- generation of complete, accurate and consistent nuclear data libraries and measured nuclear reaction cross-sections.

ERINDA offered the nuclear data research infrastructures of 13 partners (HZDR, JRC-GEEL, CERN, CENBG, IPNO, UU-TSL, PTB, NPI, IKI, IFIN-HH, NPL, FRANZ and CEA) from all over Europe to experimental teams making new nuclear data measurements. The ERINDA facilities included different neutron sources and methods for nuclear data measurement, in particular:

- Time of flight facilities for fast neutrons:
  - nELBE (HZDR, Dresden); n_TOF (CERN, Geneva); GELINA (JRC, Geel);
- Charged-particle accelerators:
  - production of quasi-monoenergetic neutrons electrostatic accelerators in Bordeaux, Orsay, Bucharest and Dresden,
  - neutron reference fields at PTB Braunschweig and NPL Teddington,
  - cyclotrons in Řež , Jyväskylä, Oslo and Uppsala with neutron energy range up to 180 MeV,
  - pulsed proton linear accelerator in Frankfurt;
- Research reactors:
  - Budapest and Řež cold neutron beam, Prompt Gamma Activation Analysis.

Within the project 3015 additional hours of beam time at the consortium facilities have been provided in 26 experiments as transnational-access including technical and travel support for the user groups. In addition, 16 short term visits (with a total duration of 106 weeks) of scientists to the consortium institutes were supported. In this way theoretical data analysis and computer simulations relevant to the experiments were performed. All ERINDA facilities were grouped in a pool. To optimize the scientific output of the experiments a Project Advisory Committee (PAC) consisting of five external experts selected from the submitted experiment proposals and decided about the best suited facility for a certain type of measurement. The transnational access budget was distributed according to the PAC decisions. The participation of post-doctoral fellows and PhD students in all ERINDA activities was especially encouraged.

Four European scientific meetings in Dresden, Prague, Jyväskylä and Geneva were organized to communicate the progress and disseminate the results of the ERINDA project.

1.2. EUFRAT

Since 2005 JRC-Geel has a programme offering access to its nuclear research infrastructure for external users. In the period 2005-2012 the programme was running with support from DG-RTD (indirect actions NUDAME and EUFRAT). To transform it into a sustainable programme, the open access runs since the beginning of 2014 as an institutional project entitled **European Facilities for Nuclear Reaction and Decay Data Measurements (EUFRAT)**. In 2017 EUFRAT 0 was selected as a pilot project to start a JRC-wide open access scheme that includes nuclear and non-nuclear research infrastructures. The JRC-Geel approach for open access to its nuclear facilities has been copied for three other transnational access projects in the nuclear data field that were supported by DG-RTD, i.e. EFNUDAT, ERINDA and CHANDA.

The nuclear research facilities at JRC-Geel are designed for the measurements of highly accurate neutron cross section and nuclear decay data in support to nuclear energy applications: safe operation of nuclear reactors, nuclear safeguards, safe handling of nuclear waste and safe, ecological and economical disposal of spent nuclear fuel. They also serve the needs for non-energy applications: production of medical radionuclides, the safety of citizen and environment, environmental tracer studies to understand climate change, new detector developments, nuclear astrophysics, cultural heritage and materials research. The nuclear infrastructure at JRC-Geel includes:

- the GELINA research infrastructure, which combines a white neutron source produced by a 150 MeV linear electron accelerator with a high-resolution neutron time-of-flight facility;
- the MONNET research infrastructure for the production of continuous and pulsed proton-, deuteron- and helium ion beams is based on a 3.5 MV Tandem accelerator and serves for the production of well-characterised quasi mono-energetic neutrons. The tandem replaces the 7 MV Van de Graaff (VdG) accelerator that was operated until August 2015;
- the RADMET radionuclide metrology laboratories, which are used for radioactivity measurements;
- an ultra low-level radioactivity laboratory, which is hosted in the deep-underground facility HADES of the SCK•CEN; and
- a laboratory for the preparation and characterisation of samples and targets needed for nuclear data measurements.

1.3. CHANDA

The **CHANDA project** 0 brought together the majority of the European nuclear data community, infrastructures and resources to prepare the methodologies, detectors, facilities, interpretation models and tools to produce and use nuclear data with the quality required to comply with the needs for the safety standards that are mandatory for present and future European nuclear reactors and other installations using radioactive materials. Significant technical, methodological and organizational challenges have previously prevented the achievement of this goal for a number of relevant isotopes and nuclear reactions and CHANDA has focused its effort on overcoming those challenges.

CHANDA included 36 partners (CIEMAT, ANSALDO, CCFE, CEA, CERN, CNRS, CSIC, ENEA, GANIL, HZDR, IFIN-HH, INFN, IST-ID, JRC, JSI, JYU, KFKI, NNL, NPI, NPL, NRG, NTUA, PSI, PTB, SCK, TUW, UB, UFrank, UMainz, UMan, UPC, UPM, USC, UU, UOslo, US) from 16 countries from EU plus Switzerland and

Norway and 18 of the most relevant facilities equipped to measure nuclear data. The project partners have been strongly involved in previous EURATOM projects producing or using nuclear data and in international organizations dedicated to the compilation, validation and distribution of nuclear data (such as the OECD's Nuclear Energy Agency (NEA/OECD) and the International Atomic Energy Agency (IAEA)) and include most of the participants in FP7 nuclear data projects: ANDES, EUFRAT and ERINDA.

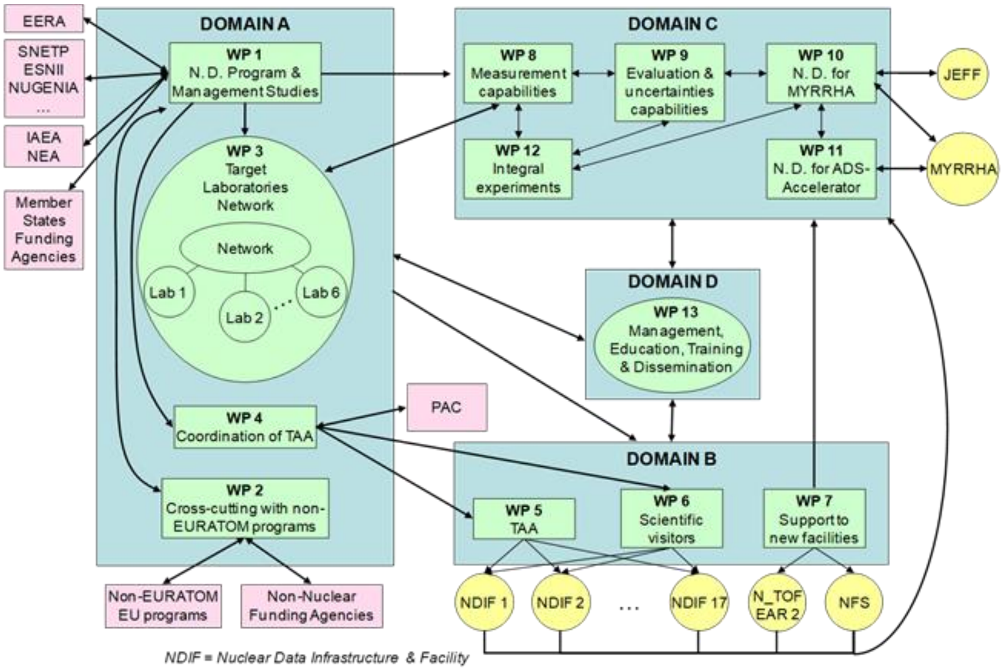


FIG. 1. CHANDA structure of activities and external connections.

CHANDA was structured in 13 work-packages (WP) organized in four Domains of activity. The relations of the different WPs and with external organizations, other projects and the facilities are described in Fig. 1. Domain C (DMC) has contributed to upgrade the capacities of the EU nuclear data facilities by development and validation of methodologies of experimental techniques, detection systems, integral measurements, evaluation methods and uncertainty estimation. This domain also produced most of the scientific and technical results like new measurements, new evaluated files and new uncertainty libraries. Domain B has contributed to setup and commission important new experimental facilities and to organize and facilitate transnational access to relevant ND facilities combining support to the facility and to the visiting teams. Domain A (DMA) included the coordination activities, enabling the development of a common vision, of a research roadmap for several years, and of the management structure to make this happen. DMA also included the target fabrication and characterization activities and their organization in the form of a dedicated network. Finally, Domain Management included the project management, but also the coordination of the education and training activities like the preparation of specific courses.

2. Technical Achievements

The two main characteristics of the ND projects of FP7 were their holistic and inclusive approach. To produce new ND for the final users involves many different steps requiring different facilities and tools. CHANDA has covered all these steps improving the tools and status of each of them but making sure that the improvement is focused on a more efficient preparation of the high priority nuclear data needs. Also, ERINDA and EUFRAT have covered the different types of facilities for the different steps of the ND preparation cycle and have articulated the support both to the facility and the visiting teams to make sure the experiments are successful.

Altogether CHANDA, ERINDA and EUFRAT have contributed to the following elements of the nuclear data preparation:

Improving the facilities: with the help of these EURATOM projects several facilities have improved their experimental conditions for ND experiments, like for example nELBE (HZDR) where the first photoneutron source at a superconducting electron accelerator went into operation, IGISOL (JYU) that was optimized to guide fission fragments into ion-traps, JRC-Geel (JRC), and others. The most significant effort within CHANDA has been on the new experimental area, n_TOF EAR2, for high flux experiments, that allows increasing a factor 30-40 the neutron flux at n_TOF, and allowing as demonstration the measurement of the ^{7}Be(n,α) reaction cross section using a sample of just 1 microgram of ^{7}Be 0. The LICORNE facility at IPN Orsay provides quasi-monoenergetic neutron beam with low background using inverse kinematics with a ^{7}Li beam on a hydrogenous target. The PTB PIAF facility and the JRC-GEEL MONET facilities received new Van de Graaff accelerators for the neutron beam production.

Integrating and developing target fabrication capabilities: with improved capabilities on PSI, U.Mainz and JRC-Geel laboratories. This action helped to better identify and describe the target needed and to actually fabricate 45 very specialized target for ND measurements, most of them highly radioactive and including samples of 10 different actinides.

New methods for cross section measurements: with developments of new detectors (micromegas, DELCO, SCONE, DTAS, BELEN, BRIKEN, FALSTAFF, STEFF), modification of facilities (n_TOF EAR2, AFIRA, GAINS and GRAPhEME at JRC), new combinations of detectors (n_TOF Total Absorption Calorimeter and a stack of 10 micromegas for capture in fissile actinides), etc.

Comprehensive developments for concurring reactions: making sure that the detector developments, new targets, neutron sources and facilities allow to properly cover the most relevant reactions including capture, fission, inelastic, (n,xn), (n,chp), …

New and improved evaluation models and tools: including the development of TALYS-1.9 that has become the reference European code in evaluation, the improvements of the databases EXFOR and Nuclear Data for Fission Fragments, and the extension of CONRAD.

Systematic and comprehensive uncertainties and correlation libraries in the evaluation: including a complete Bayesian evaluation technique which accounts for model deficiencies in update process and demonstrated with ^{181}Ta.

Validation and improvement of data using integral experiments: including the comparison of different uncertainty propagation methods, testing various integral data assimilation methodologies between the "all deterministic" and the "Full Monte-Carlo" methods, and the exchange of samples (Am) between differential (JRC) and integral experiments (MINERVE).

Fast and comprehensive dissemination of results: by close cooperating with responsible agencies, including strong collaboration with IAEA to make sure all relevant experimental results from CHANDA are readily available for evaluators and other users from the EXFOR database for experimental data. Also strong collaboration with JEFF/NEA for the incorporation of new data and evaluation tools in the JEFF activities and data libraries, and with large contribution to the CIELO exercise for the update of the most important cross sections and ND for reactor operation. Finally there has been continuous communication with the NEA High priority request list" (HPRL) for nuclear data for progress made and to get updated on the highest priority requests.

Comprehensive tools for transport problems including high energy particles: improvements of existing tools used to simulate experiments or facilities involving high energy particles (above 20 MeV) to be able to test uncertainty propagation on critical parameters for the safety of MYRRHA like power or spallation yields, improving the reliability of the high-energy nuclear models by comparing them with relevant experimental data (PSI at 590 MeV) and allowing to explain the deviations on the 210Po concentration, and a better INCL-ABLA model by refining the fission modelling.

Publication of results for specialized users and training young scientists: CHANDA scientific activities resulted in over 125 peer reviewed publications, 30 PhD theses and 18 Master theses out of these 48 theses 25 were supported by transnational access and scientific visits to experimental facilities. Also ERINDA have led to 77 refereed publications and several of the ERINDA supported experiments lead to master and PhD theses. The transnational access including user travel support was instrumental for young researchers to complete their experimental work at state of the art neutron facilities.

The three projects included the support to transnational access to experimental facilities to perform measurements, demonstrations or validations of data, model and methods. The three projects use a similar principle: the simultaneous support to facility and visiting teams together with a review and pooling system as an efficient mechanism to prepare small and medium size experiments. This mechanism has demonstrated to be efficient selecting high quality experiments and that it helps to use the right facility for each experiment, not just the closest one. The method also provides short reaction time to perform important activities identified during the duration of the project and not identified a priori. Indeed, there were 1 or 2 calls for proposals per year, and that once approved measurements could be started and completed in few months. Interesting examples were measurements at the n_TOF EAR2 commissioned during CHANDA and included in the lasts calls for proposals and even the experiments approved at the facility of U. Seville that joined the CHANDA project at the middle of the project. This mechanism has proven to be very efficient for production of basic research results, demonstration tests, calibration measurements and publications. It is also an efficient education and training tool including PhDs and Master Thesis and mobility. In addition, the whole process has helped to improve the facility performance and capabilities, by identifying potential improvements from the request from visiting teams, the suggestions from the evaluation committee, the results of research from the scientific visits of experts and the financial support to compensate the use of the facility. The process also contributes to the facility sustainability for facilities actually used by the ND community, by showing the international needs and also providing part of the operation costs.

As an example of the huge set of results and activities covered by these projects the table 1 lists the main measurements carried out:

Table 1. Differential nuclear data measurements carried out within CHANDA.

(n,f) cross sections	**(n,n), (n,xn) and (n,n'γ) cross sections**
^{240,242}Pu(n,f)	^{nat}Fe(n,n)
^{237}Np(n,f)	^{nat}C(n,n)
^{235,238}U(n,f)	^{238}U(n,n'e$^-$)
(n,γ) cross sections	^{48}Ti(n,n'γ)
^{235}U(n,γ)	^{7}Li(n,n'γ)
^{242}Pu(n, γ)	^{233}U(n,n'γ)
^{238}U(^{3}He,^{4}He)^{237}U, ^{238}U(^{3}He,t)^{238}Np, ^{238}U(^{3}He,d)^{239}Np	

Decay data	
^{95}Rb, ^{95}Sr, ^{96}Y, ^{96m}Y, ^{98}Nb, ^{98m}Nb, ^{99}Y, ^{100}Nb, ^{100m}Nb, ^{102}Nb, ^{102m}Nb ^{103}Mo, ^{103}Tc, 108Mo, ^{137}I, ^{138}I, ^{140}Cs, ^{142}Cs	γ ray and β decay emission probabilities with TAGS at JYFL
^{98,98m,99}Y, ^{135}Sb, ^{138}Te, ^{138,139,140}I	Neutron emission probabilities with the BELEN detector at JYFL

Fission yields	
^{238}U(n,f)	Penning trap at JYFL
^{233,235}U(n,f)	Isobaric beams at ILL
^{239,241}Pu(n,f)	Isobaric beams at ILL
^{235}U(n,f)	STEFF spectrometer at n_TOF/EAR2
^{235}U(n,f)	Orphee reactor at CEA/Saclay
^{238}U, ^{239}Np, ^{240}Pu, ^{244}Cm, ^{250}Cf	VAMOS spectrometer at GANIL
^{234,235,236,236}U(g,γ)	FRS spectrometer at GSI
^{238}U(n,f)	LICORNE + MINIBALL at IPN/Orsay

3. Strategic perspectives

In the preparation of the ND proposals for the 7th EURATOM Framework Program, the ND community used in all cases an inclusive approach, making sure to include all EU countries with relevant activities, adding up to 18 countries in CHANDA, also trying to include all institutions with relevant know-how, adding up to 36 institutions, and opening the pooling system for transnational access to all laboratories of potential value, 18 facilities were included in CHANDA.

This process is not simple, as at the same time we have to make sure that each participant has a significant contribution to the project according to their experience and that the effort of the project contribute to improve the high priority nuclear data needs. The process however has been very successful on all the ND projects of FP7 (ANDES, ERINDA and CHANDA) thanks to the interest and goodwill of all the potential partners that acknowledge that putting together this wide collaboration and synchronizing the priorities of the different teams to respond to the EURATOM calls, is the most efficient way to be able to address significant challenges at European level and to guarantee the survival of the ND research teams distributed along Europe. Indeed, thanks to this coordination, the relevance, visibility and impact of the European ND research has improved significantly during the last decade and can now compete at the highest world level with initiatives from USA, Russia or Japan.

In this sense, the EURATOM calls and projects have helped to maintain the nuclear data know-how in Europe by aggregation of many and widely distributed small and medium research teams. Efficient collaboration of teams with well identified capacities allows mobilizing the national resources of many teams and becomes a tool for effective addition of resources. Often the problem to organize these collaborations is to prioritize a reduced list of topics for the research, and in this sense the EURATOM calls and projects had been instrumental for the coordination and synchronization by European projects as a way to agree on common priorities. The inclusive approach, needed in all cases to incorporate the required disperse know-how, has allowed to avoid duplication and replace unnecessary competition with complementarity.

Internal competition both during the preparation of the proposals, by the pooling of the access to facilities and by selection of special actions defined within the project duration had been used to maintain high standards of quality and relevance. This mechanism was reinforced by strong continuous interaction with international bodies managing and discussing the nuclear data activities in the world (NEA/OECD and IAEA) and by an aggressive publication effort.

The resulting Nuclear Data community participating on the EURATOM projects is a system to develop and maintain the know-how more flexible and effective than large compact teams that has shown to be able to respond efficiently to evolving problems or programs with a large variety of different topics.

Strong coordination and communication of CHANDA, ERINDA, EUFRAT and previously ANDES teams has been reinforced during the whole duration of the EURATOM program, making sure that the transnational access selected could contribute efficiently to the challenges addressed by ANDES or CHANDA. This has also allowed that ERINDA and the TAA of CHANDA contributed to facility improvement and sustainability, and that CHANDA increased the European Nuclear data research community capabilities with upgraded facilities, new detection systems and methods, new tools and in general much better competitivity and visibility.

4. Success stories

Some examples of success stories can be highlighted:

Measuring the same isotope and reaction in two different facilities to reduce systematic effects. For example ^{238}U is a reference isotope and ^{241}Am 0,0 is very difficult to measure because the high intrinsic radioactivity. Both deserve for different reasons a special effort to reduce the systematic uncertainties. Several sets of measurements using same or similar samples were made for each of these isotopes combining the facilities of GELINA 0 (transmission and capture by C_6D_6) and n_TOF 0 (capture) in this case using 2 different technique (C_6D_6 and total absorption calorimeter), the combination of results allows to better understand and qualify the capture cross section of these isotopes.

With support from ERINDA, CHANDA and OECD/NEA the GEF code was developed to be a state of the art phenomenological model to give a general description of all fission observables. Results have been included in neutron particle transport codes e.g. MCNP and has led to a highly cited (web of science core collection) publication 0.

Within EUFRAT, studies of (n,n'γ) reactions in support to fast reactor developments are carried out at GELINA using the GRAPhEME and GAINS γ-ray spectrometers. The programme, which is in collaboration with CNRS/IPHC Strasbourg (FR) and IFIN-HH (RO), includes measurements on actinides (^{233}U, ^{235}U, ^{238}U, ^{232}Th 0,0) and light elements (^{16}O, ^{23}Na, ^{28}Si, ^{56}Fe). At the GAINS spectrometer measurements were carried out to establish a γ-ray reference cross section for neutron induced reactions based on the $^{48}Ti(n,n'\gamma)$ and $^{7}Li(n,n'\gamma)$ reactions. The GRAPhEME and GAINS spectrometers will be complemented with an electron spectrometer to study (n,n'γ) reactions by the detection of conversion electrons. The development of the DELCO (Detection of Electron from internal Conversion) spectrometer was part of the CHANDA project.

One of the challenges in Nuclear Data was to propose new experiments in integral and differential facilities based on isotopes of interest for the safety of nuclear systems as well as for their prior known target fabrications difficulties. By having the same origin of fabrication, complementary experiments (integral and microscopic) were proposed and performed within CHANDA to remove the target uncertainties from the comparison. A first test consisted on the pile-oscillation measurements in the MINERVE reactor (CEA) based on Am samples that were manufactured at JRC. This is a first-of-a-kind way of re-using samples that were initially designed for differential measurements at the Geel Van de Graaff, to perform an integral experiment. The experimental results had been used to validate simulation systems based on standard simulation codes for reactor physics and applications: TRIPOLI and MCNP.

Complementarily within EUFRAT, the transmission and capture cross section measurement stations of GELINA are used to determine neutron induced interaction cross section data in the resonance region in support to criticality safety analysis in out-of-reactor applications. These studies are part of a collaboration with CEA Cadarache (FR), INFN Bologna (IT), IFIN-HH (RO) and ORNL (US). The focus is on fission products with high absorption cross sections, such as Ag 0. The project includes the characterisation of pellet samples by Neutron Resonance Analysis. The pellets were previously especially prepared for pile oscillator measurements at the MINERVE reactor of CEA Cadarache. These exchanges of samples were proposed within CHANDA. NRA has also been applied to determine the amount of neutron absorbing impurities in material that is used for integral experiments in the VENUS-F facility of the SCK•CEN.

A different success history has been the organization within CHANDA of a network of radioactive samples/target producers, incorporating within its functions to facilitate the contact between target users and producers and the fabrication capabilities. The network has organized two meetings and has allowed to clarify the requirements from the users and to redefine their request in an efficient manner. This combined with the special extra support foreseen within CHANDA has allowed that from 56 original target requests, 4 were on hold, 7 were cancelled and the remaining 45 were produced and delivered. The list of targets produced included isotopes as ^{7}Be, ^{10}Be, ^{10}B, ^{13}C, ^{44}Ti, ^{70,72,73,74,76}Ge, ^{91}Nb, ^{147}Pm, ^{171}Tm, ^{204}Tl, ^{230}Th, ^{233}U, ^{235}U, ^{237}Np, ^{238}U, ^{239}Pu, ^{240}Pu, ^{241}Am, ^{242}Pu and ^{252}Cf.

Also deserve a mention, the efficient collaboration setup within the different EURATOM projects for Nuclear Data in order to join resources to make the best possible global use of the scarce resources available. In this sense, ANDES got support from ERINDA and EUFRAT to perform some of the experiments included in its program. In the case of CHANDA, the functions of ERINDA were already incorporated within CHANDA making even more efficient the integration of measurements and transnational access, but still the collaborations allowed CHANDA to benefit from the support of EUFRAT.

5. Lessons learnt and remaining challenges

Within the most important lessons learnt from the Nuclear Data EURATOM projects are:

- There is a continuous request of new or improved nuclear data that will require supporting R&D on ND still for many years.
- To be effective the R&D program on ND has to cover many aspects in a holistic inclusive and comprehensive way.
- Large, widely distributed collaborations, well-coordinated inside inclusive projects, allow performing the required R&D in an efficient way, maintaining the know-how in Europe by aggregation of many, widely distributed, small and medium research teams.
- The EURATOM financial support allows aggregating these collaborations focussing the research each time around the topics identified on the

EURATOM calls, normally well aligned with the high priority request list for nuclear data of the international organizations.

- The EURATOM projects have been very successful to produce the expected results, a large number of publications and PhD theses and to enhance the relevance and visibility of the European nuclear data R&D at global level.

Despite the success of CHANDA, several challenges remain for the future:

- Use of the tools developed within CHANDA, ERINDA, EUFRAT and previous projects to deliver more ND needed for safety, industry and society.
- Widen the existing tools to produce data needed for medical and other non-energy applications of Nuclear Data.
- Reply to new ND needs and continue improving the uncertainty and correlation libraries.
- Validation and verification towards a generic purpose ND library, not as criticality oriented as the present library verification tools.
- Further development and integration of ND know-how in research and final user tools.
- Continue maintaining the know-how in Europe by aggregation of many and widely distributed small and medium research teams.
- Continue supporting the ND facilities and neutron sources.

6. Impact and possible follow-up actions

The results of the nuclear data projects, CHANDA, ERINDA and EUFRAT have contributed to the improvement of ND for major isotopes and minor but critical isotopes (for safety, waste management and future concepts) covering the most critical reactions and data needs. These better data enable more reliable simulation and evaluation capabilities that contribute to improve safety and efficiency of the present European reactors. In addition, making available more complete nuclear data and uncertainty libraries help to progress towards best estimate calculation, with an assessment of the final uncertainties on the calculation, to become available for safety assessment, design and operation. All this elements will help to support science based decision for the energy policies.

Two new nuclear data proposals had been submitted to the EURATOM WP2018. SANDA, with 35 partners, proposing to cover some of the remaining ND challenges after CHANDA and focussed on delivering new data to the end users and to cover energy and non-energy applications, and proposal ARIEL, with 23 partners, to provide transnational access for nuclear data experiments that can be used for training and education in the nuclear field. If they are approved they will probably provide an efficient platform to address the present remaining nuclear data needs at the European Unión.

References

[1] ERINDA: ERINDA web page and the references quoted inside, http://www.erinda.org/
[2] EUFRAT: EUFRAT web page, https://ec.europa.eu/jrc/en/eufrat
[3] CHANDA: CHANDA web page and the references quoted, http://www.chanda-nd.eu/

[4] Barbagallo, et al. (2016). Be-7(n,alpha)He-4 Reaction and the Cosmological Lithium Problem: Measurement of the Cross Section in a Wide Energy Range at nTOF at CERN. PHYSICAL REVIEW LETTERS, 117. doi:10.1103/PhysRevLett.117.152701.
[5] Schmidt, K. H., et al. General Description of Fission Observables: GEF Model Code. 2016, NUCLEAR DATA SHEETS, Bd. 131, S. 107-221. ISSN: 0090-3752.
[6] M. Kerveno et al., Eur. Phys. J. Web of Conferences 146 (2017) 11012
[7] M. Kerveno et al., Phys. Rev. C 87 (2013) 24609
[8] L. Šalamon et al., Eur. Phys. J. Web of Conferences 146 (2017) 11052
[9] Mendoza, E., et al. (2018). Measurement and analysis of the Am-241 neutron capture cross section at the nTOF facility at CERN. PHYSICAL REVIEW C, 97. doi:10.1103/PhysRevC.97.054616.
[10] C. Lampoudis, S. Kopecky, O. Bouland, F. Gunsing, G. Noguere, A. J. M. Plompen, C. Sage, P. Schillebeeckx, and R. Wynants, Eur. Phys. J. Plus 128, 86 (2013)

SESSION 4
EDUCATION AND TRAINING, RESEARCH INFRASTRUCTURES AND INTERNATIONAL COOPERATION

SUMMARY SESSION 4 – EDUCATION AND TRAINING, RESEARCH INFRASTRUCTURES AND INTERNATIONAL COOPERATION

Chair: Daniela LULACHE (OECD/NEA), Head of Office of Policy and Coordination
Co-Chair: Foivos MARIAS (DG RTD, EC), Project and Policy Officer
Expert Rapporteur : Gérard COGNET (Expert, FR)

Objective

Nuclear safety remains, as always, the top priority and the European Union has an outstanding nuclear safety record. However, research must continue to maintain the highest level of nuclear safety, security and safeguards. The European nuclear sector is characterised by cutting edge technology and provides several hundred thousand people with highly skilled employment. To ensure our safety both now and in the future skilled people and well-equipped nuclear research facilities are of paramount importance. The availability of these resources is a crucial prerequisite for maintaining safety no matter what the future holds for the nuclear power sector. Europe can retain its technological leadership only if Member States maintain a diverse and well-funded nuclear R&D capability, a fit-for-purpose system for the education and training of scientists and engineers, availability of state-of-the-art research infrastructures, and reinforced international cooperation in key strategic areas with leading third countries, bilaterally or multilaterally. EU/Euratom helps to stimulate joint funding from Member States and/or enterprises, joint programming and dialogue at EU level, cross-cutting fission/fusion/non-nuclear innovative initiatives and benefits are being capitalised from the increasing interaction between European technology platforms, EU stakeholder fora, as well as International Organisations such as OECD/NEA and IAEA.

Presentations

Franck CARRE (CEA, FR)
Growing Synergies between Fission and Fusion Research towards demonstration plants

Walter AMBROSINI (University of PISA, IT)
Education, Training and mobility: towards a common effort to assure a future workforce in Europe and abroad (ANNETTE, ENEN-PLUS, BRILLIANT, CORONA-II, FP7-ENEN-RU-II, FP7-ARCADIA, FP7-NEWLANCER, FP7-ECNET, FP7-NUSHARE, FP7-GENTLE)

Michèle COECK (SCK-CEN, BE)
Improved expertise in radiation protection, nuclear chemistry and geological disposal (CONCERT, MEET-CINCH, FP7-ENETRAP-III, FP7-EAGLE, FP7-CINCH-II, FP7-PETRUS-III)

Concetta FAZIO (DG JRC, EC)
Supporting Access to key infrastructures and pan-European research (FP7-GENTLE, FP7-TALISMAN, others)

Jean-Yves BLANC (CEA, FR)
Supporting Infrastructures and Research Reactors: Status, needs and International Cooperation (FP7 and H2020 JHR ACCESS RIGHTS)

Attendance at this session was quite important, allowing a very open and fruitful discussion.

In his keynote speech, Frank Carré showed possible synergies between fission and fusion and how they could help the development of both technologies. He particularly pointed out the key technical issues which are challenging both for fission and fusion, as tritium is for Candu reactors and tokamaks. As regards fusion with view to Demo, he underlined the lack of engineers in the operating teams of fusion facilities and how exchanges of experience with people in charge of the design and operating of fission facilities could avoid some disappointments, for example in the field of gas and liquid metal cooled systems technology. He also promoted communication between the two scientific communities and, answering to a question, tried to explain how to take advantage of the large interest about fusion to increase the attractiveness of fission research topics for young scientists.

The following invited speakers succeeded in summarizing the main achievements and results regarding education and training of about 20 Euratom projects. During these presentations, several topics were pointed out by the speakers and then discussed by the audience.

- *Evolution of the needs*: The Euratom projects mainly devoted to education and training (E&T) have significantly contributed to the development of some new education programmes such as the new course on nuclear technologies with specific modules on Gen IV and LFR opened in 2015 by the University of Pitesti. They also contributed to the availability and harmonisation of nuclear programmes throughout the EU; in that respect, the role of ENEN was underlined. In some domains, project series which continued for about one decade, or more, like ENTRAP or PETRUS, enabled a real development of competences and the construction of sound and thorough bases for education. Moreover, some actions launched by these projects continue beyond the life of the project, like the PETRUS PhD event, thus proving that they meet well a real need. However, in some fields there is a need of new competences, for example for fast reactor projects. At the opposite, it seems there is no immediate need for the organisation of a new "European Radiation Protection Course" which would meet the European legislation. Still about the evolution of needs, a strong concern was expressed about the preservation of education and training in nuclear engineering to maintain competences in Member States which have decided to phase out nuclear.
- *Accreditation*: Although most of the projects have shown that mutual recognition and accreditation work properly on the European level. Some participants also underlined that mutual recognition as well as the full

implementation of the ECVET system (European Credit System for Vocational Education and Training) still pose major challenges in some fields like "radiation protection" for which national legislations seem to be a drag.

- *Regional initiatives*: Launched to create synergies among different organizations of some zone in Europe in charge of E&T in the nuclear fields, they have shown great efficiency, leading to either new joint projects (ARCADIA, CORONA II) or the creation of new structure as the virtual training centre in Baltic region (BRILLANT).
- *Mobility*: Generally recognized as a success factor, mobility is crucial for the training of young technicians and engineers in nuclear as well as for maintaining and increasing skills of scientists. In that respect, it was agreed that mobility, to be favoured, requires the allocation of adequate financial resources to make it feasible at any level. About that, the most notable action is due to the ENEN+ project which granted more than 1 M€ for mobility funding in favour of learners at different stages of their early career. The importance of the access to research infrastructures for mobility programmes made consensus but with some recommendations about the administrative aspects (see below).
- In some projects, transnational mobility was proved to be a very efficient tool to share some specific knowledge as, for example, VVER technology in the CORONA project. It has to be noted that some of the attendees proposed the opening of mobility programmes to students and scientists from third countries.
- Furthermore, a broad consensus emerged among the audience about the possibility for Euratom projects of using other EU tools for mobility like Marie Curie programme.
- Exchanges with education systems outside of Europe: For several projects, promoting and easing exchanges of students and teachers with countries outside of Europe was considered an action worth of specific efforts. Some projects were specifically dedicated to this objective: ECNET for exchanges with China, which did not meet the expected success and ENEN-RU II for exchanges with Russia, which was a great success mainly because the curricula for Nuclear Engineering and the credit systems in use in EU countries and Russian Federation were showed compatible.
- Though the experience of the ECNET project turned out to be less successful, the interest in exchanges with China was reaffirmed.
- Electronic learning: MOOC (Massive Open Online Courses) is certainly an opening to the future and maybe a good way to extend nuclear culture, for example to train or inform journalists, civil society or decision makers. However, its effectiveness to train nuclear specialists was strongly questioned in the audience.
- Exchanges and communication between projects: The need of increasing exchanges, communication, even stimulation between projects was mentioned by several participants. For them, this would enable the optimization of resources, dissemination and participation to courses and then ensuring a high-level content and delivery of E&T various nuclear domains in agreement with the European Qualification Framework, Bologna (ECTS) and Copenhagen (ECVET) principles. Moreover, sharing on experiences and information about the state of the art in E&T approaches and tools should optimize the overall quality of E&T in nuclear.

- Research infrastructures, in particular research reactors but not only, are key tools for Education and Training and for "hands-on training". Besides the vital role of "high power research reactors" (10 to 100 MWth) for material research, the importance of low-power reactors for basic nuclear education and training was reminded. The role of the JRC regarding research infrastructures and mobility programmes was discussed without, however, a consensus emerging on its role besides those of national infrastructures.
- The actual cost of operating the research infrastructures compared to the costs displayed for the access programs was discussed. Some participants requested that all costs, including waste management costs, be included into access programs.
- Among the attendance, a request of harmonisation of administrative, financial and scientific rules regarding access to research infrastructures and mobility programmes was expressed. Some of the attendees suggested that the organisation of open access could be through one entity (ENEN or JRC for example).
- The role of international support programmes like ICERR and their complementarity with national and European programmes was raised.
- Communication: Most of the participants agreed to recommend an increase of information towards non specialists and to the improvement of public understanding.

A representative of Rosatom, invited to attend this session, delivered a message aiming at continuing cooperation launched through the ENEN-RU I and II projects and developing joint research and the use of experimental facilities for education.

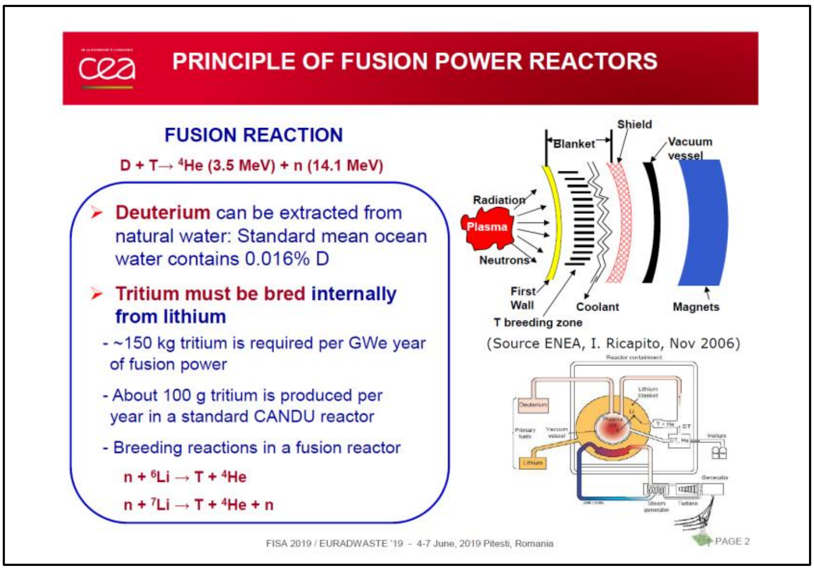
In conclusion of this session, it can be said that E&T is a pillar for nuclear expertise in Europe for future, even for countries which have chosen nuclear phase out. In that respect, Euratom plays a very important role in ensuring the long-term sustainability of an educational offer of high quality, acknowledged (ENEN certification) throughout the EU. With this in mind, support to E&T must be maintained.

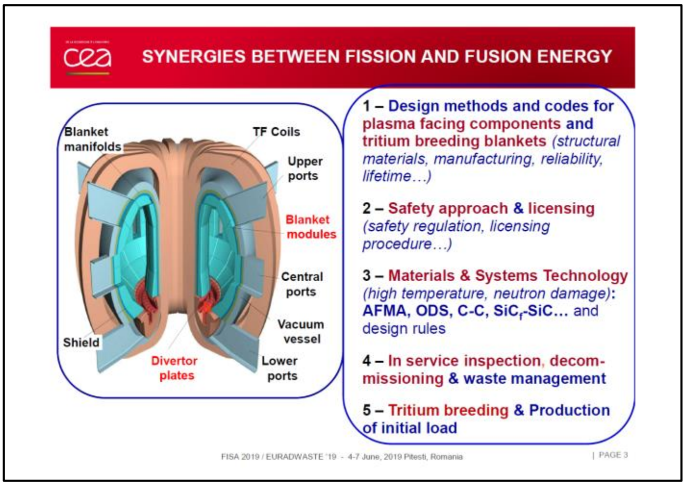
FRANCK CARRE

FISA 2019 – EURADWASTE '19

Presentation of Mr Franck Carre (CEA, FR)

Growing Synergies between Fission and Fusion Research towards Demonstration Plants




SYNERGIES BETWEEN FISSION AND FUSION ENERGY
Blanket manifolds
TF Coils
Upper ports
Blanket modules
Central ports
Vacuum vessel
Shield
Divertor plates
Lower ports
1 – Design methods and codes for plasma facing components and tritium breeding blankets (structural materials, manufacturing, reliability, lifetime…)
2 – Safety approach & licensing (safety regulation, licensing procedure…)
3 – Materials & Systems Technology (high temperature, neutron damage): AFMA, ODS, C-C, SiC_f-SiC… and design rules
4 – In service inspection, decom-missioning & waste management
5 – Tritium breeding & Production of initial load
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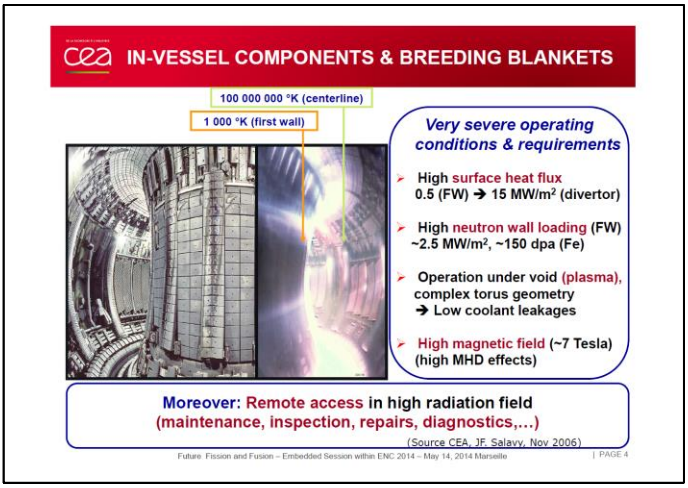
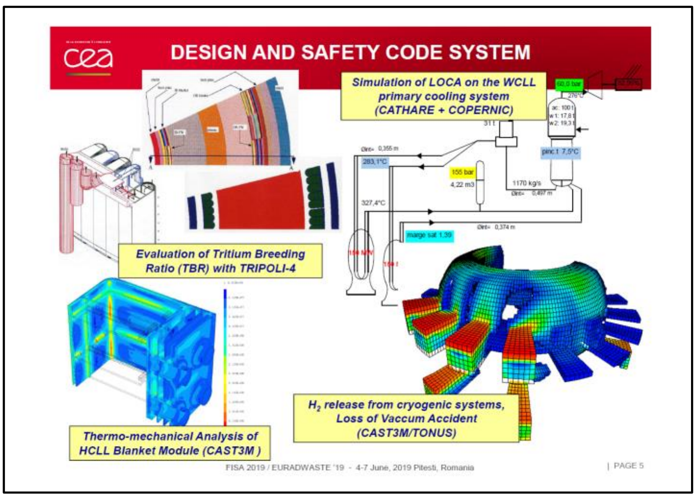

IN-VESSEL COMPONENTS & BREEDING BLANKETS
100 000 000 °K (centerline)
1 000 °K (first wall)
Very severe operating conditions & requirements
High surface heat flux 0.5 (FW) ➔ 15 MW/m² (divertor)
High neutron wall loading (FW) ~2.5 MW/m², ~150 dpa (Fe)
Operation under void (plasma), complex torus geometry ➔ Low coolant leakages
High magnetic field (~7 Tesla) (high MHD effects)
Moreover: Remote access in high radiation field (maintenance, inspection, repairs, diagnostics,…)
(Source CEA, JF. Salavy, Nov 2006)
Future Fission and Fusion – Embedded Session within ENC 2014 – May 14, 2014 Marseille
PAGE 4


DESIGN AND SAFETY CODE SYSTEM
Simulation of LOCA on the WCLL primary cooling system (CATHARE + COPERNIC)
Evaluation of Tritium Breeding Ratio (TBR) with TRIPOLI-4
Thermo-mechanical Analysis of HCLL Blanket Module (CAST3M)
H₂ release from cryogenic systems, Loss of Vaccum Accident (CAST3M/TONUS)
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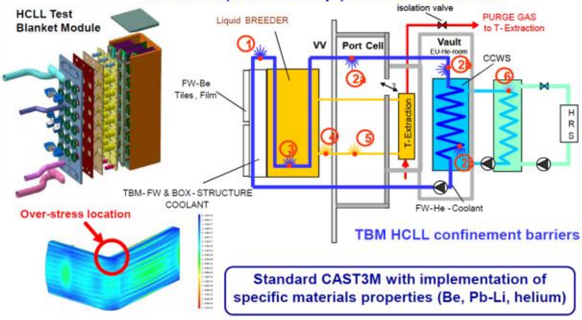
SAFETY AND LICENSING OF FUSION COMPONENTS

Analysis with CASTEM of thermal and mechanical loading of ITER-TBM *(HCLL concept)* in LOCA conditions



SAFETY ANALYSIS & LICENSING PROCESS

- **Specific aspects of D-T Fusion Tokamak reactors**
  - Inherent safety of plasmas
  - Production of radioactive nuclei by activation only
  - Low decay heat
  - Pulsed operation & Control of plasma disruption
  - Large energy stored in the magnetic configuration
- **Common features with fission reactors**
  - Confinement of radioactive materials: large Tritium hold-up, activation products in the system *(Mn, Fe, Co, Ni, Mo in steels + Cu, Co, Zn in copper alloys)*
  - Removal of power (in operation and at shutdown)
- **Safety and licensing**
  - Adaptation of Fission safety demonstration to Fusion experimental devices → Safety case of ITER and DEMO

MATERIALS FOR FISSION & FUSION SYSTEMS

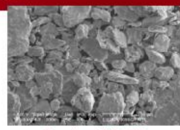
	Present Generation		Next Generation	
	Fission (Gen. II&III)	Fusion (ITER)	Fission (Gen. IV)	Fusion (Reactor)
T_{max} (structural material)	<300°C	<300°C	500-1000°C	550-1000°C
DPA max (internal components)	~1 dpa	~3 dpa (TBM)	~30-100 dpa	~150 dpa
He Production	~0.1 appm	~30 appm	~3-10 appm	~1500 appm
He/dpa	~0.1	~10	~0.1	~10
Structural material	*Austenitic steels, Zircaloy*	*Austenitic steels*	*Ferritic steels, Superalloys ? SiC-SiC ?*	*Ferritic martensitic steels, SiC-SiC ?*

*Comparable service conditions : **high temp.** (>500°C) & **high dpa** (>100 dpa)*

ADVANCED STRUCTURAL MATERIALS FOR FUSION REACTORS

Options considered

- **Low activation martensitic steel**
  - → **Replace elements subject to activation**
  - **Ni, Mo… → Mn, W…**
  - → **Low activation martensitic steel EUROFER**
    - Operating conditions 500-650°C ***(ODS)***
    - Several tonnes already manufactured



Powder of EUROFER strengthened with 0.2% Y_2O_3

- **Vanadium alloys or SiC composite ceramics**
  - → **Heat resisting materials with fast des-activation**
  - → **Less known materials → Longer term use**
    - Operating conditions
      - 700°C ***(V)***
      - 1000°C ***(SiC-SiC)***

SiC/SiC

Assembling SiC/SiC and SiC/W

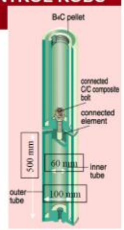
COMPOSITE MATERIALS FOR INTERNALS: CONTROL RODS

C/C & SiCf/SiC composites

→ **Manufacturing:** 2D & 3D woven fibres (C, Hi-Nicalon S), interphases, CVI or pitch densification, anti-oxidation coating (Si, B)…)

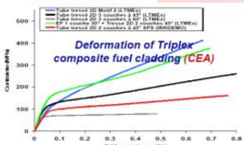
→ **Technical file for codification** of design Standards

ORNL (L. Snead)



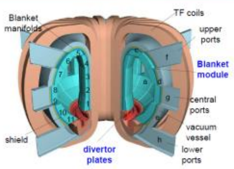
Fuel Pin Cladding
Nite Process
Kyoto University

Hexagonal wrapper tube for SFR subassembly



Deformation of Triplex composite fuel cladding (CEA)

MATERIALS CONSIDERED FOR FUSION REACTORS



Breeding Blankets (DEMO → Reactor)

- **Structural materials: EUROFER, EUROFER ODS, SiC_f/SiC** (+ beyond EU: other M/FS, V alloys)
- **Tritium breeder materials:** $LiPb_{eu}$, Li_2TiO_2, Li_4SiO_4 (+ beyond EU: Li_2O, Li)
- **Functional materials:** Be (neutron multiplier), permeation barrier & corrosion, electric insulators in **SiC_f/SiC**, shielding PP (W)
- **Coolants**: He, $LiPb_{eu}$ (+ beyond EU: Li, water SP)

Divertor (DEMO → Reactor)

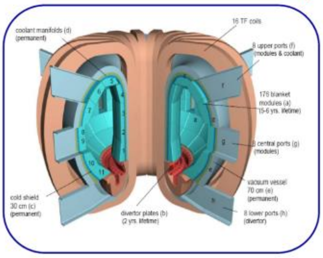
- **Structural materials: W alloys, Eurofer (+ interface in C), Eurofer ODS, SiC_f/SiC** (+ brazing?) (+ beyond EU: other M/FS, V alloys)
- **Shielding materials: Ceramics** or W tiles
- **Coolants:** He, pressurized water, $LiPb_{eu}$ (+ beyond EU: Li)

R&D needs (measurements & improvements)

- Behaviour under irradiation (mechanical, thermal, neutronic, electrical, …)
- Irradiation behaviour
- Modelling
- Compatibility between materials
- Fabrication (ex.: **CIC**, particle bed..)
- Assembly (ex.: interface, weldings…)
- Low long term activation

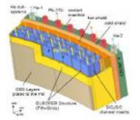
DESIGN & TECHNOLOGY OF BREEDING BLANKET (1/2)

Typical Tokamak Configuration T-Breeding Blanket: Dual Coolant Lithium Lead



Fusion Power Reactor Dual-Coolant T-Blanket	
He, 80 bars	Pb-17Li, ~bar
300, 480 °C	480-700 °C

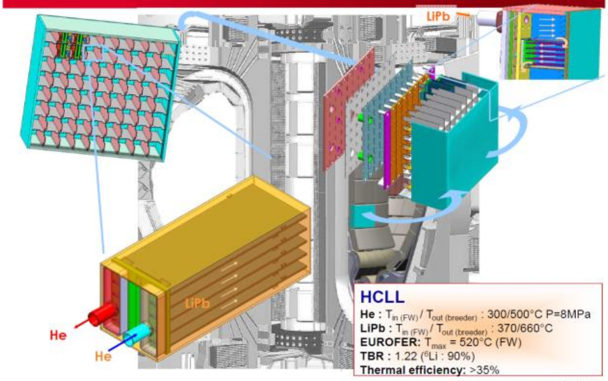
Dual-Coolant T-Blanket



Martensitic Steels (550 °C)
ODS Ferritic steels (700 °C)
SiC_f-SiC th. & elect. insulator

F W: T max= 625 °C
Channel : Tmax= 500 °C
Insert : Tmax~1000 °C

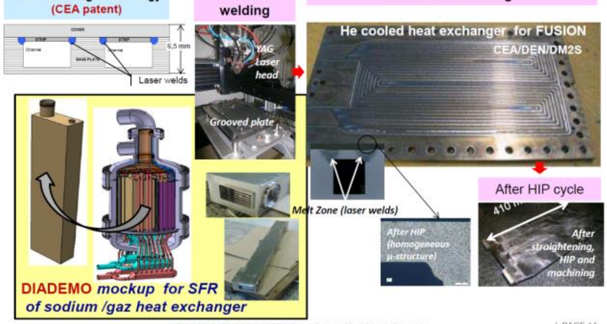
DESIGN & TECHNOLOGY OF BREEDING BLANKET (2/2)

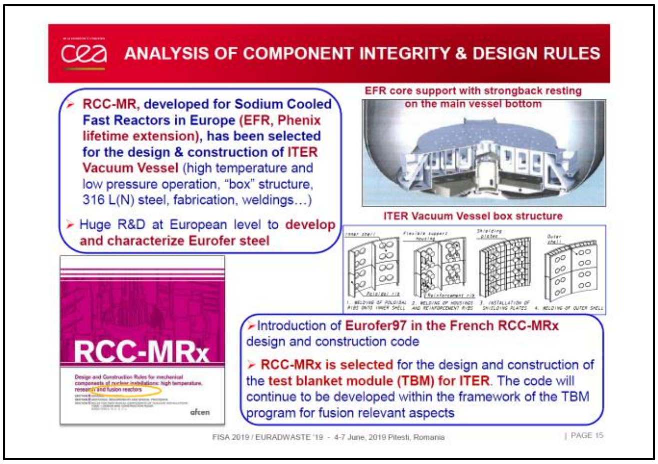


COMMON TECHNOLOGIES FOR FUSION BREEDING BLANKETS & GEN-IV FISSION REACTORS

- ***Fabrication of He Cooling Plate and Stiffeners for HCLL TBM***

Manufacturing technology (CEA patent)	Before welding	After laser welding




ANALYSIS OF COMPONENT INTEGRITY & DESIGN RULES
RCC-MR, developed for Sodium Cooled Fast Reactors in Europe (EFR, Phenix lifetime extension), has been selected for the design & construction of ITER Vacuum Vessel (high temperature and low pressure operation, "box" structure, 316 L(N) steel, fabrication, weldings…)
Huge R&D at European level to develop and characterize Eurofer steel
EFR core support with strongback resting on the main vessel bottom
ITER Vacuum Vessel box structure
RCC-MRx
afcen
Introduction of Eurofer97 in the French RCC-MRx design and construction code
RCC-MRx is selected for the design and construction of the test blanket module (TBM) for ITER. The code will continue to be developed within the framework of the TBM program for fusion relevant aspects
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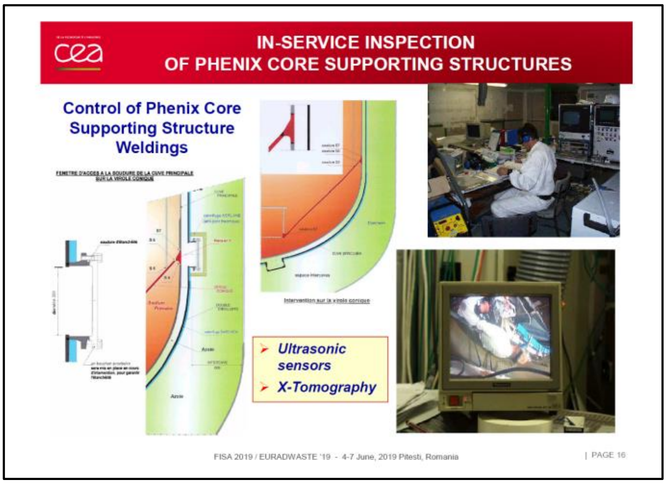
IN-SERVICE INSPECTION
OF PHENIX CORE SUPPORTING STRUCTURES
Control of Phenix Core Supporting Structure Weldings
Ultrasonic sensors
X-Tomography
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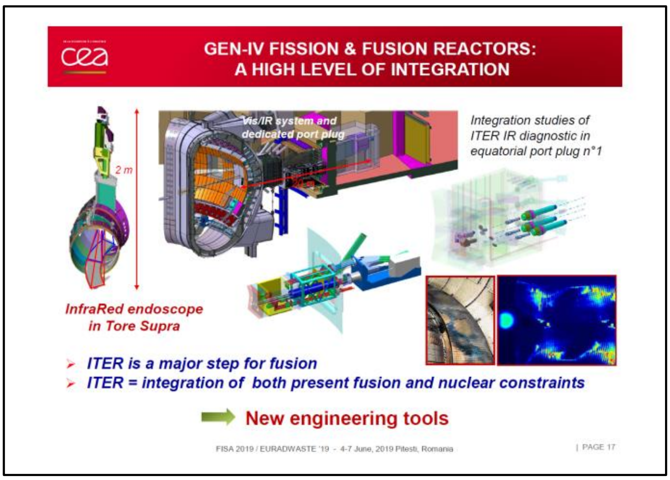
GEN-IV FISSION & FUSION REACTORS:
A HIGH LEVEL OF INTEGRATION
2 m
Vis/IR system and dedicated port plug
Integration studies of ITER IR diagnostic in equatorial port plug n°1
InfraRed endoscope in Tore Supra
ITER is a major step for fusion
ITER = integration of both present fusion and nuclear constraints
New engineering tools
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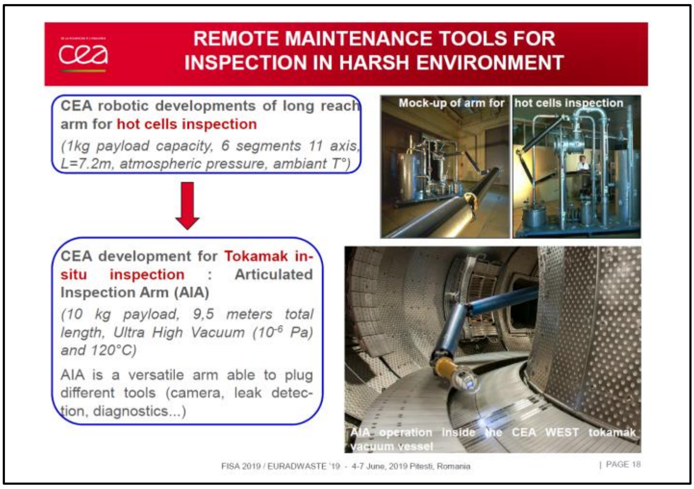
REMOTE MAINTENANCE TOOLS FOR INSPECTION IN HARSH ENVIRONMENT
CEA robotic developments of long reach arm for hot cells inspection
(1kg payload capacity, 6 segments 11 axis, L=7.2m, atmospheric pressure, ambiant T°)
Mock-up of arm for hot cells inspection
CEA development for Tokamak in-situ inspection : Articulated Inspection Arm (AIA)
(10 kg payload, 9,5 meters total length, Ultra High Vacuum (10-6 Pa) and 120°C)
AIA is a versatile arm able to plug different tools (camera, leak detection, diagnostics...)
AIA operation inside the CEA WEST tokamak vacuum vessel
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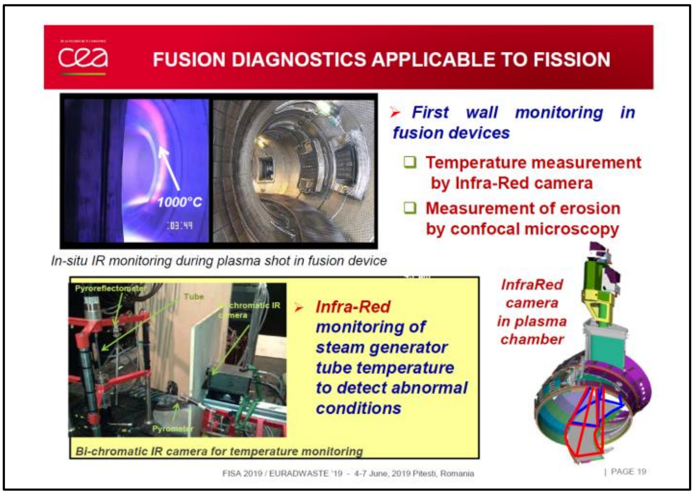
FUSION DIAGNOSTICS APPLICABLE TO FISSION
1000°C
In-situ IR monitoring during plasma shot in fusion device
First wall monitoring in fusion devices
Temperature measurement by Infra-Red camera
Measurement of erosion by confocal microscopy
Pyroreflectometer
Tube
Bichromatic IR camera
Pyrometer
Infra-Red monitoring of steam generator tube temperature to detect abnormal conditions
Bi-chromatic IR camera for temperature monitoring
InfraRed camera in plasma chamber
FISA 2019 / EURADWASTE '19 - 4-7 June, 2019 Pitesti, Romania
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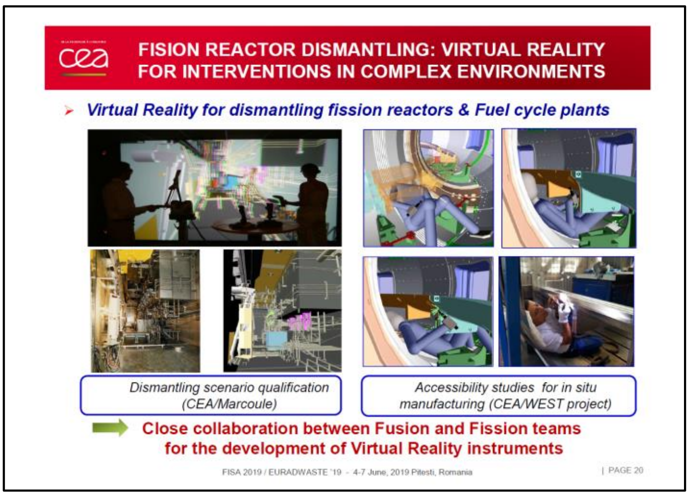
FISION REACTOR DISMANTLING: VIRTUAL REALITY FOR INTERVENTIONS IN COMPLEX ENVIRONMENTS
Virtual Reality for dismantling fission reactors & Fuel cycle plants
Dismantling scenario qualification (CEA/Marcoule)
Accessibility studies for in situ manufacturing (CEA/WEST project)
Close collaboration between Fusion and Fission teams for the development of Virtual Reality instruments
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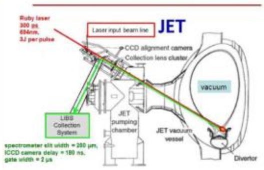
LASER INDUCED BREAKDOWN SPECTROSCOPY

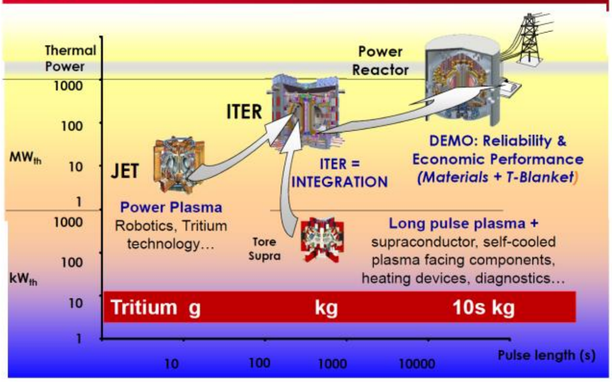
Laser Induced Breakdown Spectroscopy **(LIBS)** developed for real-time analyses (sample composition) in severe environment

Laser induced breakdown spectroscopy application in Joint European Torus (JET)
[A. Semerok et al, Spectrochimica Acta Part B 123 (2016) 121–128]

Development of LIBS (ps) for both quantitative detection (composition and profilometry) of tritium retention in Tokamak.



ITER & MAGNETIC FUSION DEVELOPMENT PATHWAY



TRANSAT: A TRANSVERSAL ACTION FOR TRITIUM

- **TRANSAT, a European H2020 project focused on Fission-Fusion commonalities on tritium** (CEA as coordinator, 8 EU countries involved, 2018-2021)

TRANSAT
TRANSversal Actions for Tritium
http://transat-h2020.eu/

- Cross-cutting support to **improved knowledge on tritium management in fission and fusion facilities**
    1. Tritium permeation control
    2. Assessment of the tritium inventory using state-of-the-art modelling tools
    3. Engineering solutions for detritiation techniques and waste management
    4. Refinement of the knowledge on outgassing, radiotoxicity, radioecology, radiobiology, dosimetry and metrology of tritium

- **First International School on Tritium organised in Ljubljana (Slovenia, 25-28/03/2019)**

SYNERGIES BETWEEN FISSION AND FUSION NUCLEAR ENERGY

Summary

- **Nuclear Design and Technology**
  - Codes and design methods
  - High temperature and neutron resistant materials
  - Gas, water or liquid metal cooled systems technology
  - In service inspection, maintenance in hostile environment
  - Dismantling and waste management
- **Safety approach and licensing**
- **Increased synergies for the Fusion DEMO reactor**
  - Optimization of blanket design for energy and tritium production
  - Demonstration of full tritium breeding and recovery
  - Production of initial tritium load
- **Education in nuclear physics and engineering**
  - Attraction of young scientists in the fields of nuclear energy
  - Stimulation of education and training in nuclear physics and engineering
- **Towards more integrated Fusion and Fission programs**

WALTER AMBROSINI

EDUCATION, TRAINING AND MOBILITY: TOWARDS A COMMON EFFORT TO ASSURE A FUTURE WORKFORCE IN EUROPE AND ABROAD

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[8] European Commission, Joint Research Centre (JRC), Karlsruhe, Germany

Abstract. The paper highlights the main features of some Euratom projects, which have been running recently in support to education, training and mobility in the nuclear fields. The described projects address various critical aspects of nuclear knowledge management, aiming at maintaining the wealth of nuclear expertise in Europe in an environment characterised by decreased attractiveness of nuclear careers. In an effort to broaden the cooperation and to further extend the opportunities for mobility, some projects ran in parallel with similar initiatives undertaken beyond the European borders. The lesson learnt in terms of successes achieved and critical aspects revealed by the different actions are finally discussed also considering recent recommendations and assessed scenarios by the European Commission for the decarbonisation of the energy sector.

1. Introduction

Since the early days of its technological deployment, nuclear energy has been the subject of both enthusiasm and aversion. The mass intensive characteristics of nuclear energy is in fact perceived alternatively as an opportunity or a deterrent, the latter view prevailing in public opinion in the periods after the occurred nuclear reactor accidents, despite of any serious technical reflection about the causes of the faulty occurrences. This situation of biased feelings is cyclically weakening the effectiveness of efforts devoted to keep and develop an adequate nuclear workforce, creating a generally unfavourable environment for attracting young human resources to the related careers.

The results of this known phenomenon range from the presence of fluctuations in the availability of nuclear personnel with the requested skills and experience to a general shortage of adequate replacements for retiring "experts" (see, e.g., [1-2]). However, the group of experts in specific nuclear disciplines is not the only one that must be considered critical; in case of new builds, in fact, also skilled personnel in disciplines other than the nuclear ones, who have anyway to operate in the nuclear sector (e.g., civil, chemical, electrical, mechanical engineers, etc.), may be found lacking in the appropriate number. In this regard, it must be considered that the personnel with these "generic skills", owing to the fact that they do not pertain specifically to the nuclear sector, may be needed at the same time also in other areas, thus creating a competition between different demands, with the potential for giving rise to bottlenecks and pinch points [3].

In general, the optimal composition of the nuclear workforce in case of new builds is depicted as having a pyramidal (or triangular) structure, at whose tip specifically educated nuclear experts are located, in relatively limited number, while the lower levels are more widely populated with personnel having generic skills, to be "nuclearized" or made "nuclear-aware" at different levels [2-5].

A common feature of all the personnel working in a nuclear environment should be at least a sound basis of education and training in relation to nuclear safety culture, as an overriding priority at all the technical and managerial levels, while the depth of competences in the rest of nuclear disciplines may vary depending on the function. In the current descriptions of nuclear workforce, the need for personnel who has received a specific and in-depth nuclear education and training (the "experts") must be considered also in view of the role it has in providing nuclear knowledge and skills to the other personnel; so, their smaller number should not lead to overlook their relevance as nuclear knowledge and skill "multipliers". It must be also mentioned that the education and training of nuclear "experts" needs competences whose accumulation requires decades in research and teaching experience, requesting a long-term investment in nuclear education and training (E&T).

In view of the above, the very reason for devoting efforts in nuclear E&T nowadays is to avoid that the occurring fluctuations in nuclear job demand be directly reflected in a decreased capability of nuclear competence transfer through generations, causing a possible permanent loss of competitiveness in the sector. Moreover, the request of two well-known European directives dealing with nuclear safety and waste management (named in short as "nuclear safety directive" [6] and "nuclear waste directive" [7]) that "Member States shall ensure that the national framework require all parties to make arrangements for education and training for their staff (…)" must be therefore considered to imply the mentioned long-term investment.

The projects shortly presented in this paper [8-17]) share the common intent to contribute, at different extents and in different contests, to nuclear E&T and to facilitate cross-border mobility and life-long learning of students and professionals. A number of these projects are led by or include the participation of the European Nuclear Education Network (ENEN). The ENEN AISBL, now an international association under the Belgian law, was constituted in 2003 in France, starting its actions with only 22 members. It celebrated its 10th anniversary in 2013 at the previous FISA/EURAWASTE Meeting held in Vilnius (Lithuania) [18]) and in 2018 it also celebrated its 15th anniversary, during a ceremony held in Brussels before its annual General Assembly [19]). The Association, whose "mission is the preservation and further development of expertise in the nuclear fields by higher Education and Training", has today 77 members who are actively involved in promoting its actions.

ENEN, its members and the other actors in the field of nuclear education and training in Europe, with the financial support of the European Commission, are part of the long-term investment that the European Union is carrying on for assuring an adequate nuclear workforce for a future decarbonised energy market. While similar efforts are needed also at the level of Member States, to assure high standards of safety and to properly deal with nuclear waste management issues [6-7], the coordinated actions described hereafter represent a common response of the European atomic energy community to the challenges posed by the preservation of present high levels of expertise in the nuclear fields.

2. NEEDS OF NEW MEMBER STATES AND SPECIFIC REGIONAL INITIATIVES

In recent years, the need was felt to make sure that New Members States (NMS – this designation is still in use even if these states are full member of the EU for 10 years and more for some of them) would be effectively included into the process of networking and inclusion in the research and education community previously established for Old Members States (OMS). In particular, a good level of participation of NMS in Euratom Projects was identified as an important aspect to be assured in welcoming these states into the European nuclear research and education community. This stimulated launching initiatives aiming at assuring a good level of networking between NMS and OMS.

In addition, the specific situation and key initiatives going on in specific areas of Europe attracted the attention, suggesting to check for the presence of adequate capacitance for carrying on the intended projects or in order to stimulate better cooperation. This was the case of the Lead cooled Fast Reactor demonstrator (called ALFRED), proposed to be built in Romania which, involving the known challenges of Generation IV reactors, requires specific expertise in the related sector. Likewise, the Baltic Region hosts a number of research centres and institutions with a considerable potential in nuclear science and technology, whose level of cooperation was deserving improvements for fully developing their potential.

Projects addressing these issues were conceived and run in order to promote cooperation and developments in nuclear science and education, aiming to respond to the needs described above.

2.1. FP7 NEWLANCER Project (November 2011–October 2013)

NEWLANCER intended to pave the way for a sustainable participation of the research institutes and universities from NMS in nuclear energy research as framed by European policies and initiatives. NEWLANCER consortium consisted of 17 partners representing nuclear research institutes (INR, INRNE, LEI, JSI, INCT, MTA EK, CEA, ENEA, SCK•CEN, APRE, NNL), universities (UPB, UL, TUS), implementers (ARAO) and SME (SYMLOG, REC) from both NMS and OMS.

All partners worked together to identify the best applicable solutions to increase the future NMS participation in the Euratom research, exploring three directions: strengthening and catalysing the full R&D potential at national level, increasing cohesion between NMS and improving cooperation with OMS research centres (see the structure of the project in FIG. ***3***).

A complex multi-level network, gathering a large number of experts in nuclear fields not only from partners' organisations, but also from many other institutes and universities from the six NMS of the consortium (Bulgaria, Hungary, Lithuania, Poland, Romania, and Slovenia), has been created having as major objective to link national and regional experts in the Euratom fields and connect them to OMS research centres with large participation, as well as to the European Technological platforms (SNETP, IGD-TP, MELODI) and other related associations or networks (EERA, NUGENIA, Euratom NCP). Involving around 160 specialists in nuclear safety, Gen III and IV, advanced materials, radioactive waste management, radioprotection and education & training (E&T), this network ensured a good national and regional representativeness. Structured into 19 National Experts Groups and 5 Regional Expert Groups, the network provided deep insights on NMS participation starting from the specialist level up to the organizational management, national and EC polices, strategies and programmes, and also a regional view on the common driving factors, difficulties and barriers in NMS involvement in Euratom.

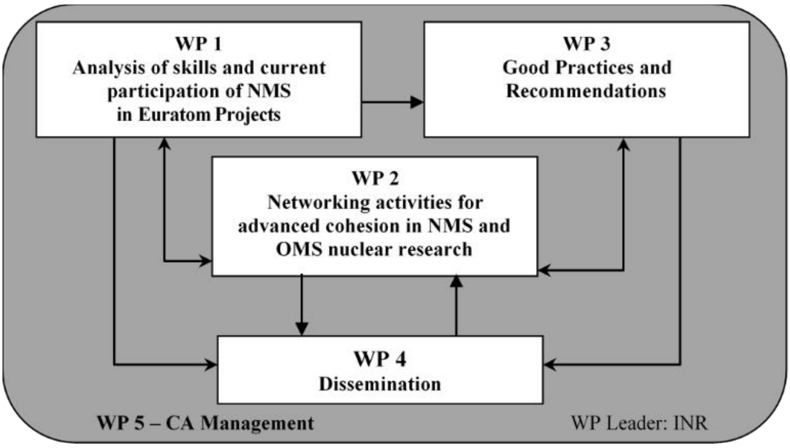

FIG. 3. Functional sketch of the NEWLANCER Project.

At national level, the networking activities consolidated the links among scientists as well as their connections with national structures (ministries, research agencies, nuclear authorities) responsible for the construction/implementation of the national research policies, strategies, and programmes. At regional level, activities focused on building advanced cohesion among NMS specialists, as well as among OMS and NMS experts facilitated the access to information and strengthened collaboration between specialists and creation of teams able to plan new projects.

In the field of Education and Training, NEWLANCER concluded that a good participation in international projects exists and as a consequence a real exchange of information about different E&T system and used methods and tools both in NMS and OMS occurred. This is an important gain and a good approach to improve the quality of the graduates. A common issue for NMS consists of a decreasing tendency of youngsters' interest for nuclear education and consequently in reduction of the nuclear education share at the level of universities. Related to nuclear training, some challenges related to implementing Generation IV systems in NMS connected with ALLEGRO and ALFRED demonstrators exist and also with the preparation of technicians to operate the existing and future nuclear installations.

Integration of teams from NMS into existing groups already created by OMS R&D organizations and having a long-time cooperation is quite open, but it is strongly dependent on the visibility of the organization and researchers itself, and also of the existing expertise. Thus, the national framework is very important to support the local competence development to reach an adequate level for the participation in European projects. The lack of national support for a specific topic creates real difficulties including co-financing aspects.

NEWLANCER's recommendations for wider future participation in future Euratom research and education programs represent the synthesis of the joint activities of the consortium [14] and the consideration of critical success factors identified in the SWOT analysis from six countries:

- improving institutional and national policy making, strategic planning and setting the nuclear research and education among priorities (implementing priorities with resources for training, modernized infrastructure, support, etc.);
- improving cooperation between all activity holders in nuclear research and development, including cooperation with universities and postgraduate students;
- including information on Euratom projects and policy in nuclear study programs;
- ensuring visibility and presence on the European scene, including academic dissemination, researcher networking, scientific lobbying.

The NEWLANCER network, resulting from this project, represented a good basis for information exchange between experts both at national and regional level and allowed incorporation of new participants and organisations. The network activity as proposed and implemented during the project to capitalize the existing expertise and complementarities will continue to provide an open space for discussion and elaboration of future project proposals. The 4 European projects (MACXIMA, EAGLE, ASAMPSA_E and ARCADIA) rooted in the NEWLANCER are a positive example. They insured the continuation of NMS participation in Euratom and offered new opportunities for a further involvement of the NMS in H2020 both in research and education activities.

2.2. FP7 ARCADIA Project (November 2013 – October 2016)

ARCADIA - Assessment of Regional CApabilities for new reactors Development through an Integrated Approach - was implemented by a Consortium of 26 members, coordinated by RATEN ICN (Romania) (see

FIG. ***4***).

The Lead Fast Reactor (LFR) is one of the six technologies of Generation IV from which are expected advantages in terms of safety, economics and environmental impact, as well as a large flexibility on the energy market in terms of power capacity. To demonstrate the viability of this technology a demonstrator, called ALFRED, is foreseen to be built in Romania. The FP7 project ARCADIA was started in 2013 with the aim to assess the ALFRED feasibility, exploring the key components of a successful implementation: competences and infrastructure, licensing and public participation, funding and feasibility aspects, national and regional support, each one addressed by a dedicated Work Package.

The education and training aspects related to the development of the LFR technology in general, and the implementation and operation of ALFRED and its supporting R&D infrastructure in particular, have been approached in WP1.

ARCADIA Consortium

RATEN ICN (Romania), JSI (SI), SCK•CEN (Belgium), ENEA (Italy), ARAO (Slovenia), MTA EK(Hungary), LEI (Lithuania), INCT (Poland), CLOR (Poland), NCBJ (Poland), IRSN (France), Centrum Vyzkumu Řež S.R.O. (Czech Republic), KTH (Sweden), NCSRD (Greece); **nuclear education**: TUS - Technical University of Sofia (Bulgaria), UPB - Universitatea Politehnica Bucuresti (Romania), UL - University of Ljubljana (Slovenia), UPIT - Universitatea dn Pitesti (Romania), TARTU Ulikool (Estonia), ISP - Instituto Superior Tecnico (Portugal); **nuclear industry**: ANSALDO NUCLEARE (Italy); and **NGOs with activity in the nuclear research**: SYMLOG - Institut SYMLOG de France (France), APRE (Italy) and REC (Slovenia).

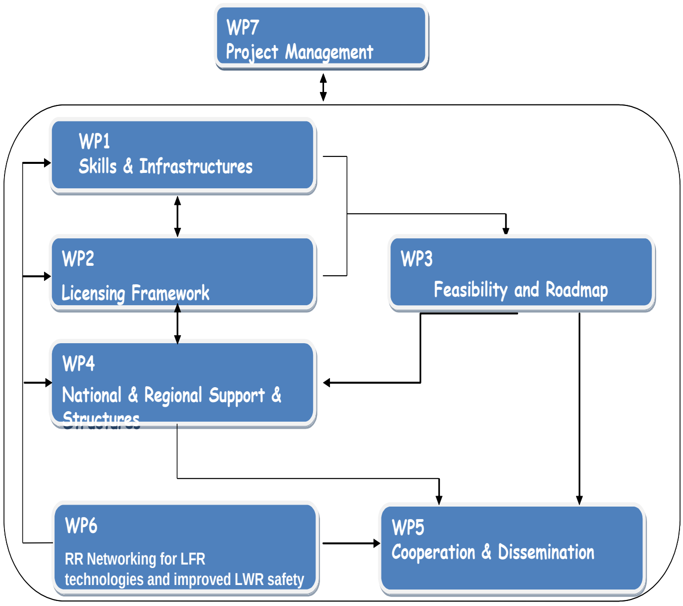

FIG. 4. Consortium composition and functional sketch of the ARCADIA Project.

ARCADIA outcomes allowed to conclude that there are good premises for the construction of the ALFRED demonstrator in Romania, in terms of competence and infrastructure, licensing and public acceptability, opportunity and competitive advantages, risks and benefits, funding and national and regional support. The existing competence at regional and European level can cope with the technical and scientific challenges raised by the final R&D on ALFRED. A set of gaps in skills and competence were however identified in a perspective of increased commitment to cope with the successive design, licensing and construction phases; consequently the ARCADIA consortium proposed methods and practical solutions to address the education and training (E&T) required to cover these gaps in due time.

The new technical skills and competences required to cover specific aspects proper of a Fast Reactor, and of a LFR in particular, often common throughout the different phases and actors involved in the project, relate to: nuclear data evaluation and preparation, in a fast spectrum; lead thermal/hydraulics; thermo-mechanics and lead chemistry; disciplines on instrumentation and control devices and systems; specific competences to ensure the management of a project of an international vocation, developed and implemented by an international consortium, and financed from different sources.

Based on the ECVET principles (European Credit System for Vocational Education and Training) and on an outcome-based pedagogical approach to lifelong learning, ARCADIA proposed an E&T programme having as main blocks:

- the application of the outcome-based competence building and the CDIO (Conceive Design Implement Operate) approach in the classic education programme;
- the professional qualification of students and professionals by attending application-specific courses delivered at Centers of Excellence by teachers and trainers qualified and accredited according to the highest pedagogical standards.

The first concrete results in the process of competence building consist in design and development of a new engineering education programme on energetic and nuclear technologies having specific modules on Gen IV and LFR. The programme was approved by the Romanian Ministry of Education and Research in 2014 and became active in the University of Pitesti starting with 2015.

The academic knowledge and competences are among the critical prerequisites needed to develop the industrial knowledge and competences. Timely filling the gaps in the competences identified in the ARCADIA project is therefore considered as an urgent activity to support a successful development and commissioning of the ALFRED reactor, and represents one of the main concerns of the FALCON consortium, the international partnership in charge with the preparation of the ALFRED project.

2.3. H2020 BRILLIANT Project (July 2015 – June 2018)

BRILLIANT Project (Baltic Region Initiative for Long Lasting InnovAtive Nuclear Technologies) was organised to establish and promote the cooperation of the research organisations in the Baltic region [10]. The project is implemented as follows: the coordinator is Lithuanian Energy Institute (LEI) (Lithuania), the partners are Narodowe Centrum Badan Jadrowych (NCBJ) (Poland), Tartu Ulikool (TARTU) (Estonia), Latvijas Universitate (UL) (Latvia), Kungliga Tekniska Hoegskolan (KTH) (Sweden), Valstybinis Moksliniu Tyrimu Institutas Fiziniu Ir Technologijos Mokslu Centras (FTMC) (Lithuania) and the industrial partner VAE SPB UAB (VAE SPB) (Lithuania). Each partner has strengths in some specific area, though lack of cooperation prevents the utilisation of full potential in the region.

Increased cooperation is intended to provide for a better solution of the challenges that the participating countries face in the field of nuclear energy development, but impact of such cooperation could be seen much broader than only the nuclear energy. The regional competences developed in the frame of the project created the basis for application of a regional approach in the planning of the energy sector in participating countries and those contributed to the implementation of Energy Union in the EU. The ultimate goal of BRILLIANT project was the development of a roadmap to establish the virtual EUROBaltic Centre of Nuclear Research and Technology, with competence centers established in all participating countries. The project covered a broad range of issues linked with the nuclear power industry and its organization is shown in FIG. ***5***, which also gives details of WP objectives. Each country (Estonia, Latvia, Lithuania, and Poland) organised two meetings with the wider public: students, industry, politicians and other stakeholders interested in the issues of nuclear power participated at these meetings.

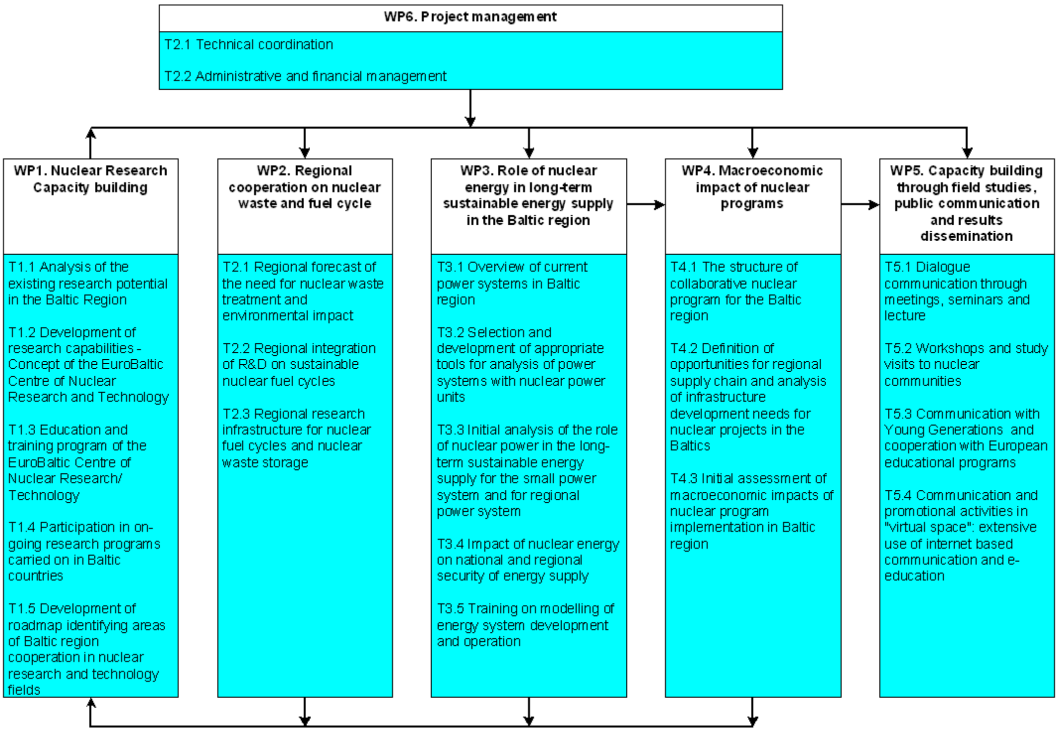

FIG. 5. Functional sketch of the BRILLIANT Project.

KTH (Sweden), through cooperation with Nova – Center for University Studies, Research and Development at Oskarshamn (Sweden) in the frame of Nova Research and Development Platform, offered an access to very unique and relevant large infrastructures. The platform offers access to SKB research data and the following facilities:

- Äspö Hard Rock Laboratory – a model for the geological repository site;
- the Bentonite Laboratory;
- the Canister Laboratory;
- site Investigation Oskarshamn.

All project partners and a number of interested experts from all participating countries took the opportunity to visit these facilities in the frame of the BRILLIANT project.

The major result achieved in BRILLIANT is the established effective cooperation among the research organisations in the Baltic region. The strengths, weaknesses, opportunities and threats were identified and a concept of the EuroBaltic Centre of Nuclear Research and Technology was developed together with the roadmap to the establishment of such center. Information of the amounts of radioactive waste in each participating country was collected. A regional integration and assessment of nuclear fuel cycle (NFC) options is divided into two parts, where the 1st part focuses on issues of regional integration of NFC research and the 2nd on modelling regional nuclear fuel cycle options themselves using FANCSEE code developed at KTH. All partners learned and developed the country specific models of energy sectors for MESSAGE tool. It must be noted that this tool was used in the frame of the project for a training on the assessment of energy security, an exercise that was performed for each country using the methodology developed at the Lithuanian Energy Institute in cooperation with Vytautas Magnus University (Lithuania). A methodology for the assessment of the macroeconomic impact was developed and tested in assessment of potential implementation of Visaginas NPP project.

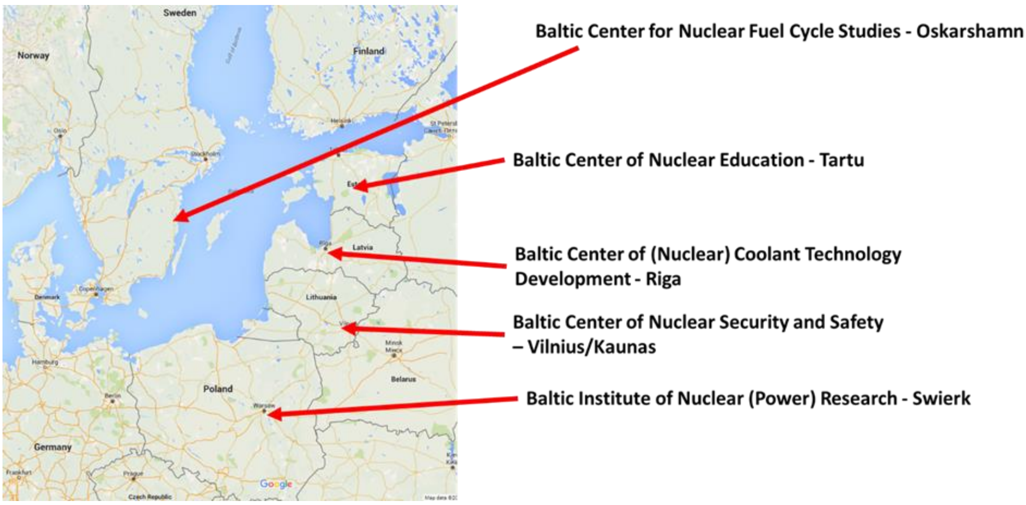

FIG. 6. Centers in the BRILLIANT Project.

To continue cooperation after BRILLIANT and to implement a concept of EuroBaltic Centre of Nuclear Research and Technology a new 2BETINA project (Baltic Basin Education and Training Infrastructure in Nuclear Applications) was developed and submitted to EURATOM call in 2018. This new proposal not only included the same partners, but expanded the geography of cooperation by the involvement of other neighbouring countries and of more universities and research centers.

3. EXCHANGES WITH EDUCATION SYSTEMS BEYOND EUROPE

The creation of the European Nuclear Education Network (ENEN) in 2003 represented an important step in promoting harmonisation by mutual recognition in nuclear disciplines in Europe, starting with nuclear engineering, but not limiting to it. While the introduction of the European Credit Transfer System (ECTS) and the implementation of the Bologna Convention in Europe were creating a common basis for exchanges and student mobility, the need was felt to approach two different countries whose education environments in the nuclear field were going to play an increasingly important role, being Russia and China. Promoting and easing exchanges of students and teachers between Europe and China was then considered an action worth of a specific efforts. As explained hereafter this operation was more successful in the case of Russia than of China.

3.1. FP7 ECNET Project (March 2011 – February 2013)

The main objective of the ECNET project was to coordinate the cooperation between the EU and China in the field of Nuclear Education, Training and Knowledge Management in the three areas of Nuclear Engineering, Radiation Protection and Nuclear Waste Management and Geological Disposal. The expected impacts of the project were:

- to promote mutual recognition of Education and Training programmes of EU and China;
- to expand exchanges of students, lectures and lecturers;
- to secure the knowledge management as appropriate.

As shown in FIG. *7*, the main work packages were related to the definition of the needs in the three mentioned nuclear fields, linked by specific interests for E&T facilities and to establish a possible system for credit recognition among the two areas of the world.

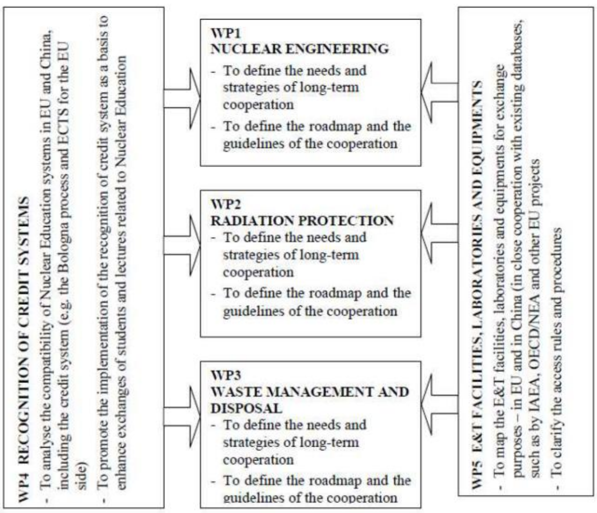

FIG. 7. Functional sketch of the ECNET Project.

As in the case of the ENEN RU projects (see below), ECNET involved two different consortia and mirror structures on the EU and the Chinese sides. The participants on the side of EU were ENEN, SCK•CEN (Belgium), CEA-INSTN (France), the Institute National Polytechnique de Lorraine (France), KIT (Germany), CIRTEN (Italy), the Universidad Politecnica de Madrid (Spain), the Imperial College of Science Technology and Medicine (UK). On the Chinese side, the Tsinghua University, the North China Electric Power University, the Southwest University of Science and Technology, the Harbin Engineering University, the Shanghai Jiao Tong University, the China National Nuclear Corporation Graduate School and the Xi'an Jiao Tong University participated in the endeavour.

The project impacted into some difficulties intrinsic in the exchange at the time, among which the language barrier. As a matter of fact, information received from Chinese partners was not sufficient to allow useful comparisons of the situations in Europe and in the fast growing economy and to develop efficiently a Europe-wide cooperation with China in nuclear E&T. However, some exchanges were possible, e.g., a double degree agreement established between the Politecnico di Torino (belonging to CIRTEN) and the Shanghai Jiao Tong University, to be considered as pilot examples that provided satisfactory results.

Though the experience of this project turned out to be not completely successful, the interest for exchanges between the nuclear education and training system in EU and in China has recently increased. This previous experience, if fuelled by a renewed interest for exchanges on both sides, may provide a useful starting point for setting up a better and deeper cooperation than it was possible with ECNET.

3.2. FP7 ENEN-RU II Project (July 2014 – June 2016)

The ENEN-RU II project was aimed at the "Strengthening of Cooperation and Exchange for Nuclear Education and Training between the European Union and the Russian Federation" and consisted of two parallel projects, on the EU side and the Russian side.

The Consortium on the EU side was composed by ENEN (B), SCK•CEN (B), CTU (CZ), Centrum Vyzkumu Řež S.R.O.(CZ), Universität Stuttgart IKE (D), TUM (D), CIRTEN (I), UPB (RO), STUB (SI), TECNATOM (E) and University of Manchester (UK). The Russian Consortium included in particular Rosatom, the MEPhI-National Research Nuclear University (NRNU) and CICET, together with other Russian organisations.

The objectives of the entire project have been:

- to further define a common basis for effective cooperation between the European and Russian networks for nuclear Education &Training (E&T);
- to define an implementation plan based on the needs of cooperation in the long-term;
- to solve the difficulties for cooperation found during the ENEN-RU project;
- to implement a collaboration plan in a sustainable manner;
- to operate the knowledge management framework;
- to list up and promote further use of E&T facilities, laboratories and equipment.

The six work packages in which the project was detailed are represented in

FIG. *8*.

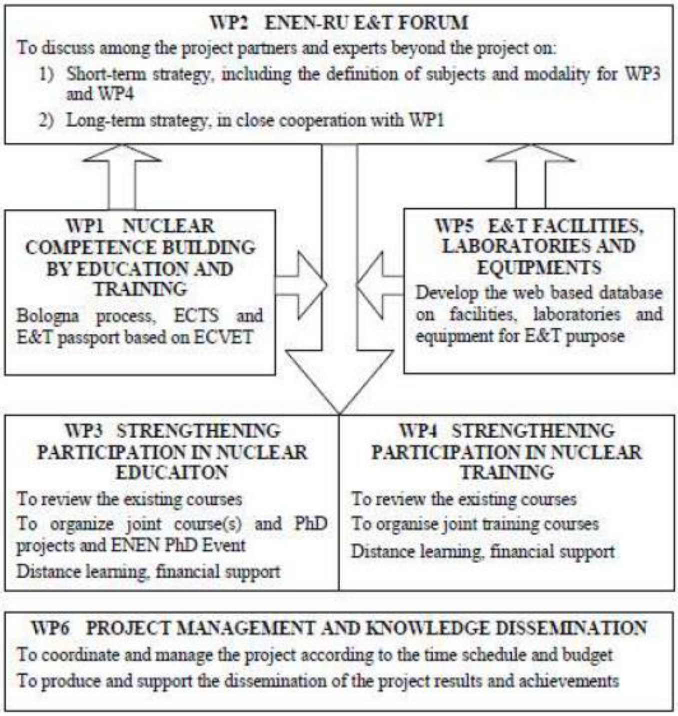

FIG. 8. Functional sketch of the ENEN-RU II Project.

The project involved several meetings and the participation of Workshops and Conferences held on either side, producing a high level of involvement in the respective environments. Among the achievements, the following can be mentioned:

- the comparison of curricula for Nuclear Engineering in EU countries and Russian Federation, showing that the credit systems in use in the two regions are compatible;
- as the outcome of the discussion within the ENEN RU E&T Forum, bilateral agreements were signed between the participants on either side (e.g., University of Pisa and MEPhI) and ENEN renewed its cooperation with MEPhI and with Rosatom-CICET;
- participation in joint courses at master and PhD levels was made possible for more than 40 students and a distance learning course was deployed;
- more than 30 individuals participated in 4 joint training courses, ("Engineering aspects of Fuel Fabrication" in Obninsk, Russian Fed. on 23-27 November 2015; Joint Education course on the "Introduction to Nuclear safety analysis of Nuclear Reactors with state-of-art Computer Programs" by TU Munich, Germany, on 25-28 April 2017; Joint Education course on "Multiphysics simulation of nuclear systems" organized at the POLIMI

campus in Milan, Italy, on 17-19 May 2017; Joint E&T course on "Simulation of different NPPs operation" organized at CTU in Prague, Czech Republic, on 30 May-2 June 2017), while exchanges of trainees and facilitators were made possible, also performing technical visits to fabrication and training centres;

- a web based database for E&T facilities, laboratories and equipment was developed; access can be granted to it, following a registration process, also to external users: several database access levels being available;
- participation in several important events on either side occurred.

The project put the basis for continuing the cooperation of ENEN with MEPhI-NRNU and Rosatom-CICET, making also possible to establish bilateral agreements among partners. Successfully overcoming the language barriers that were encountered in the first of the ENEN-RU project was another relevant outcome of ENEN-RU II.

4. CONTINUING EDUCATION EFFORTS FOR NUCLEAR TECHNOLOGIES

The need for educational opportunities stimulating students to undertake nuclear careers in a period of low attractiveness has been a continuous worry for ENEN and other players involved in the effort to maintain a sufficient level of nuclear workforce and expertise in Europe. Offering to students experiences in high level laboratories, intersemester courses and the access to that kind of general information that can be provided by Massive Open Online Courses (MOOCs) represented the target of one of the projects described below, aiming to make more lively the panorama of the nuclear educational offer in Europe. A further project moved from consideration of the ongoing introduction in European countries of the VVER technology, requesting specific training capabilities to be provided by a dedicated Academy, whose establishment was conceived in cooperation with ENEN. Both the initiatives, though not directly led by ENEN, represent efforts contributing to that process of maintaining and developing knowledge in the nuclear fields within Europe, which is continuously stimulated by the Association.

4.1. FP7 GENTLE Project (1 Jan 2013 – 31 Dec 2016)

The **GENTLE project (Graduate and Executive Nuclear Training and Lifelong Education)** ran for four years as part of the seventh Euratom Framework Programme, and was coordinated by TU Delft in the Netherlands. The other participating institutions were Budapest University of Technology and Economics (BME, Hungary), CIRTEN (Italy), the European Commission's Joint Research Centre (JRC, EC), Karlsruhe Institute of Technology (KIT, Germany), Lappeenranta University of Technology (LUT, Finland), Paul Scherrer Institute (PSI, Switzerland), Polytechnic University of Madrid (UPM, Spain), SCK•CEN (Belgium), University of Manchester (UMAN, UK), and University of Tartu (UT, Estonia),

The GENTLE project offered training to students via Student Research Experiences (SRE) and Inter-Semester Courses for graduate and postgraduate students on special topics that are generally not part of the academic program. Furthermore, a Massive Open Online Course (a so-called MOOC) was compiled and organised for students at the bachelor level interested to learn more about nuclear energy, nuclear reactors, and the nuclear fuel cycle.

- SRE: Students could follow internships at the GENTLE project partners' laboratories for which they could receive a grant. These Student Research Experiences (SREs) could last up to twenty-four months and were open to students enrolled in any European university. SREs were meant to increase the technical and scientific background of students in topics related to nuclear science and engineering. For the selection of the student and the hosting institution, the following criteria were taken into account: scientific quality, equipment, staff, benefit to the applicant, impact on the field, and gender balance. In total, 74 students participated, originating from the countries shown in FIG. ***9***:

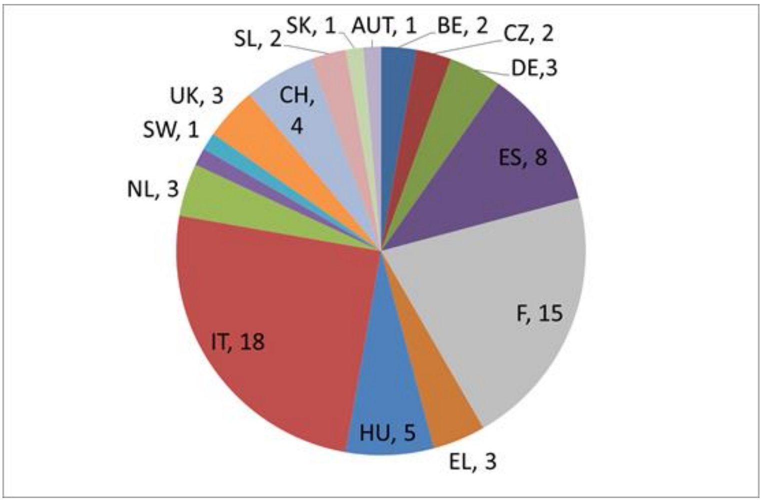

FIG. 9. Breakdown per Country of the 74 SRE attendants in the GENTLE project.

- Inter-Semester Courses (ISC) have been developed for graduate students and professionals on topics that were not part of the academic curriculum. The ISCs were organized at the participating centres and included on-site demonstrations and excursions. The ISCs typically lasted for five days. The topics and organizing institutions were: 1) Nuclear Fuels (JRC), 2) Nuclear Safeguards and Security (SCK•CEN), 3) Nuclear Waste Management (KIT, JRC), 4) Nuclear Decommissioning (UMAN), 5) Nuclear Data (JRC, UPM), 6) Reactor Techniques (BME), and 7) Thermal Hydraulics Phenomena (LUT). In total more than hundred students participated in these courses.
- Besides the above-mentioned programs, which require physical attendance of students, a Massive Open Online Course (MOOC) was organised, containing six modules: 1) Fundamentals of Nuclear Science, 2) Nuclear Fission Reactor Principles, 3) Light Water Reactor Systems and Safety, 4) Nuclear Fuel Cycle, 5) Life Cycle Analysis and Social Aspects, and 6) Next Generation Nuclear Power. The MOOC ran for the first time during six weeks from October 4 to November 30, 2016 as an instructor-paced course, which means modules were available to learners only in sequence. Every week a new module was made available to learners and they could not skip ahead. This first time it had 4543 enrolments. In the academic years 2017-2018

and 2018-2019 the MOOC ran as a self-paced course during a full year, and attracted 5878 and 2239 students, respectively. The latter number represents the status in December 2018 and is expected to increase as the course will close only in September 2019. The average age of the learners is around 26 years and the number of nationalities enrolled is typically above 140. This means that this MOOC is attracting many young people from all over the world. In all three runs, the top-3 countries of origin were USA, India and the UK. The MOOC can be followed via the EDX platform and is free to learners aiming at a non-certified enrolment. In conclusion: although the setting up of the MOOC in the consortium needed a lot of time to tune and balance the contents of each module, it has been a very inspiring and rewarding action, eventually leading to a very efficient way of teaching nuclear science and engineering at a basic level to a large community of learners and students.

4.2. H2020 CORONA-II Project (September 2015 – August 2018)

The general objective of this project was to enhance the safety of nuclear installations through further improvement of the training capabilities for providing the necessary personnel competencies in VVER area. More specific objective of the project CORONA II was to continue the development of a state-of-the-art regional training network for VVER competence (called CORONA Academy), whose pilot implementation through CORONA project (2011-2014) proved to be a viable solution for supporting transnational mobility and lifelong learning amongst VVER operating countries.

A a 9-partner-strong-consortium has been established to implement the project activities with Kozloduy Nuclear Power Plant (Bulgaria) being the project Coordinator. The rest of consortium partners were: Institute of Nuclear Research and Nuclear Energy – Bulgarian Academy of Sciences (Bulgaria); Engineering Support and Intellectual Solutions (ESIS GmbH Germany); TECNATOM S.A. (Spain); Centrum Vyzkumu Řež S.R.O. (Czech Republic); National Research Nuclear University MEPhI (Russian Federation); Risk Engineering Ltd. (Bulgaria); Budapest University of Technology and Economics (Hungary); and European Nuclear Education Network (Belgium).

The work breakdown was based on the implementation of eight work packages, whose interdependencies are shown in the FIG. ***10*** below.

The first task of CORONA II project was to analyse the proposed corrective measures from CORONA project (2011-2014). Based on the analysis' outputs, training schemes, programs and courses, were elaborated to make available an explicit and comprehensive set of training programs, addressing the training needs of the following target groups:

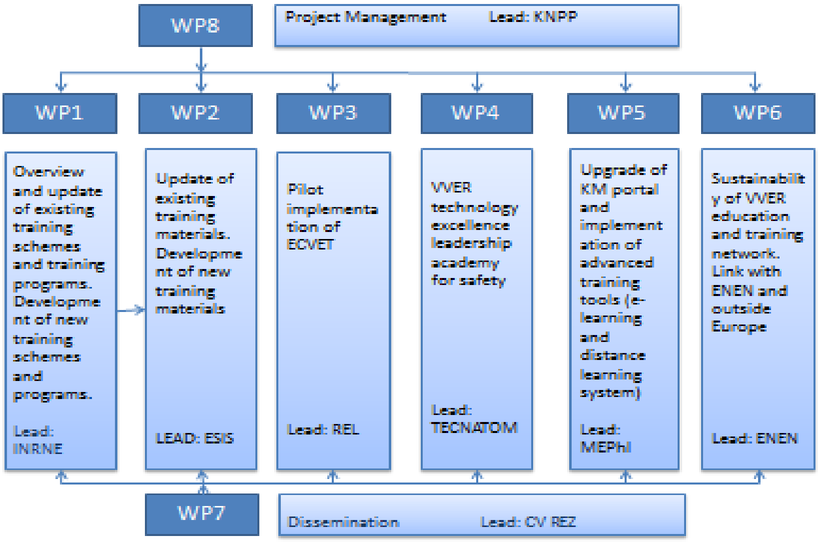

FIG. 10. Functional sketch of the CORONA-II Project.

- Group A: Specialized training on specific VVER technology aspects for nuclear professionals and researchers;
- Group B: Basic training on VVER technology specifics for non-nuclear professionals and subcontractors;
- Group C: Specialized technical training on VVER technology for students studying nuclear disciplines;
- Group D: Safety culture and soft skills training for nuclear professionals and personnel of nuclear facilities' contractors.

In the frame of CORONA I project (2011-2014) for each of the target groups pilot training was conducted to validate the materials elaborated and draw action plan to refine/ supplement the available training schemes. Within the implementation of CORONA II project the training schemes were finalized resulting in the collection of extensive training material, developed in line with the commonly accepted criteria, recognized in EU and unifying different cultural attitudes and VET approaches used by the participating organizations. In summary, the training programs developed for the identified target groups consists of 3693 training hours (incl. theoretical, practical, OJT and simulator training) for Group A, 88 training hours for Group B, 177 hours for Group C and 101 training hours for Group D.

The ECVET principle, being the EU instrument promoting mutual trust, transparency and recognition of competences and qualifications, has been embedded in all the training programs developed. The approach was tested by selecting the qualification of Radiation protection workers for pilot implementation. In this instance, roles of sending and host provider have been assigned, ECVET oriented pilot training course was elaborated and pilot training was conducted in BME, Hungary from 30 January to 2 February 2017 with 8 trainees (3 from Bulgaria, 3 from Czech Republic and 2 from Russia). Based on the results criteria and procedure for mutual recognition was developed.

Another line of activity in which the Consortium focused its effort was to propose advanced ways of providing training to the trainees by introducing distance training and e-learning approaches in CORONA II portfolio. The CLP4NET platform, dedicated to e-learning activities in the field of nuclear science and technology education, customized with the support of the IAEA, was installed on the project KM portal to allow high standards for nuclear education and training and establishing a framework for e-learning capacity. Eight of the courses from the CORONA II portfolio were adapted for e-learning and pilot sessions were conducted from 22nd to 28th January 2018 by MEPhI, Russia. Thirty (30) trainees: seven (7) from Hungary, seven (7) from Bulgaria, six (6) from Spain, four (4) from Russia, three (3) from Czech Republic and three (3) from Slovakia participated in the training. Fifteen (15) trainees participated in the course Nuclear technologies used at NPPs with VVER reactors and twenty-two (22) trainees participated in the course Design of Structures, Systems and Components.

To complete the idea for state-of-the-art training centre, it was concluded that the establishment of CORONA Academy will benefit vigorously from the natural complement of the theoretical training. In this instance a Human Factor Simulator (HFS), oriented to foster and maintain strong safety culture, was established and tested. Pilot training was carried out to ensure that the developed training materials and selected training aids and equipment ensure enough competences to develop a strong safety culture and to acquire the necessary skills to develop a right attitude to the organizational culture. One week course, combining theoretical and on-the-job training forms was conducted in the specialized training laboratories and workshops of Kozloduy NPP in June 2018 with the participation of 24 trainees from the plant.

In the long term, the specially developed training programs will ease the process of recruitment of new specialists for working with the VVER technology and will ensure the availability of well trained personnel during the whole life-cycle of the VVER installations in EU. The sustainability of education and training efforts in VVER technology cannot be effective without a permanent structure that assures its follow-up and its survey. In this frame, the integration into the ENEN Association was found to be instrumental. The link of the project with the ENEN Association will contribute to develop a long term vision and to create a coherent and dynamic strategy for achieving the integration of the education and training on VVER technology in the European level.

5. PROJECTS LED BY ENEN: ENHANCING NUCLEAR EDUCATION TO KEEP HIGH NUCLEAR SAFETY LEVELS IN EUROPE

The following three described projects represent major efforts coordinated by ENEN to cover specific needs that emerged in past years, trying to provide a remedy to the decreased interest in nuclear careers. The first project was directly stimulated by the EC after Fukushima, in the aftermath of the concerns raised in relation to the proper implementation of a nuclear safety culture, whose partial lack is often identified at the basis of occurred reactor accidents. Somehow in parallel with the stress tests ongoing in Europe, the NUSHARE project undertook the challenging task to speak about nuclear safety culture not only to usual actors in the fields (TSO and nuclear regulatory agency personnel, industrial managers), but also to a more general public of journalists and policy makers.

The ANNETTE project represents instead the attempt to establish a major long-lasting coordination among course providers in Europe aiming to propose sharp and focused courses for Continuous Professional Development to people having already a job in the nuclear fields or wishing to enter them. Though it includes a number of other actions providing further value to the action, ANNETTE is therefore focused on the quite difficult task of proposing courses in a period of low interest for them.

Finally, ENEN+ represents the latest project of the series, based on the awareness that a major effort should be established to attract and retain students in the nuclear fields, starting since the Secondary School, through the BSc, the MSc and PhD levels. It is finally recognised that student mobility, to be favoured, requires the allocation of adequate financial resources to make it feasible at any level, providing adequate grants.

These three projects are based on the conviction that, to maintain a sufficient safety level of our installations, education and training must be kept lively and, as far as possible, attractive to young people: this is the challenge implied in the mission of ENEN.

5.1. FP7 NUSHARE Project (January 2013 – June 2017)

NUSHARE was a project implementing a European Education, Training and Information (ETI) initiative proposed by the Commissioner for Research and Innovation and the Commissioner for Energy after the Great East Japan Earthquake and Tsunami on 11 March 2011 (Fukushima). Its main objective was to develop and implement education, training and information programmes strengthening competences required for achieving excellence in nuclear safety culture. Particular attention was paid to lessons learned from stress tests conducted on all EU nuclear Power Plants in response to the Fukushima accident and to sharing best practices at the European level.

NUSHARE addressed the specific needs of different stakeholders in nuclear safety by the development and EU-wide dissemination of programmes for three target groups:

- Target Group 1 (TG1), represented by journalists and civil society representatives;
- Target Group 2 (TG2), represented by staff members of Nuclear Regulatory Authorities (NRAs) and Technical Safety Organisations (TSOs);
- Target Group 3 (TG 3), represented by electric utilities, systems suppliers, and providers of nuclear services at the level of responsible personnel, in particular managers.

As a result of a planned restructuring of the initial Consortium, composed by ENEN as main beneficiary and CEA-INSTN, UPM and TECNATOM, as Third parties, with ENSTII as subcontractor, other parties joined, namely ISaR, INBEx, the World Federation of Science Journalists (WFSJ), IRSN and ENS.

Nuclear safety culture is known to be a fundamental concept, whose neglect can be easily found as an important contributor in occurred nuclear reactor accidents. As such, the project addressed its components, undertaking the difficult task to speak about it in the language appropriate to the different target groups. In relation to TG1, a first approach was based on workshops addressing French organisations of journalists. After this first phase, also owing to the stepping in of the new parties, it was possible to set up a more general Media Educational Package developed by journalists for journalists and the wider society, on the basis of the material provided by the experts of the other parties (http://wfsj.org/v2/2017/06/15/new-toolkit-on-nuclear-safety-for-journalists/).

TG2 was managed since the very beginning in a very systematic way by ENSTTI, developing training modules targeted for personnel of NRAs and TSOs. To this, INBEx added the implementation of pilot courses held in different parts of Europe with a specific training tool (named after Fermi) which gained great recognition.

Finally, TG3 was addressed by TECNATOM mainly considering the managerial levels, having so fundamental relevance in promoting safety culture among the nuclear workforce. Specific learning outcomes and pilot sessions (also with the use of micro-e-learning tools) were developed and implemented, gaining in return a positive assessment of the overall activities.

The efforts spent in the frame of NUSHARE coped with a definitely challenging subject, as implied by the ETI character of the action: the different languages to be spoken with the target groups were reflected in the diversity of the products and in the countless workshops, meetings and sessions delivered in the four and more years in which the project was developed. NUSHARE leaves behind a wake of useful material and reflections that inspired also the specific stress on nuclear safety culture impressed in the ANNETTE project.

5.2. H2020 ANNETTE Project (January 2016 – December 2019)

ANNETTE (Advanced Networking for Nuclear Education and Training and Transfer of Expertise) represents an effort delivered by a Consortium of 25 members, coordinated by ENEN. The project responded to the Euratom call of 2014 under item NFRP-10, mainly asking for Masters and Summer Schools for Continuous Professional Development (CPD). It is structured into eight Work Packages (WP), as shown in FIG. ***11***.

The first work package is devoted to "coordination" among the different nuclear fields of Nuclear Technology and Safety, Radiation Protection, Waste Management and Nuclear Fusion, the latter represented in the project by the sister network of ENEN, Fusenet (https://www.fusenet.eu/) and by its third parties. Together with networking, coordination represents the leitmotiv of the project that, in addition to the specific actions developed under the different work packages, aims at catalysing the cooperation among the different nuclear sectors. Coordinated E&T efforts in terms of a Summer School and of pilot courses for a "master" for CPD, to be established at the end of the project through an appropriate certification, are the subject of WP2. WP3 aims at reviving the production of educational material in the frame of ENEN and in Europe in general, while WP4 develops a challenging first-of-the-kind cross-border and cross-company mobility of professionals under the rules being established for granting European Credits for Vocational Education and Training (ECVET). WP5 and WP6 are assigned the task to set up courses for reinforcing nuclear safety culture and to address the novel issues coming from the process of "nuclearisation" of fusion, i.e., the transformation of the nuclear fusion sector into an industrially mature field. WP7 and WP8 keep the necessary contacts with stakeholders and manage the whole project.

ANNETTE Consortium

ENEN, CEA-INSTN (France), SCK•CEN (Belgium), Universitat Politecnica de Catalunya (Spain), TECNATOM (Spain), Framatome (Germany), CIRTEN (Italy), Institut Jozef Stefan (Slovenia), Aalto University (Finland), Uppsala University (Sweden), JRC (EU), FUSENET (Netherlands), Bundesamt Fuer Strahlenschutz (Germany), Czech University of Technology (Czech republic), IFIN "Horia Hulubei" (Romania), the Forschungszentrum Juelich (Germany), Karlsruher Institut fuer Technologie (Germany), Université Catholique de Louvain (Belgium), Université de Lorraine (France), the University of Manchester (UK), the Università degli Studi di Pavia (Italy), the Universidad Politecnica de Madrid (Spain), the University of Central Lancashire (UK), the Universidad Nacional de Educacion a Distancia (Spain), the National Skills Academy for Nuclear (UK).

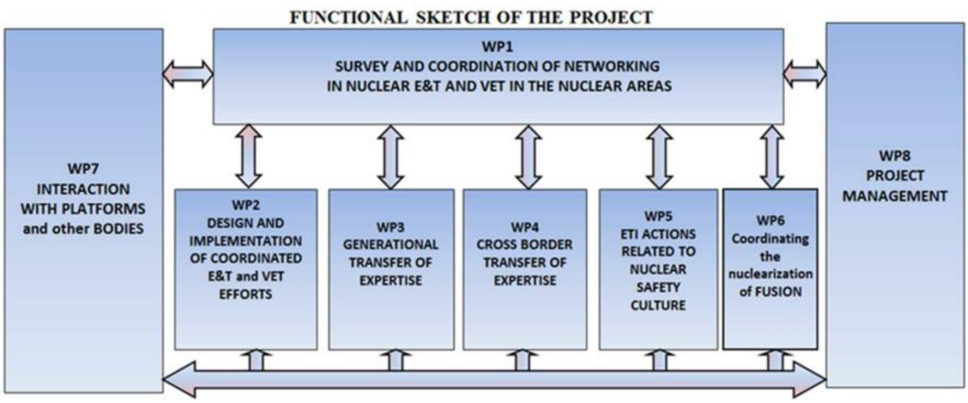

FIG. 11. Functional sketch of the ANNETTE Project.

WP1, thanks to a detailed planning, has already reached most of its objectives, carrying on a broad inquiry on the state-of-the-art about nuclear E&T and the facilities available for life-long learning, exploring networking mechanisms, studying tools for information exchange and reflecting on the ENEN certifications, to plan for future ones. WP2, WP5 and WP6 offered pilot courses, being delivered from June 2018 to July 2019, and collected more than 230 multiple expressions of interest for courses to date, though actual attendance figures are expectedly less exciting. In this frame, a very successful Summer School was organized by the Aalto University in June 2018 (www.annette.eu/summer-school/), involving lecturers selected among project participants and hosting 52 students for a full week. The students of the Summer School were selected among 85 applicants from over 20 nationalities, on the basis of nine criteria including background, command of English language, recommendation by a supervisor, gender balance, etc.. MOOCs are also being prepared on nuclear safety culture and nuclear safeguards. WP3 has already planned the delivery of educational documentation in selected nuclear sectors. WP4 has successfully tackled a challenging exchange of personnel, producing reflections on ECVET use in industry, worth of a future project to be fully exploited. WP7 is keeping tight contacts with platforms, industrial representatives and stakeholders in general; it organised an ANNETTE event at the NESTet Conference held in Berlin in 2016 and Stakeholders' events were organised as side events of the General Assembly of ENEN and at this FISA Meeting.

The most challenging part of the project will be certainly the long-term sustainability of the educational offer for the "master", to be broadened and settled into a permanent pan-European effort by catalysing the joining of additional actors, also involving the release of a new ENEN certification based on modular courses to be attended in incremental steps. The process of advanced networking, led by ENEN and materialised in the consortium by the representation of the most important nuclear fields, needs also to be settled, by coagulating further contributions, aiming to create synergies among the different groups operating in favour of E&T in the nuclear fields.

5.3. H2020 ENEN+ Project (October 2017 – September 2020)

The **ENEN+ project (Attract, Retain and Develop New Nuclear Talents Beyond Academic Curricula)** proposes cost-effective actions to attract, develop and retain new talents in nuclear professions. This is a contribution of the ENEN Association, supported by the European Commission, to the common strategic goal of all nuclear stakeholders: to preserve, maintain and further develop the valuable nuclear knowledge for todays and future generations. The ENEN+ project focuses on learners and careers in nuclear reactor engineering and safety, waste management and geological disposal, radiation protection and medical applications.

The project activities are organized in 7 work packages, depicted in FIG. ***12***. Work packages 1-4 are devoted to the attraction, development and retention of learners in different stages within the education systems (1: high school pupils, 2: B.Sc. and M.Sc., 3: nuclearization and 4: Ph.D., postdoc and lifelong learning). Work package 5 is focusing on the development of voluntary accreditation functionality within ENEN. The project is supported by the WP 6 focussing on informing and consolidating the nuclear stakeholders and WP7 dealing with the management of the project.

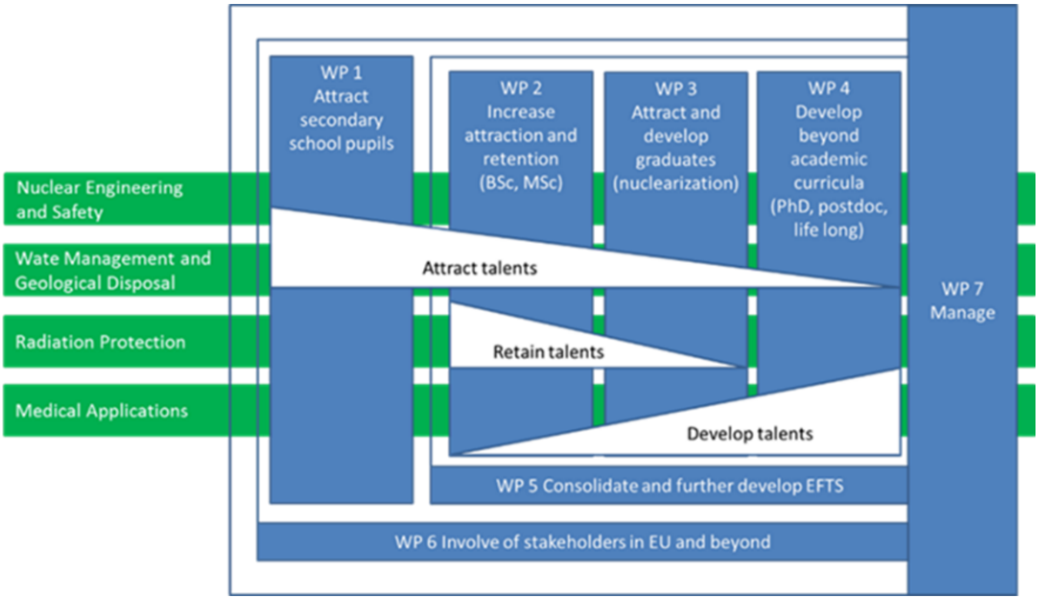

FIG. 12. Functional sketch of the ENEN+ Project.

The ENEN+ project consortium is a well-balanced blend of relevant actors in the development of knowledge, competences and skills in different nuclear sectors in Europe. It is formed by 22 partners consisting of 9 universities (Université de Lorraine (France), Aalto Korkeakoulosaatio (Finland), Budapesti Muszaki es Gazdasagtudomay Egyetem (Hungary), Universidad nacional de education a distacia (Spain), Univerza v Ljubljani (Slovenia), Universidad Politecnica de Madrid (Spain), Univesitatea politehnica din Bucuresti (Romania), Consorzio Interuniversitario Nazionale per la Ricerca Tecnologica Nucleare (Italy) and Institut Mines-Telecom (France)), 6 international organisations (ENS, FORATOM, NUGENIA, EFOMP, JRC and ENEN), 4 leading nuclear research centres (SCK-CEN (Belgium), CEA (France), Jožef Stefan Institute (Slovenia), Centrum Vyzkumu Řež (Czech republic))and, last but not least, 3 major industrial companies (Westinghouse (France), Tecnatom (Spain) and EDF (France)). In addition, several third parties including IAEA and further members of the ENEN and NUGENIA are contributing to the project.

The academic education is expected to remain the very basic building block of the future nuclear experts and scientists. A sound balance between the knowledge, skills and responsibilities may nevertheless need further shift from thinking about pedagogy in terms of “teaching” to one that considers “learning” as the primary goal. This may allow to associate pedagogy more strongly with learning outcomes and student experience, as for example engagement in the professional development activities with the support of industry, including course-release for such activities. For the main nuclear fields, the strategic priority of the community has changed to the consolidation and sustainable development of the existing courses and programs. This will be achieved through a mobility grant program for learners and the development of the voluntary accreditation functionality for nuclear education and training activities within the ENEN AISBL (AISBL = "International Non-Profit Organization" in French).

The most notable action of the ENEN+ project is mobility funding for learners at different stages of the early career. The budget for mobility grants exceeds 1 million EUR and represents more than 1/3 of the EC contribution to the project. The mobility grants are accessible through the web application and selection system (http://plus.enen.eu) to the individuals aiming at starting or improving their careers in nuclear. The individual career guidance resulting in "Personal Career Plans", developed jointly by the candidate with mentors from industry and academia, represents an essential part of the selection process, which is performed and managed by the ENEN+ project management committee. In the first 12 months of the project execution, more than 120 applicants have received mobility grants totalling at roughly 300.000 EUR.

Another notable action of the ENEN+ project is development and introduction of a communication strategy ensuring active industry and policy maker engagement in the ENEN+ initiative. The purpose of the communication strategy is to ensure consistent communication to the industry, regulators and legislators to align all stakeholders around the strategy to provide sufficient and sustainable resources for attraction, development and retention of new nuclear talents. Making the case for adequate and sustained funding and support is principally a matter of giving clear indication of the benefits to be accrued as well as periodic updates of progress achieved. ENEN+ will need to lead an advocacy effort to influence policy-making and increase the commitment towards nuclear education and research. Partnerships with media will also be attempted to develop pop-culture appeal.

The attraction, retention and development of the new nuclear talent can only be sustained beyond the project life through strong partnership and support of all nuclear stakeholders. Involvement of various nuclear stakeholders including academia, industry, international organisations (ENS, FORATOM, IAEA, NUGENIA) in the ENEN+ consortium and its communication strategy is therefore of primary importance for the success and sustainability of the proposed activities also beyond the life of ENEN+.

6. CONCLUSIONS

The projects described in this paper addressed, inter alia, different relevant aspects of nuclear E&T in Europe. From the above sections, it is clear that the deep worry for preservation and further development of competences in relation to nuclear reactors of different types and generations has motivated each specific action. In fact, while nuclear matters and careers are still attractive for many gifted students and technicians, it is anyway a fact that in different European member states the acquisition of nuclear competences is not favoured at the levels required to maintain competitiveness with other areas in the world. This displeasing feature of present policies, mostly driven by a public opinion biased by a wrong perception of nuclear risks, is endangering the wealth of experience accumulated in decades in the nuclear sectors.

An important problem to be tackled in this context is the one of the sustainability of the above described efforts, requiring the persistent and consistent communication with industry, regulators and legislators mentioned as an ongoing action of the ENEN+ project. It is important that all stakeholders be aware of and agree on the need to provide sustainable resources for attraction, development and retention of new nuclear talents.

The recent Communication of the European Commission entitled "A Clean Planet for all" [23], stating that renewable energies "together with a nuclear power share of ca. 15%, (…) will be the backbone of a carbon-free European power system" in 2050, confirms that the efforts for preserving nuclear competences are directed towards the right target and need renewed commitment from all the stakeholders. The implications of this statement by the European Commission must be considered in view of the following additional information:

– FORATOM, in a press release [20], basing on a commissioned study [21], suggests that: "If Europe is serious about decarbonising its economy by 2050 then one quarter of the electricity produced in the EU will need to come from nuclear";
– previous estimates of the effort needed for preserving an adequate share of electricity produced by nuclear in Europe led to the conclusion that: "An extrapolation to 2050 of the '20% nuclear' scenario indicates that 100-120 units should be built in Europe." [22].

Whatever will be the exact share of electricity produced in Europe by nuclear energy in 2050, it seems quite probable since now that decommissioning, and several nuclear new builds will be needed by that time. Preserving education and training in the nuclear fields even in adverse policy conditions, as achieved through the projects described in this paper, will certainly turn out as a valuable common investment, which will maintain the competences in a technology having a vital role for the sustainable development of Europe.

REFERENCES

[1] Report of the Committee for Nuclear Energy Competence in Finland, 2012, Publications of the Ministry of Employment and the Economy Energy and the Climate, 14/2012. https://ehron.jrc.ec.europa.eu/sites/ehron/files/documents/public/report_of_the_committee_for_nuclear_energy_competence_in_finland.pdf

[2] Veronika Simonovska, Ulrik von Estorff, 2012, Putting into Perspective the Supply of and Demand for Nuclear Experts by 2020 Within the EU-27 Nuclear Energy Sector, JRC Scientific and Policy Reports, Report EUR 25291 EN. http://publications.jrc.ec.europa.eu/repository/bitstream/JRC70083/ehro-n%20putting%20into%20perspective%20report_2012%2005%2025_online.pdf

[3] Sustaining Our Nuclear Skills, Nuclear Sector Skills Strategy: Government and Industry in partnership, 2015, Department of Energy & Climate Change, HM Government. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/415427/Sustaining_Our_Nuclear_Skills_FINAL.PDF

[4] J. L. Delgado, J. I. González, J. M. Camarero, Training capabilities analysis of the Spanish nuclear industry, CEIDEN. https://ehron.jrc.ec.europa.eu/sites/ehron/files/documents/public/training_capabilities_analysis_of_the_spanish_nuclear_industry.pdf

[5] OECD-NEA, Nuclear Education and Training: From Concern to Capability, Executive summary, OECD 2012. https://www.oecd-nea.org/ndd/pubs/2012/6979-nuclear-education.pdf

[6] COUNCIL DIRECTIVE 2014/87/EURATOM of 8 July 2014

https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014L0087&from=EN
[7] COUNCIL DIRECTIVE 2011/70/EURATOM of 19 July 2011
https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32011L0070&from=EN
[8] ANNETTE Project Page on the ENEN Website
www.enen.eu/en/projects/annette.html
[9] ENEN+ Project Website
https://plus.enen.eu/
[10] BRILLIANT Project Website
http://balticbrilliantproject.eu/
[11] CORONA-II Project Website
http://corona2.eu/
[12] ENEN-RU II Project Page on the ENEN Website
http://www.enen.eu/en/projects/enenru2.html
[13] ARCADIA Project Website
http://projectarcadia.eu/
[14] NEWLANCER Project Description
http://www.apre.it/media/46200/9__newlancer_project.pdf
[15] ECNET Project Page on the ENEN Website
http://www.enen.eu/en/projects/for-nuclear-community/ecnet.html
[16] NUSHARE Project Page on the ENEN Website
http://www.enen.eu/en/projects/nushare.html
[17] GENTLE Project Website
http://gentleproject.eu/
[18] Walter Ambrosini and Founding Members of ENEN, Lessons learnt from 10 years of ENEN collaboration: from a knowledge to an end-user driven approach, Paper Presented at the FISA 2013 Conference, Post-FISA Workshop #2, 17 October 2013 - Vilnius, Lithuania
http://www.enen.eu/en/about/the-10th-birthday-enen.html
[19] Leon Cizelj, The ENEN Association today and tomorrow, Presented at the Event of the 15th Anniversary of the European Nuclear Education Network, Brussels, March 1st, 2018
http://www.enen.eu/en/about/the-15th-birthday-enen.html
[20] Foratom Press Release, Nov 22, 2018.
https://www.foratom.org/press-release/nuclear-must-account-for-one-quarter-of-the-energy-mix-to-ensure-that-europe-meets-its-2050-low-carbon-targets/
[21] FTI Energy (2018), Pathways to 2050: role of nuclear in a low-carbon Europe
https://www.foratom.org/2018-11-22_FTI-CLEnergy_Pathways2050.pdf
[22] María Teresa DOMÍNGUEZ, 2012 Interdisciplinary Study, benefits and limitations of nuclear fission for a low-carbon economy, Topic 2: SET Plan
https://www.eesc.europa.eu/resources/docs/symposium2013_programme_15feb13-26-june.pdf
[23] A Clean Planet for all, A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy, Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic And Social Committee, the Committee of the Regions and the European Investment Bank, Brussels, 28.11.2018, COM(2018) 773 final.
https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_en.pdf

MICHELE COECK

IMPROVED EXPERTISE IN RADIATION PROTECTION, NUCLEAR CHEMISTRY AND GEOLOGICAL DISPOSAL

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Abstract. In the past 5 years several projects were launched in FP7 and H2020 with the aim to support competence building in nuclear by fostering education and training (E&T) initiatives. ENETRAP III, CONCERT, CINCH II, MEET-CINCH, PETRUS and EAGLE deal with advanced E&T in the fields of radiation protection, nuclear chemistry and geological disposal and the transfer of basic knowledge about ionising radiation, its benefits and risks, to the general public. They were launched with the overall objective of maintaining and extending nuclear know-how and competences in Europe and ensuring sustainable knowledge transfer to current and future generations.

This paper describes the aims and achievements of these projects and, based on insights and experiences from these projects, provides some recommendations for future policy support regarding maintaining competences in nuclear industry and research.

1. Introduction

Several studies show a gap between the current demand for competences in the nuclear sector and the supply thereof. Extrapolated towards the future, this gap is only expected to increase due to a perceived shortage in in-flow to compensate the retirements and additional needs in new developments such as for example the medical area, research and decommissioning.

Within this perspective, attracting new people, maintaining a high level of nuclear competences in different domains and assuring sufficient well-trained personnel and adequate knowledge management is crucial to ensure (i) future safe use of ionising radiation and (ii) the development of new technologies in a safe way.

One of the main goals of the Euratom research and training programmes is to contribute to the sustainability of nuclear energy by generating knowledge (research) and developing competencies (training). Therefore, the EC has supported several Framework Programme and Horizon 2020 projects which included dedicated work packages (WPs) on the transfer of high-level knowledge and understanding in specific nuclear fields. These projects put their efforts in assessing the current state and needs in E&T in Europe (or build upon the results of previous projects), identify the appropriate educational practices and technologies to use, coordinate international collaboration and efficient use of available funds, and implement and assess novel E&T initiatives.

In this paper we focus on general education in radiation protection, geological disposal and nuclear chemistry as well as advanced specialized training in these domains as an essential part to prevent the decline in expertise and to ensure the availability of elevated knowledge, skills and attitudes which can meet the future demands. These are provided in ENETRAP III, CONCERT, CINCH II, MEET-CINCH, PETRUS and EAGLE.

2. Short presentation of the E&T projects dealing with radiation protection, nuclear chemistry, geological disposal, and information and communication about ionizing radiation to the general public

2.1. ENETRAP III

Occupational, public and environmental radiation protection (RP) is a major challenge in the industrial applications of ionising radiation, both nuclear and non-nuclear, as well as in other areas such as the medical and research area. As is the case with all nuclear expertise, as described above, there is also a trend of a decreasing number of experts in radiation protection. The **ENETRAP (European Network on Education and Training in RAdiological Protection)** series of three projects started in 2005 and focussed on both the policy and its implementation regarding E&T in radiation protection, at the European and national level. E&T in RP has a strong link with the legal requirements. ENETRAP contributed to the revision of the Euratom Basic Safety Standards (BSS - Council Directive 2013/59/Euratom) through the introduction of the new definitions of the Radiation Protection Expert (RPE) and Radiation Protection Officer (RPO) and provided European guidance for Member States implementing this BSS in their national legislations. In addition, it launched an educational network to organise a European Master in Radiation Protection and developed several training courses for RP professionals.

2.2. CONCERT

The **European Joint Programme for the Integration of Radiation Protection Research CONCERT** was launched in 2015 and aims to stimulate the contribution of Member States to the development of a joint European strategic research agenda (SRA) in the field of radiation protection. This research agenda is expected to be multidisciplinary in science, be tailored to societal needs, make full use of newly gained knowledge in all disciplines of life sciences and humanities and fully integrate E&T especially for the young generation to build up and maintain competences needed for a successful and sustainable radiation protection regime in Europe today and in the future. The promotion of joint national and European research and other co-funded integration activities will ensure that human health risks and the possible impact on the environment are better understood and quantified and that radiation protection strategies are optimised. This will be achieved by an open exchange of knowledge and information between scientists, regulators, stakeholders involved and society as a whole. CONCERT runs over a period of 5 years, until 2020.

2.3. CINCH II and MEET-CINCH

In order to maintain European nuclear competences (operating power plants, radio pharmacy, medicine, disposal of radioactive waste), specific expertise in nuclear and radiochemistry (NRC) is of strategic relevance. In the period 2010–2016 **CINCH I** and **CINCH II (Cooperation in Education in Nuclear Chemistry)** were supported within Euratom FP7. The projects aimed at mitigating the special skill-based deficits within nuclear chemistry at Master and Doctorate levels and the decline of number of staff qualified in this field culminating in founding the NRC network and the NRC European Master.

The **H2020 MEET-CINCH project** proactively brings the results to the end-users at the VET (Vocational Education and Training) level. The nuclear (chemistry) awareness shall be increased and new talents shall be attracted to NRC by developing a Massive Open On-line Course (MOOC). A modern teaching toolkit based on the flipped classroom concept covering all aspects of NRC is developed and will be available via an e-shop.

2.4. PETRUS III

Since 2005, the **PETRUS (Programme for Education, Training and Research on Underground Storage)** initiative coordinates universities, radioactive waste management organisations, training providers and research institutes' efforts to develop a cooperative approach to E&T in geological disposal of radioactive waste. The objective is to ensure the continuation, renewal and improvement of the professional skills by filling the gap between growing demand for structured education and training, and the offering that is fairly limited. Launched as a part of ENEN II project under FP6 and later granted two times in the frame of FP7, PETRUS proposes innovative strategy for sharing resources from both academia and industries in the development of reliable E&T programs.

2.5. EAGLE

Together with education and training, information and communication to the general public are key factors in the governance of ionizing radiation risks. Communication about ionizing radiation with the general public has to be further improved. The FP7 project EAGLE (Enhancing educAtion, traininG and communication processes for informed behaviours and decision-making reLatEd to ionizing radiation risks), which was active from 2013 until 2016, made an analysis of the state of the art and the existing needs in education, training and information. It aimed at coordinating the information and communication about ionizing radiation at European level.

Further in this paper we will describe in more detail the aims, initiatives and achievements of these projects and their suggestions for future approaches. We will conclude with some common needs and recommendations for future European policy support in the domain of education, training and competence building in nuclear.

3. Project aims, initiatives and main achievements

3.1. ENETRAP

In 2005 the first **ENETRAP** started. It ran for a period of 2 years. The main goal was to set up actions (i) to better integrate existing E&T in RP activities and national resources and capacities in European countries in order to combat the decline in both student numbers and teaching institutions and (ii) to develop more harmonised approaches for E&T in RP in Europe in order to combat the decline in the RP workforce, to promote cross-border mobility, and to provide the necessary competences and expertise for the continued safe use of radiation in industry, medicine and research.

One of the main deliverables of this first ENETRAP project was the establishment of an academic consortium which enabled the creation of a European Master in Radiation Protection. The European Master is now a sustainable education programme lead by CEA-INSTN.

In the field of training, ENETRAP made an extensive review of the needs, capabilities and (legal) requirements for radiation protection E&T in all European countries. It also advised on the integration of on-the-job training (OJT) and work experience (WE) in the complete continuous professional development (CPD) programme of the RP workforce.

The project studied existing national courses as well as international programmes such as the IAEA post-graduate educational course (PGEC) and the Saclay-based RP course and proposed a common curriculum that could be used in all Member States, however, this programme was never fully implemented during the project period.

In ENETRAP II, the Consortium partners worked further on a suitable and acceptable European common training scheme which could serve as high-quality "reference standard" specifically with respect to the training for the radiation protection expert (RPE) and the radiation protection officer (RPO). This scheme could act as basis or mutual recognition of for examples RPEs throughout Europe.

The definitions and requirements for RPEs and RPOs were later on adopted in the revised European Basic Safety Standard (EURATOM 2013/59). A reference training curriculum for the RPE was developed and further detailed in terms of learning outcomes in knowledge, skills and competences following the ECVET approaches.

A book was developed by the partners of the ENETRAP II project which contains the basics of the European Radiation Protection Course, which later became available as e-book [1].

Pilot session of the ENETRAP reference training scheme were organised. However, due to a lack of official recognition of the course at European level, the number of participants remained low.

FP7 ENETRAP III added new and innovative topics to existing E&T approaches in RP developed earlier, such as a European database on E&T in RP [2], to allow further capacity building in RP. In addition, a guidance document was written for implementing E&T programmes for RPEs and RPOs, hereby providing extremely important assistance to all EU Member States who are expected to transpose the Euratom BSS requirements into their national legislations. Next, various pilot sessions of specialised training modules were organised in ENETRAP III according to the ECVET principles. Three modules were aimed at RPEs working in different sectors: power plants and research reactors, the medical area and geological disposal. Another course was aimed at the lecturers itself; this was a unique deliverable in E&T projects which, up to then, only focussed on the scientist, engineer or workers, but not on the lecturer who needs to demonstrate expert knowledge but also excellent didactic skills and knowledge of the EC credit systems and E&T approaches.

For all the activities in the ENETRAP project series, the consortium strongly connected with all stakeholders, i.e. end-users, E&T providers, legal authorities, and to other relevant international organisations, groups and networks dealing with E&T in RP. All output from the ENETRAP projects series can be found on the project websites but also on the website of the sustainable EUTERP Foundation (European Training and Education in Radiation Protection Foundation) [3].

During about one decade, the ENETRAP Consortia have experienced a willingness throughout Europe to cooperate in order to strengthen E&T in RP. However, national legislations are rigid and there seemed no immediate need for the organisation of a European course that meets the European legislation. More interest was shown for the guidance document helping Member States to implement national E&T programmes in line with the European requirements as set out in the BSS.

Next to development and delivery of appropriate E&T for different type of RP professionals, it is first of all essential to attract motivated people to the sector.

As a third overall conclusion we can state that retrievability of project results and collaboration between different groups, networks, platforms, … can still be optimized.

3.2. CONCERT

The **CONCERT project** under Horizon 2020 aims to contribute to the sustainable integration of European and national research programmes in RP. CONCERT as a co-fund action strives to achieve the attraction and pooling of national research efforts in RP with the EURATOM research programme in order to make better use of public R&D resources and to tackle common European challenges in RP more effectively by joint research efforts in key areas.

The 5-year (2015–2020) lasting EJP CONCERT successfully interlinks research in all areas of application of ionising radiation throughout Europe. Institutions from almost all EU countries plus Norway and Switzerland have joined forces to combine their expertise and research activities in order to improve RP. CONCERT unites the necessary scientific expertise from the fields of radiobiology, biophysics, epidemiology, medicine, radioecology, and dosimetry among other things at European level and integrates them into joint research projects. The work of CONCERT is based on the current strategic research agendas of the European research platforms MELODI (radiation effects and risks in the low dose range), ALLIANCE (radioecology), NERIS (nuclear and radiological emergency preparedness), EURADOS (dosimetry) and EURAMED (radiation protection in medicine).

By joint programming, defining joint research priorities and road mapping, CONCERT is guiding RP research in Europe. This joint effort is performed with a strategic perspective on supporting excellent science, on building and maintaining high competence in radiation science and RP as well as further promoting integrative and multidisciplinary research on a European level. A crucial step was, of course, to initiate and fund concerted joint research actions.

CONCERT was running two open RTD calls in 2016 and 2017 respectively to strengthen the scientific research in strategic priority areas of RP defined by the European radiation research platforms. Within the scope of the calls, universities and research institutions from all over Europe had the opportunity to join forces in consortia and to submit proposals. Altogether nine research projects are currently funded by CONCERT.

Parallel to the research funding activities, CONCERT developed a research agenda in social sciences and humanities in relation to RP that was included as an integral part in the second call for research projects funded by CONCERT.

Further priorities of CONCERT's integrative activities are the development of a joint research roadmap for all RP research sectors, increased E&T activities for young scientists, and provisions for optimal use of European research infrastructures for RP research.

These integrative activities of CONCERT together with the research funding activities stimulate multidisciplinary work in research and translational work towards societal needs in RP for the general public, workers, patients and the environment [4].

For providing effective E&T in RP on all levels in Europe in the future, CONCERT recommends:

- To address the need of knowledge, skills and competences as well as to identify gaps in the RP area by building networks and pooling capacities on a European level;
- To reinforce the link between existing E&T systems and job opportunities in research, medicine and industry by involving stakeholders more closely in competence building processes;
- To provide opportunities for exchange of knowledge (in particular when new research technologies become available) and sharing of experience and training in the use of infrastructures by building networks of universities/networks of professional training for developing joint degree programmes/developing a flexible framework for joint training

modules/activities facilitating recognition of competences, promotion of lifelong learning and borderless mobility.

Therefore, E&T in RP should be promoted as an integral part of all funded research projects on a national and European level.

3.3. CINCH

The **CINCH project series (Cooperation in Education in Nuclear Chemistry)** focus on the special skills within nuclear chemistry which are of strategic, as well as immediate, importance for the maintenance of European nuclear operations and options within the evolving EU economy. It aims to develop a long-term Euratom fission training scheme to provide a common basis for the fragmented activities in this field. In the first two projects, CINCH and CINCH-II, status quo in NRC education at European universities was assessed, minimum requirements for bachelor, master and postgraduate programs to achieve approved NRC curricula were defined, and a number of theoretical and practical courses were developed using hands-on and e-learning approaches and platforms. The projects were built around the SAT methodology (Systematic Approach to Training). While CINCH-I dealt with the first three phases of the process (analysis, design, development), CINCH-II concentrated on the implementation and evaluation.

The main results of these projects were

- European Master in Nuclear Chemistry;
- Completing a pan-European offer of training courses for the customers from the end-users;
- Modern E-learning Tools to Enhance Teaching in Nuclear Science, and IV) Vision, Sustainability and Awareness;
- Development of standards for mutual recognition regarded the quality of training.

Two important outputs were produced: (i) training passport requirements for NRC and (ii) assessment criteria for hands-on courses.
The third consecutive project (MEET-CINCH) is addresses the end-users in a more focused way offering platforms for immediate practical value [6]. Building on the results of the previous projects, MEET-CINCH will counteract the massive lack of NRC expertise by three actions. A teaching package for high schools and a MOOC on NRC for the chemists of the bachelor level are built in order to attract young persons to the NRC field and convey them its fascination and relevance. Two additional actions focus on vocational training and (university) education. MEET-CINCH develops new E&Tapproaches based on remote teaching and the flipped classroom concept further developing material generated in the previous projects, such as the NucWik platform and the remote controlled RoboLab experiments [5]. MEET-CINCH will provide ECVETcourse modules in an e-shop adapted to the needs of end-users which have been surveyed in the previous projects. After the end of MEET-CINCH the e-shop will be continuously operated by The European Network on Nuclear and Radiochemistry Education and Training (NRC-network, http://nrc-network.org/) as part of a sustainable European Fission Training Scheme (EFTS).

CINCH experienced that, in order to counteract the loss of competence in many member states, NRC and RP needs to be made attractive to young persons. Offering E&T needs to be augmented by sustaining (and financing) state of the art research proving that nuclear topics such as NRC are an active field of research and offer a wide variety of perspectives for a professional carrier.

It is of utmost relevance to finance EU projects dedicated to E&T. In these projects, the efforts of all member states for NRC education are coordinated, harmonized and symbiotic effects are generated. European universities as well as research centres and partners from industry should be involved.

However, it is just as important to link these E&T projects and actions to projects and joint programming in basic and applied nuclear research. In the past, this was successfully demonstrated by linking the CINCH projects with ASGARD, ACCEPT, SACCESS and GENIORS. European networking was even strengthened by winning ENEN as a partner in MEET-CINCH. Future links with JOPRAD shall be established taking care of needs defined by IGD-TP.

3.4. PETRUS

Rooted in the belief that pooling radioactive waste community's efforts and resources is essential in overcoming the loss of knowledge and skills, which in time might jeopardize the safety and security in Europe, the PETRUS initiative was launched in 2005 to improve E&T in the field of radioactive waste disposal.

During 12 years, PETRUS built a network of trust, mutual support and knowledge transfer among European universities, research centres, and radioactive waste management organisations. A strong bond was created between knowledge providers and end users, encouraging mutual understanding and showing that through better cooperation, it is possible to develop adequate framework for sharing reliable and sustainable knowledge.

The main results from the PETRUS project series were:

- The assessment of current and prospective needs of end-users and the establishment of the basket of knowledge that students/trainees must be provided with to satisfy requirements in terms of immediate and future skills.
- The effective implementation of a European Master's curriculum, based on common courses taught in several partner universities, by using synchronous distance teaching. A set of around 130 hours of lectures have been elaborated using different courses available in the PETRUS partner universities.
- The development of framework for qualification oriented modular training programmes for professionals. PETRUS was pioneer in introducing the ECVET principles from the early beginning of the project. The concept of Professional Development (PD) programmes was settled and skills and competences that employers require for their present and future staff have

been listed. As a practical exercise, two job profiles have been defined and translated in terms of learning outcomes in a "Competency-Based" curriculum encompassing several modules.

- The organisation of PETRUS PhD event that intends to bring together PhD students and young researchers, along with professionals and academics in radioactive waste disposal. The event is designed as an opportunity for selected PhD students to present their works in all areas related to radioactive waste management and disposal. It also gives attendees the opportunity to follow subject-specific lectures prepared by acknowledged academics and experts. Like the PETRUS Master's program, the event continues beyond the life of the project. The fifth edition of the event is expected in July 2019.
- The integration within the ENEN Association that ensures the continuation of the initiative beyond the PETRUS project [8]. Under the umbrella of the ENEN, a dedicated Working Group continues to work in order to reap the full benefits of the efforts and accomplishments achieved so far.

Obviously, much remains to be accomplished in the sphere of E&T in radioactive waste disposal. The long lasting experience of PETRUS, the learned lessons and the methodologies developed are now sources of inspiration for other European projects such as the ongoing ANNETTE project.

Faced with the delay in the implementation of ECVET system across Europe, the PETRUS project series developed and tested various concepts related to ECVET, leading to several recommendations for the practical implementation. The PETRUS III project elaborated a framework for the learning agreement model (that is essential for the accreditation evaluation), the learner profiles (including the criteria for accepting the students), a model for linking ECVET and ECTS systems, the description of the prototype of the planned program and the Memorandum of Understanding. Further the duties of competent institutions in the procedure of implementation as well as relevant information for the evaluation of the administrative efficiency and transparency as a part of the quality control were drafted.

3.5. EAGLE

The H2020 EAGLE project set out to identify and disseminate good practices in information and communication processes related to ionizing radiation. For this purpose, the consortium reviewed national and international data, tools and methods as well as institutional work in order to identify education, information and communication needs and coordination possibilities at European level. The lessons learned from the nuclear accident in Fukushima also provided valuable input. The main goal of the project was to enhance public understanding of ionizing radiation and to facilitate a coordinated communication approach.

Moreover, EAGLE fostered a move towards the ideal of citizen-centred communication, including a participative component. The project brought together representatives of nuclear actors, users of ionizing radiation, authorities, mass and social media, and informed civil society. The project website contains the scientific reports and records of many rich interactions [9].

In the final stage of the project, the EAGLE partners wrote a series of recommendations intended to help European actors in the field of ionizing radiation to move closer to a citizen-centred communication process, supporting better informed decision-making about ionizing radiation risks (IRR). The recommendations are mostly addressed to information-source institutions including schools (official communicators), and thereby reflect a standard of quality that other communication actors—media and civil society representatives—can expect.

Specific recommendations related to the education, training and information material (ETI) are:

- It is not advisable to prepare the ETI materials and activities on a common template in all EU member states.
- Contribute to citizens' science projects by organizing or promoting projects about ionizing radiation, sharing information and verifying collected information.
- Support science correspondents by offering E&Trelated to IR topics including emergencies. In addition, some funds for scholars could be established in order to encourage knowledge gathering in a journalistic population.
- Establish "Science Media Centres" as a centralized scientific data service for journalists. Sources can foster this type of resource by becoming dues-paying members and by contributing information and expertise. Similar "Science Education Centres" can be established for teachers.

4. Common conclusions and recommendations

Retaining human competences and know-how in the nuclear disciplines and ensuring a high level of education and training (E&T) remain essential if Europe is to maintain its exemplary record in nuclear activities. Through the projects ENETRAP, EAGLE, CONCERT, CINCH and PETRUS, a large effort was made towards the harmonisation and enforcement of education, training and information in radiation protection, nuclear and radiochemistry, and radioactive waste disposal.

The E&T projects described in this paper have significantly contributed to the availability of state of the art course materials and some of them have also developed and implemented new approaches to facilitate and optimize the learning effect. In addition, for example in the case of ENETRAP, contributions to European policy and guidance documents was made.

Some projects have also shown that, on a European level, aspects such as mutual recognition, accreditation and the full implementation of the ECVET system still pose major challenges in all these fields, as well as related nuclear fields.

From the E&T projects highlighted in this paper, it can be concluded that education of students and early stage scientists and training of nuclear professionals in specialised domains is an essential part of competence building. In addition, general information and communication to enhance public understanding of the origin and applications of radioactivity and the accompanying risks and benefits is of utmost importance and might facilitate attractiveness of the sector for potential new workforce.

Attracting new people to meet the future needs is one of the biggest challenges the nuclear sector is currently faced with. Initiatives that overcome the lack of interested young people and increase awareness about the challenges and innovation possibilities in the nuclear sector, that will contribution to the wellbeing of society, should be supported at European level.

The young generation deserves suitable education and training in the nuclear themes.

Firstly, these E&T initiatives should be of high quality: the course content should reflect the latest findings from research. Therefore, a direct connection between the research centres and the training centres is advisable. Specifically for vocational E&T in RP, it is still challenging to translate research outcomes in E&T programmes.

It is of paramount importance that the new findings in research are correctly communicated in terms of impact on the RP system and its practical implementation. A more active approach should be developed to integrate new insights in the initial and continuing training programmes for professionals offered by training institutes, on expert level as well as on the level of the workers exposed to ionising radiation.

Secondly, the content delivery should be optimized according to the learning outcomes and lecturers should not only be experts in their field but should also have excellent didactic skills and be aware of the latest teaching technologies and national and international guidelines and standards regarding ECVET, ECTS and other European E&T standards and methods.

Project outcomes should be sustainable: many projects described above have liaised with a sustainable platform that will foster the project results and makes them available to the dedicated community. E&T project that have not build in such an approach should be encouraged to develop a project repository, complete and easy accessible, so that the outcomes of the project become available to a broader community.

Cross-project outcome management is not yet well established. This would however be of added value to the E&T stakeholders in the different nuclear domain. It is important to bring together all initiatives developed in both research and E&T projects, in order to optimize resources, dissemination and participation to courses and to ensure a high-level content and delivery of E&T various nuclear domains in agreement with the European Qualification Framework, Bologna (ECTS) and Copenhagen (ECVET) principles. Next to making available course curricula and/or content, sharing of return on experiences and information about the state of the art in E&T approaches and tools will optimize the overall quality of E&T in nuclear. Platforms should be encouraged to work together,

With respect to the various professional actors identified in the Euratom Basic Safety Standard, no specific E&T guidance documents exist (yet) on the implementation of the E&T requirements for the following professionals in RP: occupational health services, dosimetry services, emergency workers. European guidance on E&T for RPEs, RPOs, MPEs and medical professionals were already developed in other European funded projects, such as ENETRAP. In CONCERT the E&T WP7 is starting a summary of the needs of other job profiles.

References

[1] Philippe Massiot, Christine Jimonet - European Radiation Protection Course: Basics https://books.google.es/books?id=o2n0AwAAQBAJ&hl=en&source=gbs_slider_cls_metadata_9_mylibrary

[2] E&T database in radiation protection: http://euterpdb.org

[3] European Training and Education in Radiation Protection Foundation (EUTERP): http://euterp.eu/

[4] European Joint Programme for the Integration of Radiation Protection Research (CONCERT): http://www.concert-h2020.eu/

[5] Cooperation in education in nuclear chemistry (MEET-CINCH): https://www.cinch-project.eu/

[6] NucWik platform: https://nucwik.wikispaces.com/

[7] Programme for Education, Training and Research on Underground Storage (PETRUS): http://www.enen-assoc.org/en/training/petrus-iii.html

[8] European Guidance on the Implementation of the Requirements of the Euratom BSS with respect to the Radiation Protection Expert and the Radiation Protection Officer. ENETRAP III, http://euterp.eu/uploaditems/ENETRAPIII/ENETRAP-III-European-Guidance-Document-amended_RAPJES_post_Article_31.pdf

[9] Public platform for communication about ionizing radiation (EAGLE): http://eagle.sckcen.be

CONCETTA FAZIO

INFRASTRUCTURE AND INTERNATIONAL COOPERATION IN RESEARCH AND KNOWLEDGE TRANSFER: SUPPORTING ACCESS TO KEY INFRASTRUCTURES AND PAN-EUROPEAN RESEARCH. LESSONS LEARNED

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Abstract. Access to research infrastructures has been supported by the European Commission under different financial schemes. During the 6th EURATOM Framework Programme the instrument introduced by the European Commission were the Integrated Infrastructure Initiatives (I-3). Moreover, funding schemes to support Education and Training for students and professional developments were defined also. The main difference between these two funding schemes is that I-3 are topic driven projects with access to infrastructure components, while the Education and Training related projects have a mobility component that is applied for the different research topics. The outcome of projects as TALISMAN (I-3), EFNUDAT/NUDAME (I-3), GENTLE (mobility), ENEN-plus (mobility), NUGENIA-plus (mobility within TA of NUGENIA) and ESNII-plus (I-3 similar) will be shortly presented as well as the future European Commission plans in the field of access to research infrastructure.

1. Introduction

Pooling and integration of research infrastructures as well as their access had the objective to promote in Europe the development of networks with high quality research infrastructures and their optimum use on a European scale based on the needs expressed by the research community. The infrastructure access scheme called integrated infrastructure initiative (I-3) has the objective to promote access to infrastructure for European researchers or research teams for their research needs, irrespective of the location of the infrastructure. I-3 projects have in general three components, which are (i) networking, (ii) transnational access to infrastructure and (iii) joint research initiatives. Past I-3 projects have been conducted around specific topics as e.g. the FP6 EURATOM supported projects VELLA (Virtual European Lead Laboratory), EFNUDAT (European Facilities for Nuclear Data Measurements) and NUDAME (Neutron data measurements at IRMM) and ACTINET-I3 (Actinide Network) as well as the FP7 EURATOM project TALISMAN. These five projects as indicated by their acronyms were focused on three major topics: liquid lead technology to support the development of lead cooled reactor systems (VELLA); nuclear data measurement for nuclear reactor physics and basic science applications (EFNUDAT and NUDAME) and actinides science (ACTINET-I3 and TALISMAN). Furthermore, the European Commission has supported along the past EURATOM framework programs several projects and initiatives related to Education and Training, aimed at attracting young talented students and professionals to the nuclear field. These projects and initiatives were more people centred and crosscutting different nuclear topics. The components of the Education and Training projects are the development and execution of specific classroom or (i) on-line courses for students, (ii) training for professional development and (iii) mobility schemes. Examples of projects with such type of scheme that are completed or ongoing are GENTLE, ANNETTE (without mobility grants) and ENEN-plus (more focussed on mobility and dissemination). Finally, mobility grants are also part of projects that are built around specific topics as for instance NUGENIA-plus and ENSII-plus. In the following chapters, an overview of the above listed projects will be given and more in particular the outcome of the mobility grants implemented in the projects TALISMAN, GENTLE and NUGENIA-plus will be discussed in terms of organisation of the access to the infrastructures and achievements. Finally, this manuscript includes also the recent initiative of the Joint Research Centre to grant access to its research infrastructures.

2. Transnational access to research infrastructure

As already mentioned in the introduction, the access to research infrastructure has been organised in Europe along three different schemes:

- Integrated Infrastructure Initiatives;
- Mobility Grants within topical projects;
- Mobility Grants within Education and Training projects.

In all three cases, access to research infrastructure is granted to researcher, research teams or students. However, the Integrated Infrastructure Initiative had the aim to pool specialised infrastructures around specific topical areas (e.g. liquid metal technology, nuclear data, actinide science), while the mobility grants were more people centred and focussed on promoting mobility into different research infrastructures. Hereafter a brief overview is given for TALISMAN, NUGENIA+ and GENTLE corresponding to the three different schemes, respectively and where appropriate extension and examples from the other projects are included.

2.1. TALISMAN

The **TALISMAN project** was established as a follow-up of the previously successfully concluded Network of Excellence ACTINET-6 and Integrated Infrastructure Initiative ACTINET-I3. The importance to establish a network of competences and infrastructure for actinide science is due to the fact that, actinides of interest for nuclear energy are radioactive elements and their study requires specific tools, facilities and licences that are available only to few European academia and research organisations. Therefore, it is strategic to coordinate the European actinide infrastructures and to strengthen its scientific community in view of performing excellence research and developing excellent professionals in the field. In this context, TALISMAN had the objective to establish a network of Actinide facilities and infrastructures across the EU to structure and foster their joint development in terms of capacity and performance. TALISMAN supported Transnational Access to these facilities through the organization of periodic calls for Joint Research Projects (JRP) and conducted a set of Joint Research Activities (JRA) involving member organisations, with the objective to improve the performance of infrastructures by developing new relevant instrumentations and/or data of common interest.

TALISMAN has also promoted training and education actions through the organisation of summer schools, networking meetings for trained young scientists, attributing travel grants to students attending international conferences on actinides sciences.

The facilities pooled in TALISMAN were hot laboratories belonging to CEA, JRC, KIT, NNL, Chalmers University and HZDR; as well as beamlines belonging to KIT, PSI and HZDR (see Fig. 1).

FIG. 1. Infrastructures pooled within the TALISMAN project. Courtesy S. Bourg, CEA. Details on the facilities can be gathered at the link: http://www.actinet-i3.eu/.

The selection of the transnational access to be funded was organized through calls for proposals (two times per year over three years). At the end of each call, the proposals were sent to the Project Scientific Advisory Committee that received a list of ranking criteria, established by the Executive Committee of the project. These criteria were related to (i) the originality of the subject and its compatibility to the TALISMAN portfolio, (ii) the skills of the teams (both visitor and pooled facility), (iii) the relevance of the choice of the Pooled Facility and that all results had to be publishable.

Within the TALISMAN project, 6 calls were published and in total 107 proposal for infrastructure access were received. From the 107 proposals 96 were granted and 91 were concluded (5 proposals were cancelled due to issues encountered by the visiting teams).

The distribution of the access over the seven involved infrastructure is shown in Figure 2 and Figure 3 summarises the access over the three broad scopes defined within the TALISMAN project, i.e. scope 1= separations, scope 2= environmental actinide chemistry and scope 3= irradiated materials.

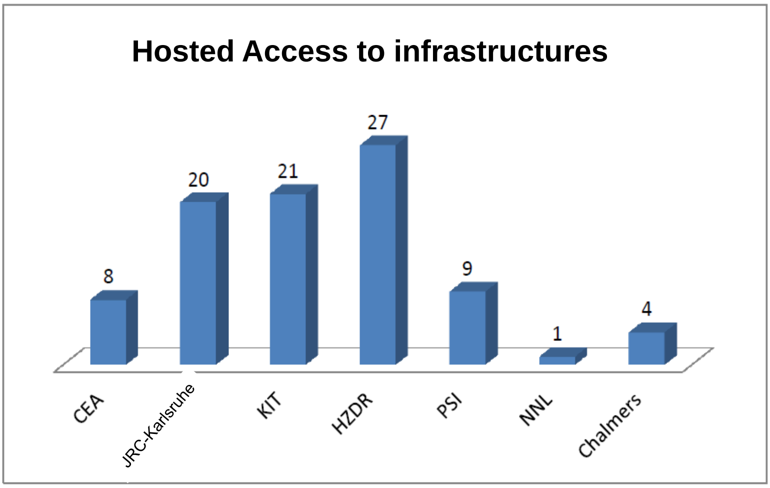

FIG. 2: Frequency access to the infrastructures pooled within the TALISMAN project. (Courtesy S. Bourg, CEA)

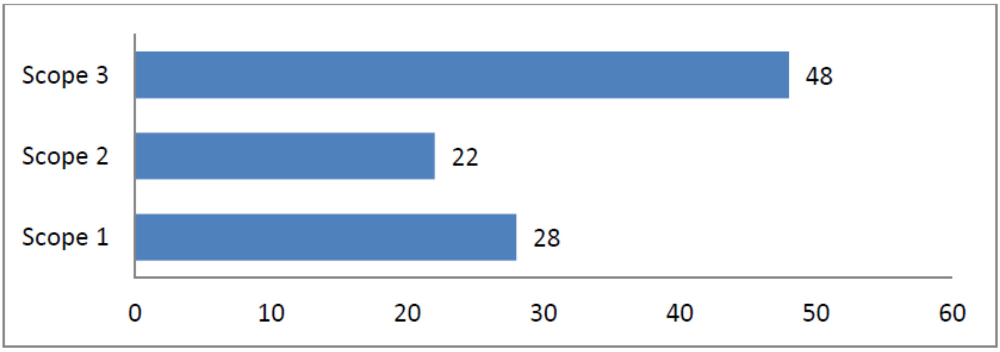

FIG. 3. Access to infrastructure distribution over the three broad TALISMAN scopes: scope 1= separations, scope 2= environmental actinide chemistry and scope 3= irradiated materials. (Courtesy S. Bourg, CEA)

The teams hosted at the pooled infrastructures through the TALISMAN grants were either researchers/scientists and/or students.

In figure 4 the countries of origin of the different research teams asking for accessing the pooled infrastructures are reported. As shown in this figure, TALISMAN was not restricted to only European research teams but research teams from France, Germany and UK were the most numerous.

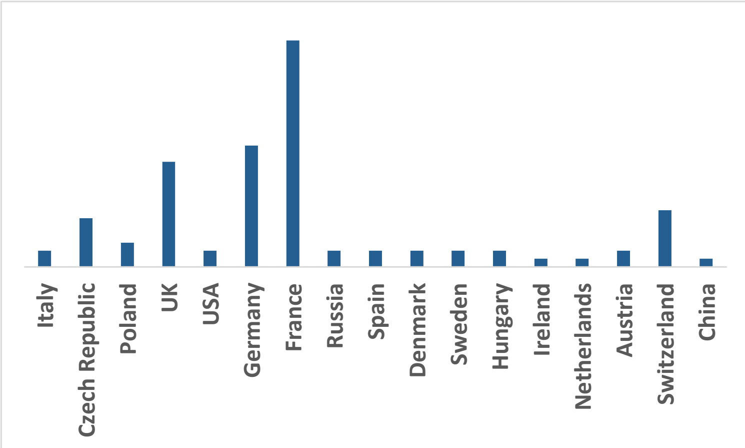

FIG. 4. Countries of origin of the research teams asking for access to infrastructures. Data taken from [1].

2.2. NUGENIA-PLUS

The objective of the FP7 EURATOM NUGENIA-PLUS project was to support the NUGENIA Association in its role to coordinate and integrate European research on safety of the Gen II and III nuclear installations in order to better ensure their safe long-term operation, integrating private and public efforts, and initiating international collaboration that will create benefit in its activity fields. [2].

The project was a combination of a Coordination and Support Action and a Collaborative Project. The Coordination and Support Action was aimed at establishing a management structure to carry out the planning and management of R&D including project calls, proposal evaluation, project follow-up dissemination and valorisation of R&D results in the area of safety of existing Gen II and future Gen III nuclear installations. The part dedicated to collaborative project, was based on thematic calls for research proposals organized among the NUGENIA technical areas, i.e. plant safety and risk assessment, severe accident prevention and management, core and reactor performance, integrity assessment of systems, structures and components, innovative Generation III design and harmonisation of procedures and methods.

Within NUGENIA-PLUS also mobility grants were offered with the scope to allow young and senior professionals to visit selected key NUGENIA infrastructures (including experimental facilities and modelling and simulation platforms). The overall objective of this action was to enhance the relationships between European R&D facilities and NUGENIA end users. Two type of mobility grants were defined, namely short training periods for post-doc students and researchers (typically less than 1 months) and long training visits for more experienced staff (from 1 to 3 months). As far as the rules for application was concerned, it was established that the grants were limited to members of NUGENIA-PLUS consortium in terms of hosting organisation and in terms of applicants, but exemptions from this rule were also foreseen.

Within NUGENIA a "Resource Map" which included a database of infrastructures (experimental facilities and modelling platforms) was established that allowed the applicants to select the most suitable infrastructure and related contact person for its grant application. A team established within the work package addressing the mobility grants evaluated the proposals. The criteria for evaluating the proposals were: (i) topic within the NUGENIA roadmap; (ii) training related to infrastructures; (iii) quality of application and requested funding within the budgetary framework.

During the one year of continuous call (there were no deadline for applications), 18 mobility grants have been assigned. As shown in figure 5 the applicants were from 9 different EU countries with the majority belonging to research organisations and universities. The organisations hosting the grant holders were belonging to 8 different EU countries as shown in figure 6. The geographical distribution of applicants and hosting organisation is quite interesting since one can identify a rough pattern from Central and Eastern Europe towards Western Europe. This pattern might be due to the communication effort performed for the NUGENIA grants. A further explanation could be that some infrastructures are not available in these European regions.

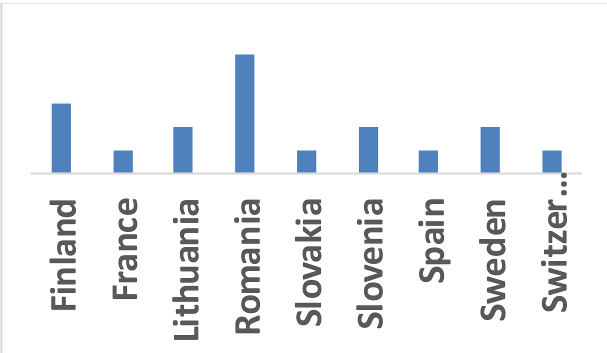

FIG. 5. Countries of origin of applicants. Data taken from [3].

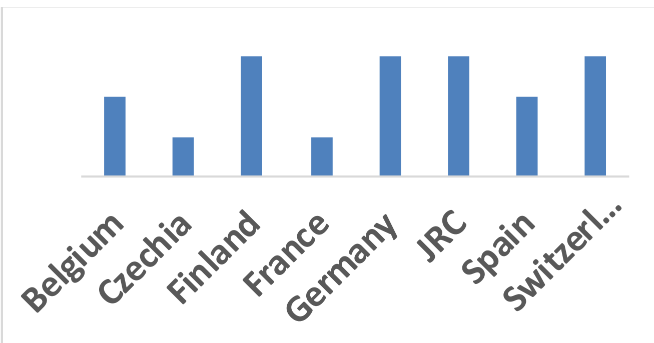

FIG. 6. Countries of origin of hosting organisations. Data taken from [3].

Among the 18 grants three were long-term visits and fifteen short term visits. The topical distribution of the grants was quite diversified, although the majorities of the topics were within the areas of (i) Severe Accidents and (ii) Integrity assessment of System and Structures. The distribution is shown in figure 7.

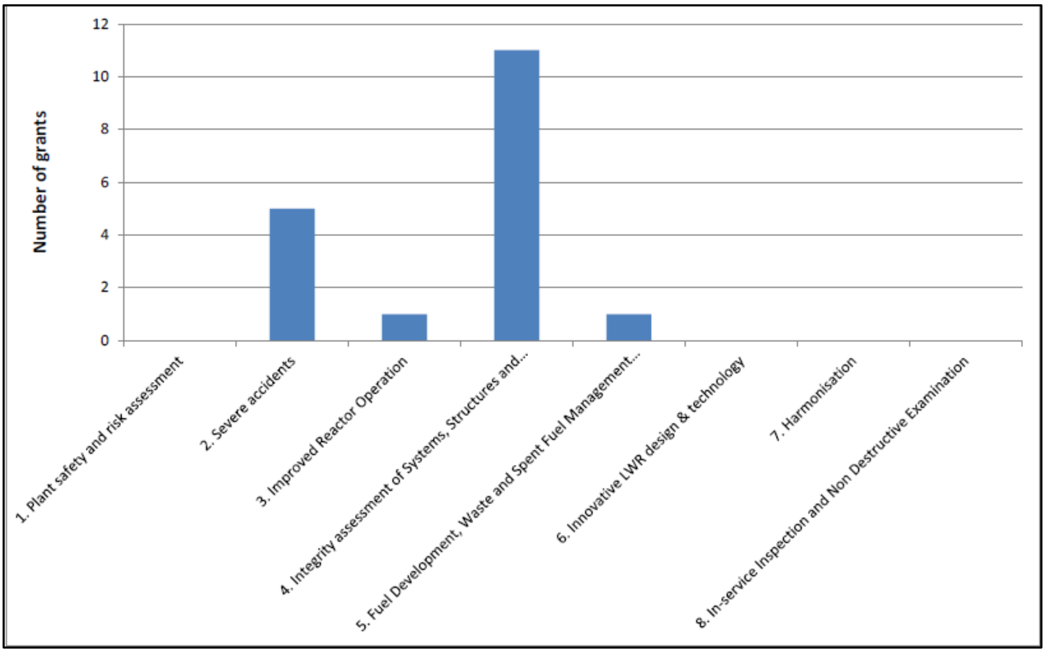

FIG. 7. Number of Nugenia grants per Technical Area. Graph taken from [3].

The NUGENA-PLUS responsible for the grant assignment did also a critical review of the process and defined the following conclusions and recommendations:

– A more efficient communication of the availability of the grants and its open call without deadline would have improved the number of applications (indeed, the budget allocated to the grants were not fully exploited)
– The administrative part concerning the coordination and transfer of the grants can be simplified. The coordination (organisation and payment of the grants) should be with one organisation, whereas in NUGENIA it was split over two different project partners. Also the payment can be simplified moving from real costs to lump sum.
– The distribution over the technical areas was not even. Indeed, two topical areas get more interest with respect to the others, but no further assessment was done with this respect.
– A further recommendation that was formulated on the basis of the experience gathered during the calls for access to infrastructure was that the members of the evaluation committee should be well defined and the number of participants to this committee should be in the order of 4-5.

Within the ESNII-PLUS project a similar approach as for NUGENIA-PLUS was adopted. The first step of ESNII-PLUS was the identification of available research facilities associated to the research needs for the different reactor concepts [4].

A "Research Facility map" resulted from this analysis and within ESFR-SMART a mobility grant program for SFR was launched. The call for the grants were organized similarly to the I-3 approach, however results of the outcome of the grant assignment were not made available at the time of writing this manuscript since the project is still ongoing.

2.3. GENTLE

GENTLE (Graduate and Executive Nuclear Training and Lifelong Education) was a joint effort by leading academic and research institutions in Europe to coordinate an Education & Training programme in the field of nuclear fission technology. The members of the consortium contributed to the common objective of creating a sustainable lifelong education and training programme in the field of Nuclear Fission Technology meeting the needs of European stakeholders from industry, research and technical safety organisations.

Specifically, GENTLE implemented the following education & training tools:

- Student research experiences (SREs) to facilitate access of European students to Europe's unique and specialised laboratories and work hands-on on cutting-edge research.
- Inter-semester courses for graduate and post-graduate students on topics related to nuclear fuel, nuclear safeguard and security, nuclear waste management, nuclear data etc.
- A professional course (resulting in a Massive Open Online Course MOOC) for young professionals working in, among others, industry, consultancy companies or regulatory bodies, to enhance their knowledge of nuclear reactors and fuel cycles.

An essential tool to achieve the training objective of GENTLE was the SREs. The SREs could last between 1 and 24 months at the participating research establishments of the GENTLE consortia and applicants could come from any European academic institutions. The SRE proposals were defined as common research between the applicant and the hosting research institution and were focused on the understanding of basic phenomena related to material behaviour or process technology, the development of analytical methods, or measurement and modelling of fundamental properties.

The selection was based on a written proposal, directly submitted by the student, which was then examined by the GENTLE SRE evaluation committee. Scientific quality, availability of equipment, staff and materials at the hosting institution, training benefit to the applicant, and impact on the field were the main selection criteria.

Within the GENTLE project particular attention was devoted to the rules that are summarised hereafter [5]:

- Applicants had to fill in a dedicated form stating the main objectives of the research proposal, as well as a reasonably detailed work description, indicating a suitable host institution (beneficiary) and local supervisors for their SREs

- The minimum stay of students within GENTLE SREs shall be 1 month, the maximum 24 Months, but can be subject to local rules at the hosting organization.
- Candidates belonging to partner as well as non-partner European academic or research institutions can apply.
- Students must be enrolled in an EU academic or research institution but must not necessarily have a European citizenship.
- Agreement on local grant rules (€/month) of the hosting institution shall be applied. The recommended grant is in the order of 1000 €/month.
- The grant could not be used to extend PhD studies at the institution where the PhD is performed. Only one application plus one extension were allowed (with a maximum total duration of 24 months).
- During the complete SRE, the students had to be enrolled at the university.
- SREs within the same town/region were allowed, but will not be supported financially.

Moreover it was established that all members of the GENTLE consortium could recruit students within SRE projects approved by the evaluation committee and the costs had to be claimed by the beneficiaries (either host or sending institution, provided the latter is also a GENTLE partner) who will recruit the student. A suitable administrative and financial framework for the reimbursement of SRE costs was defined by each partner separately, due to the different legal conditions to which each GENTLE participant was bound. Some of the partners had already defined such framework, while others had to define and implement it.

At the end of the GENTLE project a final report on SRE was published, where statistical analysis of this training tool was done [6]. What follows is a summary of this analysis.

A total of 84 SREs were granted during the GENTLE project duration (2013-2016), corresponding to 10-20 SREs per year (depending on the single SRE duration). Forty-seven SRE applications were received for 2016, while during the two years 2014 and 2015 in total thirty-seven applications were received. This more than double number of applications for 2016 was the result of important efforts done to advertise GENTLE to EU students and most probably also due to a sort of "word-of-mouth chain reaction", which has increased the popularity of the GENTLE SRE initiative among EU students in nuclear-related subjects.

In the next figures statistics about the accepted SRE projects over the whole duration of the project (2013-2016) are shown. Figure 8 shows the origin of the academic institutions at which the students were enrolled. 16 EU countries and most of the main countries having nuclear education and training programs were represented and most students were from universities located in Spain, France and Italy.

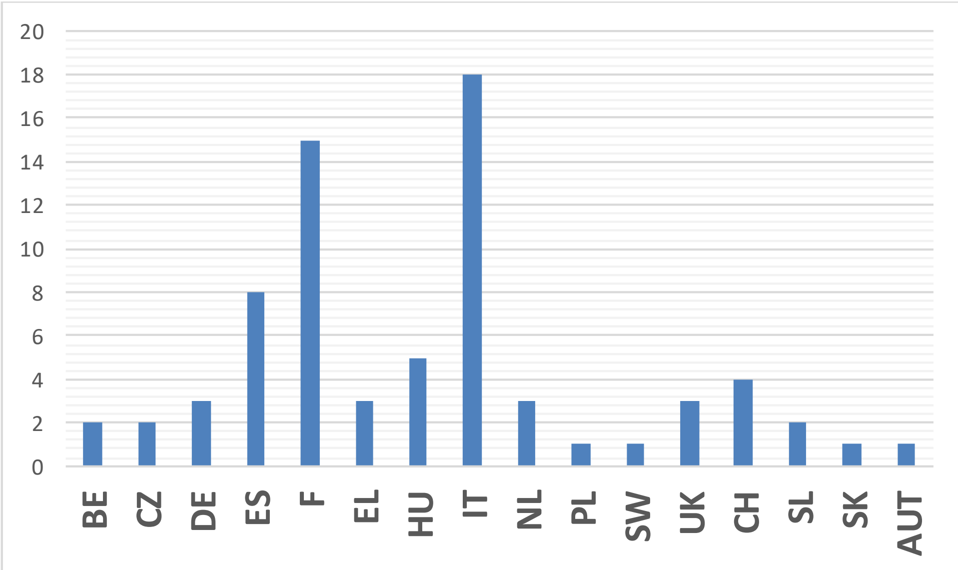

FIG. 8. Distribution of the GENTLE SRE students per country of the academic institution in which the students are enrolled. AUT = Austria; BE= Belgium; CH= Switzerland; CZ=Czech Republic; DE = Germany; ES = Spain; F = France; FIN = Finland; EL= Greece; HU = Hungary; I = Italy; NL = The Netherlands; PL= Poland; SL = Slovenia; SK= Slovakia; SW = Sweden; UK = United Kingdom.

Figure 9 shows the number of SREs per GENTLE beneficiary. It can be noticed here that the majority of GENTLE partners hosted SREs. It is worth pointing out that the main experimental facilities available at GENTLE partners (namely at SCK-CEN, KIT, PSI and JRC) have been largely used for SREs and JRC infrastructures hosted more SREs with respect to the other partners.

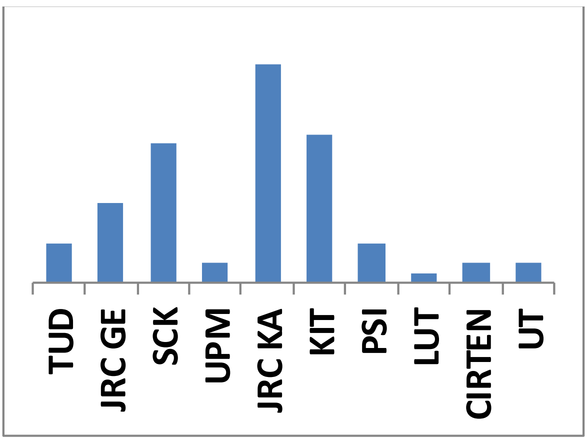

Fig. 9. Distribution of SREs over the beneficiaries.

Figure 10 schematically shows a rather well-balanced distribution of the accepted SREs among various research and engineering topics. In Figure 11 one can see that more student-months were devoted to experimental work rather than computational-modelling activities. This is rather understandable, considering that experimental work in nuclear-related topics often require complex facilities that are not available at universities. Therefore, students willing to perform experimental work in these fields are more easily motivated to seek external internships in research centres offering access to such facilities.

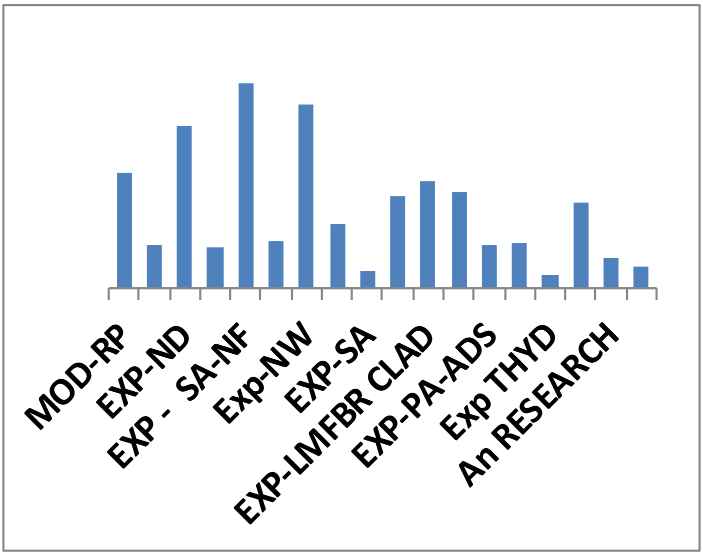

FIG. 10. Distribution of SRE over the different topics. Legend of the Graph: RP=REACTOR PHYSICS; ND=NUCLEAR DATA; SA=SEVERE ACCIDENTS; NF=NUCLEAR FUEL; NW=NUCLEAR WASTE; PA=PARTICLE ACCELERATORS; MSR=MOLTEN SALTS REACTOR; CLAD=CLADDING; FPC=FUEL PERFORMANCE CODE; THYD=THERMAL HYDRAULICS; An=ACTINIDES; NSteel=NUCLEAR STEELS; EXP=EXPERIMENTAL; MOD=MODELLING

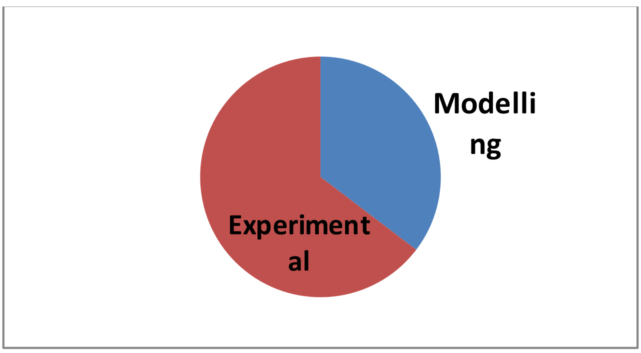

FIG. 11. Share between Experimental and Modelling SREs.

In summary, the GENTLE SRE program was highly successful and very popular. This large popularity increase of the project GENTLE over the years shows the success of the initiative as a whole, and specifically of an intense advertisement activity, including the regularly updated website <www.gentleproject.eu>. Many students and supervisors have shared their disappointment about the fact that this project was ending, which should be encouraging about the launch of further similar international projects supporting the mobility of students.

The quantitative statistics and qualitative feedback from students and hosts paint a very positive picture of this activity: a large number (seventeen) of EU countries sending students for GENTLE SREs and a very broad spectrum of nuclear-related subjects were covered by the SREs. In conclusion, GENTLE Student Research Experiences have been an effective and highly successful tool for supporting student mobility across EU nuclear-related facilities.

The ENEN+ project (Attract, Retain and Develop New Nuclear Talents Beyond Academic Curricula) can be considered as a follow-up of the GENTLE SRE experience. Indeed, ENEN+ proposes cost-effective actions to attract, develop and retain new talents in nuclear professions with the objective to preserve, maintain and further develop the valuable nuclear knowledge for todays and future generations. The ENEN+ project focuses on learners and careers in nuclear reactor engineering and safety, waste management and geological disposal, radiation protection and medical applications. The most notable action of the ENEN+ project is mobility funding for learners at different stages of the early career. The mobility grants are accessible through the web application and selection system (http://plus.enen.eu) to the individuals aiming at starting or improving their careers in nuclear.

3. Conclusion and further/future initiatives

In the above paragraphs the experience gathered during the implementation of different transnational access to infrastructure funding schemes have been summarised. As described before, over the past years there have been different approaches to grant access to the infrastructures. The approaches have been either infrastructure and topic oriented or people oriented. In all case, successful accomplishments of the projects have been reported. The important lessons learned within the different projects are related to the definition of rules (administrative, financial and scientific) to grant access and to the advertisement of the mobility opportunity and reaching out to the European nuclear community.

Moreover, it could be relevant to elaborate a blended approach for the transnational access to infrastructures through mobility grants at pooled facilities within the different topical areas as done within ACTINET, NUGENIA, ESNII, VELLA etc. and also people oriented as done within GENTLE and ENEN+. Ideal would be if such type of initiative would be coordinated centrally taking care of all organisational and administrative issues in order to aim at a harmonised access scheme as well as coordinating the different topical/pooled facilities. This centralised entity could be for instance ENEN. In support to this approach, ENEN has already started to create a database of infrastructure as documented in the report [7].

Within the European Commission there is a further initiative initiated over the last year and that concerns the access to all Joint Research Centres Infrastructures including the nuclear one, with the objective to exploit their full potential. The JRC open access has the aim to promote innovative research and development; dissemination of knowledge; improve related methods and skills; training of researchers and technicians and collaboration at European level. More information on open access opportunity can be find at the JRC science hub link https://ec.europa.eu/jrc/en/research-facility/open-access. In combination of this JRC initiative there will be within the Horizon 2020 framework a further action in collaboration with RTD in order to make available mobility funds to the European Community dedicated to European research teams, students and SMEs to support their access to the nuclear JRC infrastructures.

References

[24] S. Bourg et al., Talisman Final Report, 2016.
[25] https://cordis.europa.eu/project/rcn/110017/factsheet/en
[26] R-W Bosch, J-C Bouchter, WP3.3 Nugenia Training Grants Final Report, 2016
[27] P. Agostini et al, Experimental Facilities Dedicated to ESNII concept, 2017
[28] D. Manara et al, Deliverable D2.1 "Periodic report with extended scientific summaries of SREs and list of publications", 2014
[29] D. Manara, Deliverable D2.3 "Periodic report with extended scientific summaries of SREs for 2016"
[30] Facilitate Access to Infrastructures and EURATOM projects, Database on infrastructures. Deliverable report issued within the ENEN+ project, 2018.

JEAN-YVES BLANC

SUPPORTING INFRASTRUCTURES AND RESEARCH REACTORS: STATUS, NEEDS AND INTERNATIONAL COOPERATION

IAEA ICERR (INTERNATIONAL CENTRES BASED ON RESEARCH REACTORS) AND IGORR (INTERNATIONAL GROUP ON RESEARCH REACTORS)

FP7 AND H2020 JHR ACCESS RIGHTS

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Abstract. The panorama of research reactors in the world is at a turning point, with many old ones being shutdown, a very few new ones under construction and many newcomer countries interested to get access to one or to build one domestic research reactor or zero-power reactor. In this evolving context, several actions have been set up to answer this international collaboration need: the IAEA has launched the ICERR initiative, the OECD/NEA is proposing the P2M joint project proposal. In France, the Jules Horowitz Reactor (JHR), under construction at CEA Cadarache, within an International Consortium, will be one of the few tools available for the industry and research in the next decades. The paper presents some update of its construction, its experimental capacities and the European support through FP7 and H2020 tools. This paper provides also some insights of international tools (ICERR, P2M) and about the International Group on Research Reactors (IGORR) and how they complement or interact with the JHR.

1. Introduction

The panorama of experimental research reactors has recently evolved, with the shutdown of several important Material Testing Reactors (MTR):

- the Osiris reactor in CEA, France at the end of 2015,
- the Japan Material Test Reactor, by mid-2017,
- and the Halden Boiling Water Reactor, in Norway, in June 2018.

A quick look at some major remaining MTRs in operation today indicates that several of them are quite old: ATR (USA, 1967), MIR and SM3 (Russia, 1967 & 1961 resp.), BR2 (Belgium, 1962), HFR (Netherlands, 1961), although LVR-15 (Czech Republic, 1995) and the TRIGA in Pitesti (Romania, 1980) are younger. The probability of final shutdown in the next 10 to 20 years of the facilities built in the sixties appears very high.

To cope with that, few projects of new MTRs with a respectable power are really under construction: JHR at CEA Cadarache, France, MBIR (sodium-cooled, fast-neutron reactor) at RIAR, Dimitrovgrad, Russia, and a new reactor to replace HFETR of NPIC near Chengdu, China. Most importantly, only JHR and MBIR will present both an important experimental capacity and the possibility of international access. In the USA, the decision last year to launch detailed design studies of the Versatile Test Reactor (VTR) project means also good news.

At the same time, several newcomer countries are contemplating the possibility of buying a small research reactor, like Jordan, which started the Jordan Research and Training Reactor (5 MW) by December 2016, or Saudi Arabia, where a small 30 kW reactor is under construction at KACST, Riyadh.

In this evolving context, several initiatives have been launched to increase the international cooperation around the remaining facilities.

2. The Jules Horowitz Reactor

2.1. Generalities

A detailed presentation of experimental capacities of the Jules Horowitz Reactor (JHR) could be found in reference [1]. The JHR is under construction on the CEA Cadarache site (fig. 1). It will be operated as an international user's facility for materials and fuel irradiations for the nuclear industry or research institutes, but it has a second objective to produce medical radioisotopes [2]. The detail of the pile block manufacturing has been presented recently [3].

Fig. 1. Jules Horowitz Reactor – October 2017.

The construction is made within the framework of an international consortium: CEA, EdF, AREVA SA, Framatome, Technicatome (France); European Commission with JRC as Observers; CIEMAT (Spain); SCK-CEN (Belgium); VTT (Finland); UJV (Czech Republic); Studsvik AB (Sweden); NNL (UK); DAE (India); IAEC (Israel). Some contacts are ongoing with other foreign entities to discuss their potential interest to join the consortium, or to participate in future programmes.

2.2. General description

The JHR is a 100 MWth pool-type reactor with a compact core cooled by a slightly pressurized primary circuit. The nuclear facility comprises (fig. 2) a reactor building with all systems dedicated to the reactor and experimental devices and an auxiliary building to support both reactor and experimental devices operation, including hot cells, storage pools and laboratories.

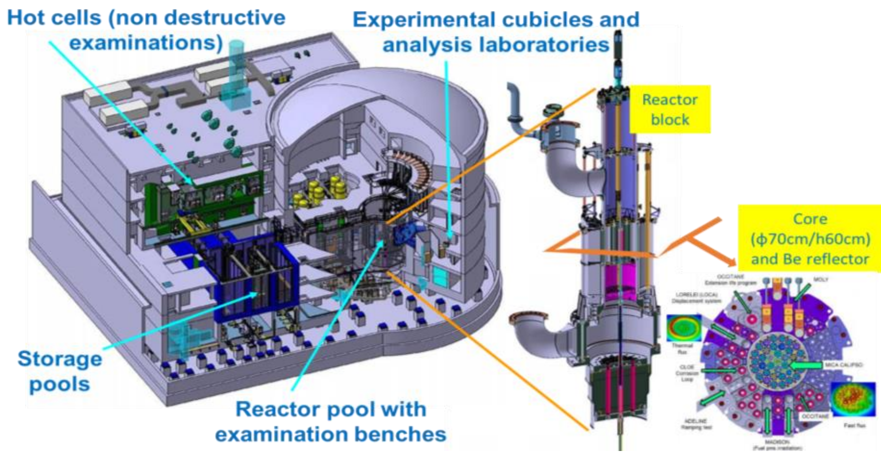

FIG. 2. General structure of the JHR.

The facility is designed to operate 20 experiments simultaneously. Locations for irradiation are either in the core or in the beryllium reflector.

- 10 locations within the core will provide for a high fast neutron flux (5.5.1014 n.cm-2.s-1 above 1 MeV corresponding to a maximum of material damage 16 dpa/year),
- About 20 locations in the beryllium reflector will provide a high thermal neutron flux (up to 3.5.1014 n.cm-2.s-1 corresponding to about 0.1 dpa/year). Material experiments requiring a low ageing rate, such as the pressure vessel steel, will be installed inside the reflector.
- Four to six water channels through the reflector will be equipped with displacement devices to control accurately the distance to the core and therefore the irradiation flux (for an accurate stable power, for power ramps, or for power cycling...).

The JHR will also provide for non-destructive examinations with:

- A coupled gamma-scanning and X-ray tomography bench located in the reactor pool,
- A similar bench in the storage pool of the Nuclear Auxiliary Building.
- A neutron imaging system bench located in the reactor pool.

The other post-irradiation examinations will be performed at the nearby LECA-STAR hot laboratory for fuel PIE, or at the LECI hot lab for materials PIE or at the customer hot laboratory.

2.3. Main experimental devices

Several test devices are under design or mock-up manufacturing. Some of them will be available for the start-up of the reactor (MADISON, ADELINE, MICA), the others being part of a second fleet (LORELEI, OCCITANE, CLOE):

- MADISON for LWR fuel testing under nominal conditions, (evolution of the fuel micro structure, clad corrosion, fission gas releases …),
- ADELINE for LWR fuel under off-normal situations, especially for power ramp testing,
- LORELEI for LWR fuel under large break LOCA conditions,
- MICA could perform in-core irradiation on vessel or clad materials (tensile, Charpy, CT samples, etc...),
- OCCITANE will be dedicated to ageing of pressure vessel steel,
- CLOE will be dedicated to corrosion experiments (IASCC) on stainless steel components.

Other test devices are also considered, such as the RISHI loop, cooled by circulating Na, for material irradiation, but all these loops will not be all implemented at JHR early years of operation, but progressively. Some devices are also designed for the start-up phase of the reactor, such as the neutron start-up sources, the neutron poison absorbers, the start-up instrumentation devices and the monitoring devices [4].

2.4. Preparing the experimental programmes

Several actions are running to gather a scientific community around JHR and to prepare the first experimental programmes once JHR in operation:

- The Consortium established three Working Groups to prepare the fuel irradiations, the material irradiations and for technology issues linked to experimental devices.
- A JHR scientific and technical seminar is organized every year.
- In April 2019, a first JHR school was added to the Seminar. Thirteen young scientists/engineers from the consortium members get lectures about the needs of MTR to answer key-questions about fuel and material behaviour under irradiation and create a first forum of scientific exchanges.

Some other actions are described in the following paragraphs. This list is not exhaustive.

3. The European Support to JHR: FP7 and H2020 JHR Access rights

The European Commission has been supportive of the JHR access from the beginning. Its financial support has been conveyed since 2009 using several contracts with the Joint Research Centre and the DG-RTD, through the JHR-Collaborative Project (2009 – 2010) and using FP7 and H2020 frameworks.

By mid-2018, the European Commission has secured 5.15 % of the guaranteed access to irradiation capacity. It makes the EC the larger foreign contributor to the JHR, because seven bilateral foreign partners have taken 2 % each and India 3 %.

This support will continue with three new actions:

- A complementary funding of Euratom to increase its access rights up to 6 % (Indicated on the last H2020 Euratom call as OA6) ,
- An interest of the Joint Research Centre (JRC) to develop together an experimental test loop that would fit current and future requirements for material and/or fuel tests in the JHR, to be confirmed within the 2021-2025 Euratom financial allocation,
- A Coordinated Support Action (CSA) to build a roadmap for the use of Euratom Access Rights for the benefit of EC Member States to get access to JHR Experimental capacity.

The CEA is very thankful to the European Commission for its continuing support.

4. The IAEA initiative: ICERR (International CEntres based on Research Reactors)

4.1. ICERR concept

In 2014, IAEA Director General Yukiya Amano approved a new initiative, namely the IAEA designated International Centre based on Research Reactors (ICERR), which will help Member States to gain access to international research reactor infrastructure.

The Terms of Reference (See IAEA web site) for designation of an ICERR give more details on this concept: "The proposed scheme of "IAEA designated International Centre based on Research Reactor" (ICERR scheme) is intended to help IAEA Member States gain timely access to relevant nuclear infrastructure based on RRs and their ancillary facilities. ICERRs will make available their RRs and ancillary facilities and resources to organizations/institutions of IAEA Member States seeking access to such nuclear infrastructure (named Affiliates). For Affiliates, ICERRs will provide an opportunity to access RR capabilities much sooner and, probably, at a lower cost. This availability may obviate the need, for example, to build a new RR in their country.

The implementation of the ICERR scheme will also contribute to enhance the utilization of some existing RR facilities […]. On the other hand, an ICERR could benefit, for example, from additional scientific and/or technical resources made available by the Affiliate (e.g. Secondees) and by the increase of its international visibility."

In answer to this IAEA initiative, several entities submitted their candidacy, and after an expert audit, the ICERR label was awarded to:

- CEA Saclay and Cadarache, with JHR and ancillary facilities, i.e. LECA-STAR and LECI hot labs, EOLE-MINERVE, ISIS and ORPHEE reactors, in September 2015;
- The RIAR in Dimitrovgrad, Russian Federation, in 2016;
- SCK-CEN in Belgium, in 2017;
- INL and ORNL, in the USA in 2017.

A few other candidacies are foreseen in the coming years.

4.2. Implementation of ICERR on the JHR

Today, CEA has signed seven bilateral agreements with the following affiliates:

- Jozef Stefan Institute, Slovenia,
- CNESTEN, Morocco,
- CNSTN, Tunisia,
- BATAN, Indonesia,
- COMENA, Algeria,
- JAEC, Jordan,
- FANR, United Arab Emirates.

IAEA is not engaged of these bilateral agreements but is acting as a facilitator. For instance, IAEA could, in some cases, provides funding for travel and accommodation expenses through its Technical Cooperation tools.

The technical content and the implementation of these agreements are adapted to the needs and interests of the different partners. It could consist, as examples, in sending a secondee to CEA Saclay or Cadarache for hands-on training, sending CEA engineers to help for implementing neutron beam activities on an affiliate reactor, analysis by CEA of an affiliate's safety report, measurement campaign inside an affiliate's reactor, participation of foreign scientists to CEA experimental campaigns, co-tutorship of a PhD, exchanges on nuclear instrumentation, core physics calculation of the affiliate reactor, etc.

The ICERR concept is very interesting for JHR future programmes, because it constitutes a second circle of partners around the JHR, the first circle being the members of the Consortium. It also gives to the CEA an opportunity of access to foreign facilities and therefore to increase international exchanges and relationships.

5. The OECD/NEA initiative: the P2M joint project proposal

During many years, the nuclear community extensively used the Halden reactor for experimental programmes, under the aegis of the Nuclear Energy Agency of the OECD. Its premature and definite shutdown last year induced a reduced experimental capability available to answer the needs of companies willing to develop nuclear fuel and materials. In 2018, the OECD/NEA [5] held several workshops or technical meetings, gathering its Nuclear Science Committee (NSC) and Committee on the Safety of Nuclear Installations (CSNI) members, for providing the basics of a new vision for building international joint research projects, as they are considered as an efficient way for improving the R&D knowledge and maintaining skilled teams. For that aim, an implementation, networking several infrastructures (MTRs and hot cell laboratories for post-irradiation examinations) on a same program, is clearly a relevant approach.

With this objective, the P2M R&D program, proposed to the OECD/NEA by a "core group" gathering SCK•CEN, CEA and EDF, is currently the first and the most developed proposal. It aims at discriminating, ranking and quantifying mechanisms that appear in a LWR fuel rod during any type of power transients, with a focus on those provoking a moderate to high load on the clad. This focus includes power levels initiating a central melting of the fissile material. A first step (called "Task 1") includes two tests and will be implemented in the BR2 MTR thanks to the PWC-CD boiling capsule. It aims at obtaining a predetermined molten volume fraction at the hottest part of the experimental rod. Then this final status will be analysed by non-destructive and destructive examinations at the LHMA (SCK•CEN) and LECA-STAR (CEA Cadarache) respectively. Both tests are planned fall 2020 and fall 2021 respectively, and Task 1 is expected to be completed by mid-2023.

6. The IGORR: International Group on Research Reactors

This International Group, started in 1989, organizes about every year and a half an international conference on research reactors. IGORR-19 was held in Jordan in March 2019 and IGORR-20 is foreseen in RIAR, Dimitrovgrad, Russia, during the first week of September 2020. It represents a very good forum where representatives of research reactors around the world can discuss the challenges of their field. The participation, from 17 papers and 52 attendees from 10 countries in 1989, increased thirty years later to around 210 papers or posters and 230 attendees from 40 countries, showing the growing interest for this forum [6].

IGORR is often jointly organized with RRFM, the European Nuclear Society conference on Research Reactor Fuel Management, started in 1997. Sometimes IGORR also hosted some embedded IAEA Technical Meeting on ageing management issues (e.g. in 2013), on Low Power Research Reactor Utilization (e.g. in 2014) or an IAEA Workshop on Safety Reassessment of Research Reactors (e.g. in 2017).

This contributes to give the maximum synergy between entities working on research reactors.

7. Conclusions

In a worldwide landscape of ageing research reactors, the future would be limited to a few new facilities open to international programmes. JHR ambitions to be one of these. As its construction is progressing, it is of vital importance to start with the best test devices and the most adapted to the customers' needs.

To reach these targets, CEA designed JHR from the start as an international user's facility. This is particularly true when looking at the Members of its Consortium, which include many European countries, plus India and Israel. Thanks to the important and continuing support of the European Commission, through its FP7 and H2020 powerful tools, the JHR will offer access to European countries. Moreover, several other international initiatives are also well adapted to enhance these collaborations, such as the IAEA ICERR label, the P2M project of the OECD/NEA, and the IGORR forum.

References

[1] C. Gonnier, J.-P. Chauvin, G. Bignan, B. Maugard, "Update of the JHR experimental capacity and first orientations for the experimental programs", IGORR 2019.

[2] J-P Coulon, M. Antony, C. Chapuis, "Production of radio-isotopes at Jules Horowitz Reactor", RRFM-IGORR 2019.

[3] F. Duquesnoy, F. Witters, P. Parraud, "Jules Horowitz Reactor (JHR): Manufacture of the reactor pile-block", IGORR-2019.

[4] J.-P. Coulon, "Jules Horowitz Reactor (JHR): start-up equipments and experimental utilities", IGORR-2019.

[5] D. P. Parrat, "Networking multinational fuel and materials testing capacities for science, safety and industry: The P2M Joint Project Proposal in the frame of the OECD/NEA", IGORR 2019.

[6] D. Selby, K. Rosenbalm, "IGORR: The First Twenty-Five Years", RRFM-IGORR 2016

WORKSHOP REPORTS

FISA 2019 TECHNICAL WORKSHOP N°1. INFRASTRUCTURES AND INTERNATIONAL COOPERATION, CO-FUNDING INSTRUMENTS, AND PARTNERSHIPS IN RESEARCH AND INNOVATION

Co-Chairs: Helena ZATLKAJOVA (DG RTD, EC) and Margaret McGRATH (PALLAS, NL)
Rapporteur : Gérard COGNET (Expert, FR)

Objective

Large research infrastructures are at the core of the knowledge triangle of research, education and innovation, producing knowledge through research, disseminating it through education, and applying it through innovation. They offer unique research services to users from different countries, attract young people to science, and help to shape scientific communities through top-level research in their respective fields, and nuclear safety research and training.

To fulfil the key objectives EU/Euratom R&D programmes of maintaining high levels of nuclear safety, knowledge and building a more dynamic and competitive European industry, promoting Pan-European mobility of researchers are implemented by co-financing transnational access to research infrastructures and joint research activities through Research and Innovation and Coordination and Support Actions' funding schemes. Establishment by the research community of European technology platforms is being capitalised. Mapping of research infrastructures, financial mechanisms and funding instruments, and E&T capabilities are stimulating closer cooperation within the European Union and beyond, with the benefit from multilateral international agreements and synergies of initiatives between Euratom, OECD/NEA, IAEA and international fora.

Lessons learned and latest initiatives towards large research infrastructures and E&T, challenges and opportunities to promote further utilisation of experimental facilities for collaborative research and training purposes, and practical key recommendations to strengthen international cooperation will be the objectives of this workshop.

Round Panel

Jules Horowitz Reactor, Anabelle LOPEZ (CEA, FR)

Extreme Light Infrastructure, Ionel ANDREI (ELI-NP, RO)

MYRRHA, Hamid AIT ABDERRAHIM (SCK-CEN, BE)

New NEA in-pile testing Framework following the positive Halden experience, Markus BEILMANN (OECD / NEA, FR)

Report

Participation in this workshop was quite small (less than 10 participants). Despite this, presentations gave rise to intense discussions. Several topics were discussed:

- Role of large infrastructures for maintaining and improving knowledge in particular in the field of materials for nuclear reactors (including fuels) and for fusion
- Importance of large research infrastructures and international cooperation to attract young scientists;
- Available tools and funds for investments
- Economic models and administrative tools appropriate for the operation phase of large infrastructure;
- How to share the burden of operating a large infrastructure and the benefits both from the scientific and economic points of view;
- Synergies between research and material testing reactors;
- Importance of medical isotopes production both for Europe medical sector and economy of research reactors;
- Participation of third countries in Euratom projects;
- Role of the JRC to maintain research infrastructures and complementarity with national ones;

The participants agreed on the following recommendations:

- Continue to strongly support and maintain large research infrastructures across the EU, in particular material testing irradiation reactors both for fission and fusion developments;
- Promote synergies between the use of the different tools and programmes (structural funds for example) which can be used for coherent and coordinated investment for research infrastructures and their operating phases;
- Improve communication, in particular towards the EU Parliament and decision makers, about the need of research reactors for the medical sector and education;
- Communicate more towards the public about the international cooperation in using research infrastructures;
- Need to strengthen the synergies between RTD direct and JRC indirect actions of the Euratom research and training programme to maximise the impact in using and sharing access to infrastructures
- Pay more attention to the right accesses and property rights to the EC funded projects.

FISA 2019 TECHNICAL WORKSHOP N°2. INNOVATIONS BEYOND TECHNOLOGY

Co-Chairs: Foivos MARIAS (DG RTD, EC), Guillaume GILLET (EIT-KIC-InnoEnergy, FR),
Expert rapporteur: Stefano MONTI (IAEA)

Objective

One of the strategic initiatives launched in 2015 by the European Commission is 'Open innovation' aiming at far more involving far more actors in the innovation process, from research and academic communities, to industry, entrepreneurs, users, governments and civil society. They all need Open innovation to capitalise on the results of European research and innovation, by creating the right ecosystems, by bringing together multi-disciplinary teams to generate ideas and solutions in an open innovation environment, and by increasing investment, by bringing more companies and regions into the knowledge economy.

'Innovation beyond technology' is about a technology developed for one sector e.g. aerospace, aircrafts, telecoms, big science, automotive or nuclear industries used in a totally different area. And technology transfer results from the process of using a technology, expertise, know-how or facilities for a purpose for which they were not originally intended.

It opens the minds and the way for strengthening relationships and for transferring new technologies to spin-offs, to industry and the marketplace, to transform European's capability for innovation in specific areas and to help capture and drive future economic growth. Exploiting the innovation potential in European and/or International industrial and academic communities will only be achieved by being a focal point where small and medium enterprises, large industry and end users can work together with researchers to challenge barriers, explore and develop new ideas, and bring these to commercial reality. Practical key recommendations to strengthen cross-sectorial cooperation in key areas will be the main objective of this workshop.

Round Panel

Space Industry, Zsuzsanna TANDI (WIGNER Research Institute, HU), ESA technology transfer (absent)

Big Science industry, Marcello LOSSASSO (CERN, CH)

Nuclear industry, Antony WOAYE-HUNE (FRAMATOME, FR)

EIT - Making innovation happen, Guillaume GILLET (EIT InnoEnergy, FR)

Main outcomes of this Workshop on 'Innovation beyond technology':

- The peculiarity of long timescale for nuclear projects, which last sometimes many decades, is an aspect to be taken into account. Critical issues are knowledge management aspects related to the project and ways of engaging and motivating staff working on those projects.
- Innovation is not only about technology but also social innovation, stakeholders and public engagement, regulatory framework and safety standards, and last but not least innovation in capacity building and knowledge management.
- Results of the technology innovation carried out by public bodies like CERN are freely available and not subject to IPR.
- European nuclear Industry is favourable to a European collaborative initiative, involving non-nuclear industries which need to innovate, toward a global sustainable growth, especially because the extra-European competitors' pressure is getting stronger and stronger.
- Fall out of innovation in nuclear sector on many other industrial sectors is an historical fact still true nowadays.
- EIT instrument/initiative could be better used by the nuclear community in particular by business-oriented projects which can consist on development of particular components/instrumentation/system but also in some cases of entire reactor concepts (e.g. microreactors) in case a deployment timescale is short enough (e.g. order of magnitude of 5 years).
- EIT is a successful example putting together: investors, industry, education institutions, research institutions for business-oriented projects in particular in the energy sector. It can be better utilized for nuclear power and non-power projects.

FISA 2019 TECHNICAL WORKSHOP N°3. E&T NETWORKING EVENT

Co-Chairs: Prof. Walter AMBROSINI (Università di Pisa, IT), Panagiotis MANOLATOS (DG RTD, EC)
Expert Rapporteur: Teodora RETEGAN (Expert, Chalmers University of Technology, SE)
Panelists: Prof Dr Javier DIES LLOVERA (Commissioner, Consejo de Seguridad Nuclear, ES), Prof. Dr. Joerg STARFLINGER (Vice-President of ENEN, Uni Stuttgart Germany, DE), Dr. Nathan PATERSON, President (ENS YGN, BE), Dr Pavel ZHURAVLEV (ROSATOMTECH, RU)

The workshop has been opened by Prof. Walter Ambrosini, which invited the panellists and participants to introduce themselves in order to establish a good connexion between the official participants and the audience.

He further introduced the objectives of the Technical workshop as following:

Objectives

The objectives of the TW3 were the dwindling education, training and knowledge management in many nuclear disciplines. Many bottom-up initiatives have been launched since then, resulting among others in preserving and further development of nuclear education and training, however the long-term sustainability of nuclear education and training seems to be exposed to larger risks than two decades ago.

He introduced the concept of "networking" by presenting ANNETTE Project and ENEN+, concluding that Networking is therefore a magic word in this field, meaning that we should act as far as possible together in order to preserve nuclear competences in the nuclear fields: this is a specific mandate of ENEN. Two recent examples were presented, which were crystalized as eventual "routes" for the advancement in networking envisaged in the SET Plan Roadmap for E&T: the creation of an Advanced Network as the "integration route" and Advanced Network as the "coordination route".

Practical key recommendations on the paramount importance of guaranteeing an adequate supply of experts and trained cross-sectorial workers will be the main objective of this workshop.

The items for reflection during the workshop were introduced in the form of a set of questions:

– How is nuclear education a "cause of concern"?
– What are the bottom up and top down strategies to preserve nuclear education?
– How can we engage stakeholders in the common networking effort for nuclear E&T, e.g. as catalyzed by ENEN?

– How to involve the general public (as a major stakeholder) in this process?

Panel discussions

Each panelist started presenting their own view over this topic, like for example a 33 years own experience (Prof. Dr. Javier DIES LLOVERA) where some key points were highlighted: Achieve communication with students at an early stage → building a community-based support & stimulate interest in the future careers in nuclear technology.

Adequate sizing of a number of master's degrees in nuclear safety / nuclear engineering / radiation protection by country. → backbone for R&D groups.

Enhance support to Universities with well-established master's degrees, here there were several examples given.

Prof Dr. Joerg STARFLINGER gave his perspective where his experience in ENEN have led to the conclusion that there were bottom-up approach (2 decades) which were: sufficient to maintain the education system and generate warnings; insufficient to attract many good students, no notable improvements; closures of operating plants may suspend the nuclear education. There are top-down (strategic) approach needed:

– Policy studies to review current and plan future activities.
– Develop & implement nuclear ET(KM) strategies consistent with the long-term visions/plans for nuclear.
– Demand oriented approach with close connection to industry (main stakeholder)

ENEN can contribute with tools, insight, experience and ideas.

Dr. Nathan PATERSON gave his perspective after being involved in YGN and having, as he presented, an a-typical nuclear technology career. The overall conclusion was that Nuclear education in Europe is generally speaking not in a bad shape with some exceptions:

– Public perception and volatile political support are poison for the attractiveness of the studies,
– A lack of job positions, career opportunities and the availability of technical jobs with brighter reputation are existentially threatening the European nuclear competence,
– Commitment needed from above, i.e. governmental level down to the industry.

Also, for answering the question: "Nuclear Education: A Cause for Concern?" The obvious answer would be, from his perspective: "No" in terms of quality of studies however "Yes" in terms of interest of people due to external factors.

For the question: "How can we fix it?": The Public relations need to "talk nuclear", raise awareness within personal network, Support the Young Generation (Network).

Dr. Pavel ZHURAVLEV presented the very long history of the Russian education and training experience, started officially by a state decree in 1967 and which was the precursor of the current ROSATOM. Also, he presented to current activities, like the umbrella ROSATOM Technical Academy comprising on 6 training facilities and 2 training centres (at NPPs facilities) as well as the composition of the key activities: 290 training programmes conducted by 120 professional trainers and training specialists. He presented an initiative called "ENEN-Ru Forum" (which was at the third project, stating 2011) as a possible base for future cooperation with Europe. The focus is on the competence building in the areas of advanced nuclear power technologies through the use of experimental infrastructure and simulation software.

Main discussion and concluding remarks

The main discussions were around the dwindling number of students which are willing to start, continue and afterwards stay in the branch of Nuclear technologies/research. Many programs, especially in the universities have created a "magic number" of how many students are needed for a course or a program to be given. Also, in many countries, there are not new chairs in nuclear related fields and in some cases, some are in "stand-by", no reason given. Most of the times this is a political decision.

Trainee, promotion schemes and mobility (with a serious scholarship which can cover costs and accommodation) as seen as a positive approach to maintaining the know-how, however needs to be backed-up with good entrance salary, development scheme and clear paths for advancements in order to be attractive for younger generation.

It would be good if other funding opportunities would open to nuclear related programs, like Marie-Curie.

As concluding remarks, the general request was that there must be a Nuclear education strategy for 2050.

There must be a clear definition and tracks of the jobs which are needed in order to be able to adapt the current know-how.

A high-impact publication, maybe even a memorandum conveying the discussions and the identified issues must be written and made public, where at least 8-9 scenarios on the needs, issues and existing and future path lines for nuclear field should be presented and discussed. This is aiming at awareness for the decision makers.

Younger generation present in the room acknowledged that maybe there is a future in nuclear field, but the communication of this reality does not really reach them. The media channels used by current projects are not up-to date to the age group intended.

Many career paths are entirely personal and up to the interested to follow, however there is a clear need for a thorough analysis of the current situation, the future need and finally a strategy summing up all the above. This needs to be done yesterday.

FISA 2019 TECHNICAL WORKSHOP N°4. ALFRED: A SIZEABLE OPPORTUNITY FOR EUROPE

Co-Chairs: Teodor CHIRICA (FORATOM, BE), Giovanni VILLABRUNA (FALCON, IT)
Expert Rapporteur: Giacomo GRASSO (ENEA, IT)

Objective

The drastic reduction of the amount of radioactive waste and its long-term radiotoxicity, together with the enhancement of the safety characteristics, acted as important factors in programmes to support the development of Generation IV nuclear systems. The steady and rapid increase of the readiness of the Lead Fast Reactor technology opens to the possibility for a short-term perspective, with the deployment of commercially viable LFR-based SMRs.

To materialize this vision, the ALFRED project is being promoted by the FALCON international consortium, for a European demonstrator of the LFR technology to be realized in Romania. FALCON, led by Ansaldo Nucleare and gathering ENEA and RATEN-ICN, is addressing the undeniable challenges posed by the development of an innovative technology, by investing in the design and licensing activities, and on all the supporting R&D actions, also involving other organizations at European and Romanian level, historically engaged in the LFR development.

Besides, FALCON members and supporters share the belief that ALFRED is an invaluable opportunity: for Europe, to take a synergic leadership at the trailing-edge of nuclear technology; for Romania, to host a world-class research infrastructure.

The panelists, renowned experts in the field and representatives of the above institutions, will provide background information and their strategy to address the above challenges, converting them into opportunities for European competitiveness.

Round Panel

A firm determination through passion and commitment, Prof. Serban Constantin VALECA (Senate Vice-President, RO)

A collaborative effort for a common vision, Alessandro ALEMBERTI (Ansaldo Nucleare, IT)

Achievements and challenges for the full technological readiness, Mariano TARANTINO (ENEA, IT)

Aims and ambitions of the Romanian industry, Teodor CHIRICA (ROMATOM, RO)

A cohesive national support for qualified human resources, Dumitru CHIRLESAN (CESINA, RO)

Local, regional and national preparation to be a perfect host, Marin CONSTANTIN (RATEN ICN, RO)

FISA 2019 TECHNICAL WORKSHOP N°5. CROSS-CUTTING FISSION, FUSION AND NON-NUCLEAR ENERGY SYNERGIES, CHALLENGES AND OPPORTUNITIES

The workshop started with a short introduction by the chairman Mykola DŽUBINSKÝ, followed by 5 chained presentations addressing either topics for which potentiality for crossed research activities and innovation have already been identifiend and are even ongoing, or those ones suitable to feed future collaborations on specific isues of common interest:

Cross-cutting fission, fusion and solar thermal energy challenges. Lorenzo Malerba (CIEMAT) presented and discussed the rationale for the identification of commonalities in the field of materials between the GenIV and the Fusion as well as the Fusion and the Non-nuclear technology fields, which is based on the commonalities between the expected operating conditions (high temperature, aggressive environment, high irradiation dose in the case of fission and fusion).

The following common topics have already been identified for the synergy Fusion - Fission:

- F/M steels for current or future concept designs,
- innovative high temperature resistant steels,
- ceramic materials,
- physical modelling and modelling-oriented experiments;
- and for Nuclear / Non-nuclear:
- temperature resistant materials, compatibility issues, -
- protection from aggressive environment (liquid metals, molten salts, gases, …),
- steels for high temperature applications: existing and advanced,
- refractory materials: metals and ceramic composites: existing and advanced, materials qualification,
- advanced modelling and characterization.

The latter are identified in a position paper jointly prepared by EERA (European Energy Research Alliance) and EUMAT (European Technology Platform for Advanced Engineering Materials and Technologies), see www.eera-set.eus/category/position-papers/) and appear also, together with the former, in the strategic research agenda of the EERA Joint programme on Nuclear Materials: Materials for Sustainable Nuclear Energy, www.eera-jpnm.eu. These documents are openly available to identify topics for cross-cutting projects between fusion, fission and also non-nuclear energy. However, there is currently no common European framework wherein nuclear and non-nuclear energy can collaborate in a joint project. Lorenzo also showed the example of heavy liquid metal technology as a common issue for fission, fusion and thermal solar.

Synergies between fission and fusion: an industrial perspective. Alessandro Alemberti (Ansaldo Nucleare) emphasized that engineering activities do not care whether the heat is generated by fission, fusion, sun or whatever chemical process. No matter the way heat is originated, a system to remove it and produce electricity is needed, so as buildings, materials resistant to high temperature and radiation, control and safety systems, etc…. What is needed is competence and skill in different fields of engineering, supported by an open mind approach to be flexible, understanding potential advantages and problems of a specific technology application. Engineering and technical aspects need to use the same expertise and capabilities for both fission and fusion… Synergy potential is deeply underground, but is there: it is just a matter of disclosing it. Alessandro pointed-out that in his personal experience Fission- Fusion synergies are maximized by the special need for materials development in a high temperature and high radiation environment for both types of systems, as pointed out in the previous presentation as well. Alessandro also cited the Ansaldo experience on development of steam generators (helical type) for nuclear reactors applied also for molten salt energy storage in the frame of solar applications, citing the fact that important synergies can take place especially in terms of design and simulation tools validation.

TRANSversal Actions for Tritium. Christian Grisolia (CEA) presented the current program to assess technologies to minimize tritium permeation at source and to capture and store it from the treatment of metallic waste and liquid and gaseous effluents, that implies the assessment of its inventory, the adoption of state-of-the-art modelling tools, as well as the refinement of the knowledge on outgassing, radiotoxicity, radioecology, radiobiology, dosimetry and metrology of tritium, the engineering solutions for detritiation techniques and waste management, the tritium permeation control. All these topics already profit from the synergy between the fusion and fission technologies. Moreover, Christian claimed that interaction between experts of both fields is not only advantageous to the tritium technology, but can - and must - profit to the whole fusion system design, e.g. in the fields of safety (including the licensing process), nuclear design and operation, maintenance and waste management.

Non-nuclear energy Solar Technology. Florian Sutter explained the difference between direct and indirect (solar) energy conversion (with thermal storage). He claimed that the thermal storage is much more cost-efficient than battery-based. He presented commercial thermal storage systems in molten nitrate salts at 400°C (for parabolic trough technology) and 565°C (for solar tower technology) and pointed out that future storage systems aim to reach 720°C to drive supercritical CO_2-cycles. The lifetime of the thermal storage is expected to reach 30 years. A possibility for cost-savings of the structural materials of the storage system is to use low-alloyed steels in combination with alumina coatings, the test of which is underway. The operating temperatures and the needs for corrosion/permeation protection are very similar to the issues affecting GenIV of fusion systems.

An alternative solution for heat extraction in solar, currently under investigation, uses falling particles with no freezing problems.

As a general comment to the presentation, it can be considered that any system allowing convenient energy storage is profitable to the deployment of nuclear energy (no matter whether fission or fusion originating) because today the management of production fluctuation is a major challenge for the operators.

Common challenges concerning design codes for fusion and fission components. Jarir Aktaa (KIT) presented an exhaustive comparative investigation of the properties demanded to structural materials for Fusion and GEN-IV systems (e.g. resistance to temperature, pressure and DPA) and addressed the main challenges they have to face in both of them: creep, fatigue, inelastic collapse, progressive inelastic deformation (ratcheting), ageing, as well as environmental effects such as irradiation induced swelling, creep, hardening, loss of ductility and embrittlement, effect of the coolant and its impurities (e. g. helium in GFR).

He also emphasized that most of design rules in existing codes are applicable for fusion materials validation, however for some of them verifications are needed. Moreover, due to cyclic softening and, in case of irradiation, loss of ductility, existing design rules of certain failure modes require modification or development of advanced new ones.

At the end of presentations, an open, extended and exhaustive discussion among the workshop participants fueled and bred ideas for cross fertilization among fusion, fission end sometime non-nuclear technologies R&D and innovation in many, different fields of endeavor such as:

- Reactor physics
  - Cross-sections data bases
  - Computation methods
  - Validation process and experiments;
- Materials (high DPA, high temperature, thermal shock, compatibility with aggressive environments, e.g. not heavy liquid metals or molten salt, used in solar, fission and fusion for different purposes, but even commonalities between SCWR and geothermal energy);
- Measurement devices;
- Severe Accidents
  - Dust and powder explosion,
  - Air / water ingress;
  - Operation / Power extraction, including Tritium properties and permeation control;
- Maintenance;
- Phasing-out / dismantling + Energy storage (from solar);
- Waste and waste management including recycling and the development of specific disposal acceptance criteria for activated metals.

Eventually, the crucial problem of the licensing was addressed and the suggestion was made to extend to the fusion designs (e.g. DEMO) the exercise carried out for GEN-IV ones in the framework of the SARGEN-IV Euratom project, which aimed at declining the generic safety requirements in a way addressing and accounting for their features and specificity.

It was finally emphasized the need to strengthen the collaboration among fission and fusion people in the fields of safety, materials, nuclear engineering, nuclear operation and maintenance, as well as teaching and tutoring. Synergies between fusion and fission technology (and also non-nuclear technology) exist; they only have to be accurately identified. In the case of materials this identification largely occurred already. For other fields it was suggested to gather an expert group with this objective. Integration of nuclear industry representatives was also suggested to facilitate the sharing of competence among fusion and fission people.

It was stated that in order to increase trust in the Fusion industrial future, a comprehensive exercise project including safety aspects from the very beginning in view of licensing should be settled.

The workshop ended with the release of the following comprehensive recommendation: "*It is recommended expanding synergies and fostering collaboration in R&D and innovation between fission and fusion technologies, with inclusion of non-nuclear ones when appropriate (e.g. materials and devices in extreme conditions, energy storage), to support and foster the achievement of a decarbonated energy production*".

FISA 2019 TECHNICAL WORKSHOP N°6. DECOMMISSIONING CHALLENGES AND OPPORTUNITIES

Co-Chairs: Pierre KOCKEROLS (DG JRC, EC), Athanasios PETRIDIS (DG RTD, EC)
Expert Rapporteur: Christine GEORGES (CEA, FR)

TECHNICAL SUMMARY

Nuclear decommissioning is an industrial activity expected to grow worldwide and creating opportunities for high-skilled workers. The European Union has acquired a large know-how in the field and can position itself today as a leader in the world. The European scientific community has a key role to play to support the European industry in this endeavor through a contribution to innovation, standardization and harmonization of the highest safety standards, development and/or capitalizing the best technologies available. R&D challenges and opportunities in technical and non-technical fields identified should enable all relevant stakeholders to jointly improve safety, to support its value chain, to reduce costs and minimize environmental impact in the decommissioning of nuclear facilities. There is indeed a broad consensus among the industry that, even if various dismantling techniques reached a certain the level of industrial maturity, there are still specific challenges ahead:

- need for solutions to pending problems in decommissioning of back end facilities or other legacies and associated waste treatment on site
- need for optimization, methodology and even standardization wherever possible in NPP decommissioning

Also, non-technological issues i.e. competence maintenance, education and training, dialogue with society regulators, etc. More impulse is needed to develop and to use research and innovation in Decommissioning projects, to promote and organize at international level the co-financing of developments and demonstrators by actors with common objectives.

Building confidence through the steps needed for the generation and management of knowledge on decommissioning, identifying key research areas, creating synergies between European partners, and supporting international collaborative platforms whenever applicable are all key enablers. Universities, research laboratories and industry should engage in innovative approaches, benefit from a vibrant education and training culture, basic academic MSc / PhD / Engineering / Managerial education as well as continuous professional development of competences. The use of advanced technologies across all nuclear and engineering fields should guarantee a new generation of skilled experts will be available whenever needed, having high levels of safety implemented throughout the sector for decades.

The workshop provided two general presentations on the European projects aiming at addressing these issues (the SHARE and the ELINDER projects), as well as three topical presentations on developments of decommissioning technologies.

The workshop was closed with a presentation on the past and future perspectives of the EURATOM support in the field of decommissioning.

SHARE project to identify a decommissioning R&D roadmap, Christine GEORGES (CEA, FR)

The objective of SHARE project is to provide an inclusive roadmap for joint near future research, for stakeholders jointly to improve safety, reduce costs and minimize environmental impact in the decommissioning of nuclear facilities, with commitment to:

- build confidence in the steps needed for the generation of knowledge on decommissioning and its safety, economic and environmental aspects
- encourage the future coordination of Research and Innovation (R&I) activities strategically recommendable for financing in the next decades
- facilitate access to expertise and technology and maintain competences in the field of decommissioning and environmental remediation for the benefit of Member States.

A Strategic Research Agenda (SRA) will be set to define research priorities, develop a roadmap, and suggest joint activities that can actually be achieved in the field of decommissioning aiming at safety improvement, environmental impact minimisation and cost reduction. The SRA will consider all the research and innovation activities in the field of decommissioning. It identifies the knowledge gaps and defines and prioritizes research topics. In addition to innovation and technological challenges, it also addresses policy, economics and social issues. The non-technological issues, may be organised as cross-cutting activities (e.g. maintaining sustainable competence, education and training, dialogue with regulators).

The goal of the roadmap is to organise the topics identified in the SRA in such a way that those relevant for joint activities are addressed along an implementation time-line. A proposal for the deployment plan for the roadmap will also be provided, envisaging how the joint activities could be implemented.

The identification of the most promising research topics will support EU and stakeholders in their understanding and evaluation of the strategic topics to be recommended for financial support in the next decades.

Decommissioning R&D in Germany, Walter TROMM (KIT, DE)

In Germany, a large number of nuclear power plants are shutdown and the last seven reactors will finish their operation by 2022. Many installations are thus in dismantling or are expected to start dismantling soon. On the contrary, there is no complete waste route in operation as the disposal sites have still to be commissioned. A key element in decommissioning is thus the clearance process which allows to release the largest part of the output of the dismantling. For the remaining radioactive waste, the Law of 2017 ensures that a handover of the liabilities to the State is possible.

With this perspective in Germany, the Karlsruhe Institut für Technologie (KIT) has developed competences in its division dedicated to deconstruction and decommissioning of conventional and nuclear buildings with various projects in support of the related industrial activities. It includes the improvement of processes and techniques, the automation and remote handling of procedures and, the efficiency of the project management. Some practical examples of decontamination equipment, manipulators and robotic systems were illustrated and commented. Laboratories are designed for testing remote equipment for characterisation, decontamination and free release measurement.

The R&D and building of competences at this level has been integrated in a Decommissioning Cluster, which includes KIT, the University of Stuttgart, the Karlsruhe DHBW high school, PSI (CH) and the JRC (EC). It is however emphasised that it may beneficial that the EC would in the future have a role in promoting the knowledge in decommissioning.

An industrial demonstrator to prepare graphite reactor dismantling, Michel PIERACCINI (EDF, FR)

The unavailability of devoted graphite disposal and other uncertainties has obliged the French EDF to review its decommissioning strategy and to propose starting with the construction demonstration facility for the dismantling of graphite.

Such a facility would be conceived as a first step that would allow implementing automated systems for the dismantling, checking the feasibility of the dismantling scenarios, testing 3D scanning and modelling. It could help increasing safety and mastering delays and costs by determining the most appropriate tools, reducing the amount of waste, reducing radiological exposures and optimising procedures. The demonstrator could also allow training of operators.

The demonstrator would be installed on the site of a shutdown reactor; Chinon A2 has been identified as a representative graphite reactor for such a pilot project.

As several EU countries face similar uncertainties related to the decommissioning of their graphite reactors (UK, Spain, Italy, Germany, Lithuania) and as it is expected that the dismantling scenarios will be similar for all kind of reactors, an opportunity is created to have the demonstrator facility launched as a new European project.

Laser Cutting Techniques for Decommissioning, Julien GUILLEMIN (ONET, FR)

In the frame of decommissioning industrial activities, special attention is required to improve the performance of cutting technologies, which should be deployed in many circumstances remotely, be reliable and meet the highest safety standards.

Laser cutting is widely used today in the industry and high-power lasers are commercially available. In view of the decommissioning, CEA has developed innovative laser cutting tools which have been implemented by ONET

Technologies for the dismantling of the UP1 reprocessing plant in Marcoule, France. Support is also provided to the dismantling of the Fukushima Daiichi NPPs. A prototype has been developed for cutting both in air and underwater, allowing to cut metallic pieces of up to 40-50 mm under 5 m of water and on-going improvements to reach 100 mm. Also, non-emerging cutting (deep gouging) is under development. With the evolutions and building of experiences over recent years, laser cutting has reached an acceptable Technology Readiness Level (TRL).

Laser cutting is not yet considered for all cases of dismantling applications due to a lack of experience and remaining safety concerns related to its implementation. To bring the benefits of this already mature technology to further fields of applications, R&D needs to focus on the two main topics in terms of safety:

- the protection from the residual light and reflexions on the surroundings of the laser beam
- the confinement of the cutting environment due to the gases and aerosols generated.

European learning initiatives for nuclear decommissioning and environmental remediation, Pierre KOCKEROLS (DG JRC, EC)

The European Commission's Joint Research Centre (JRC) has investigated the opportunities for stimulating the development, coordination and promotion of adequate education and training programmes at EU level in nuclear decommissioning. Building on the existing experiences available, the JRC along with several partners in the EU Member States who have experience with training in the decommissioning field have launched a joint project to consolidate and improve their existing training programmes, facilitate their promotion and enhance opportunities.

The overall aim is to raise the interest of students and professionals and to stimulate careers in this important and expanding field, by offering a modular, attractive set of theoretical and practical learning opportunities, consisting of a series of courses including lectures, practical hands-on exercises and visits to relevant facilities in the vicinity of the training venue. 'Generic' training modules will serve as a general introduction and give a synopsis of the main decommissioning aspects. Additionally, 'specific', topical training modules will address more in detail 7 specialised topics which have been identified as pinch point areas, i.e. areas in which knowledge, skills and competences can be improved. Additionally, a series of complementary e-learning courses will serve as induction for participants with less experience in nuclear, with a view to prepare for the courses.

The joint training programme project is called **ELINDER (European Learning Initiatives for Nuclear Decommissioning and Environmental Remediation)** and is implemented from 2018 onwards.

To ensure a coherent and harmonised approach, shared minimum quality criteria, including learning outcomes, will be defined for acceptance of the courses within the ELINDER programme, thus receiving the "ELINDER stamp".

The ELINDER approach may in the future be integrated in a larger forum in Horizon Europe which may be created by the European Commission to disseminate the knowledge in the field of decommissioning.

FISA 2019 TECHNICAL WORKSHOP N°7. 13TH ENEN PhD Event & Prize 2019

Main outcomes of 13th ENEN PhD Event & Prize 2019:

The 13th ENEN PhD Prize & Event took place in the framework of the FISA EURADWASTE Conference in Pitesti, Romania, on 5 June 2019. After one full day of presentations, questions and answers, the jury decided that the 3 Winners of the ENEN PhD Event & Prize 2019 were:

- Claire Le Gall, "*Contribution to the study of fission products release from irradiated nuclear fuels under severe accident conditions: effect of oxygen partial pressure on the speciation of Cs, Mo and Ba*";
- Wael Hilali, "*Debris Bed Formation in Degraded Cores of Light Water Reactors*";
- Florian Muller, "*Hydraulic and statistical study of metastable phenomena in PWR rod bundles*".

The three winners were selected from the finalists according to the evaluation of the Jury based on their presentations and the work delivered within the application and at the conference. They were awarded grants to attend an international conference with a support from ENEN up to 1000 Euro (conference fee, travel, accommodation and expenses - upon receipt of justification documents) and hereby encouraged to present the result of his/her research work.

The following finalists were selected, among all applications received, and invited to present their research work at the event:

- Erik Branger, "*Enhanced verification of irradiated nuclear fuel using Cherenkov light*";
- Wael Hilali, "*Debris Bed Formation in Degraded Cores of Light Water Reactors*";
- Elke Jacops, "*Development and application of an innovative method for studying the diffusion of dissolved gases in porous saturated media*";
- Claire Le Gall, "*Contribution to the study of fission products release from irradiated nuclear fuels under Severe accident conditions: effect of oxygen partial pressure on the speciation of Cs, Mo and Ba*";
- Florian Muller, "*Hydraulic and statistical study of metastable phenomena in PWR rod bundles*";
- Pablo Romojaro Otero, "*Nuclear Data Analyses for Improving the Safety of Advanced Lead-cooled Reactors*";
- Alberto Tosolin, "*Experimental investigation and modelling of thermo-chemical and thermo-physical properties of fluorides for the Molten Salt Fast Reactor*";
- Evgenii Varseev, "*Simulation Model of Mass transfer and crystallization process in liquid metal coolants*".

This year's event was highly remarkable because of the friendly and competitive spirit of the participants, and questions between the participants raised the interest and appreciation for each other's work. A group picture was taken with all the attendants.

The members of the ENEN Jury were:

- Prof. Francisco Javier Elorza (Universidad Politécnica de Madrid, Spain)
- Prof. Petre Ghitescu (University Politechnica Bucharest, Romania)
- Prof. Iztok Tiselj (Jožef Stefan Institute, Slovenia)
- Prof. Piero Ravetto (CIRTEN, Italy)

- Prof. Danny Lathouwers (TU Delft, The Netherlands)

With this activity, ENEN aims to promote the research of PhD students, and in particular experimental work, in order to set up a bridge between PhD students and professionals in the nuclear field. The ENEN PhD Events are co-sponsored by the European Nuclear Education Network Association (ENEN), the European Commission Joint Research Centre (JRC), and the organizer of the international conference.

JOINT CONCLUSIONS
FISA 2019
EURADWASTE '19

Summary and main conclusions of the FISA2019 Conference

provided by Stefano Monti (IAEA), Section Head, Nuclear Power Technology Development section, Division of Nuclear Power, Department of Nuclear Energy

Despite different energy policies in EU Member States, Europe produces about 25% of its electricity through the operation of 126 reactors. It represents about 50% of European clean electricity production. Moreover, in a number of EU Member States nuclear energy plays a significant role as a component of low carbon electricity supply to address, in particular, the obligations under the Paris Agreement on climate change, also highlighted in the latest 2050 roadmap for carbon-neutral economy.

Nuclear energy also contributes to security of energy supply and competitiveness of European industry.

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

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

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

In view of these first realizations, after a first broad-spectrum investigation of all the possible technology options which has characterized the last 20 years of R&D, there is an increasing consensus in the European nuclear community on the need to focus on the most promising innovative nuclear energy systems and associated fuels and fuel cycles for Europe. Concentration of effort, critical mass and synergies between national and European programmes seem to be seem to be necessary conditions for success.

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

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

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

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

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

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

- Ensuring a top-level education & training, involving basic academic education as well as continuous professional development and capacity building, is of paramount importance to create a new generation of nuclear researchers and experts able to maintain high levels of safety in all the fields, as well as address the challenges posed by advanced nuclear power and non-power technologies of European interest;
- It is more and more urgent to assure adequate maintenance and strengthen a robust, enduring and efficient infrastructure base across the EU to underpin all aspects of research and innovation throughout the sector;
- It is highly advisable to capitalize on the European Technology Platforms SNETP- NUGENIA, -ESNII, -NC2I as well as ENEN as for E&T. ETPs have proved to be very effective in fostering and strengthening collaboration between research/academic institutes and industry. This successful mechanism of collaboration should be enhanced and further implemented
- International cooperation and synergies with initiatives launched by other international agencies like NI2050 (Nuclear Innovation 2050) & NEST (Nuclear Education, Skills and Technology Framework) by OECD-NEA, ICERR (International Centre based on Research Reactors), Collaborating Centres and E&T networks by IAEA, GIF task forces on infrastructure and E&T have to be encouraged and intensified.

Finally, there are significant cross-cutting benefits and synergies that can be realised between fission and fusion energy research programmes, as the latter evolves from activities focused on basic plasma physics to ones focused more on technology and safety-related aspects.

- In a number of EU Member States nuclear energy plays a significant role as a component of low carbon electricity supply to address, in particular, the obligations under the Paris Agreement on climate change, also highlighted in the latest 2050 roadmap for a carbon-neutral economy.
- Nuclear energy also contributes to security of energy supply and competitiveness of European Industry
- All the EU Member States, including those with no NPPs, have a primary interest to ensuring nuclear safety throughout the EU
- Despite different energy policies in EU MSs, Europe produces about 25% of its electricity through the operation of 126 reactors. Maintaining a high level of safety and competitiveness is a major challenge and requires the establishment of a coordinated and focused R&D programme at European level, well interconnected with IAEA and OECD-NEA activities

- Most European countries operating NPPs are now considering prolonging the lifetime of their reactors from an originally foreseen 40 years' operation to 60 years. In order to safely extend the lifetime of these reactors, the nuclear sector needs to have, in addition to a skilled and well-trained workforce, reliable tools to assess the ageing and degradation processes of components and structures, as well as methods and guidelines for their validation. The contribution from the Euratom R&D programme to this top priority must continue and be focused on the expressed needs of the European industry
- Industrial scale deployment of so called Generation IV nuclear energy systems is expected around the middle of the 21st Century. European contribution, above all to safety, sustainability, non-proliferation resistance, physical protection and competitiveness aspects of these innovative systems is clearly recognized at the international level. JRC remains the implement agent of Euratom in GIF whilst specific indirect actions should be aimed at coordinating the contribution from interested Member States

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- Limited resources at European level on advanced reactors and related fuels and fuel cycles suggest prioritization on the most promising nuclear systems for Europe
- In the meantime there is the need to maintain flexibility within current and future Euratom programmes to consider, at appropriate time, other emerging nuclear technologies, including those given high priority in other regions of the world, like for instance SMRs, nuclear-renewable hybrid energy systems, etc.
- Non-electric applications of NP, like H2 production, district heating, several industrial applications, desalination, etc. are of increasing interest in many regions of the world including some EU Member States. They have the potential to decarbonize the whole energy sector. Synergies with chemical industry should be developed as soon as possible and related R&D in Europe should be focused on near-term deployment

- Despite the planned life extension of aging NPPS, a number of NPPs in Europe are expected to be shut-down in coming years. Decommissioning and dismantling industrial-oriented R&D activities have to be appropriately supported by forthcoming Euratom programmes
- Many efforts have been devoted during last decades to develop advanced physical models and computer simulation codes of high fidelity, including in the very challenging area of severe accident M&S. However new technologies such as artificial intelligence, on-line monitoring, deep-learning, etc. are rapidly being introduced in many advanced technology sectors. Forthcoming Euratom programmes should take into account these new trends and foster the early involvement of European industry and TSOs which represent the final users
- Nuclear applications and technologies, and related competence and expertise, in the fields of medicine, radiation protection and in general non-power applications are recognized of great value for a modern society in all the EU Member States. As a consequence Euratom programme should be seen as an integral part of the broader Horizon Europe proposal able to capitalise on synergies over a much wider range of research areas. Joint projects between Euratom and Horizon Europe programmes should be pursued whenever possible (mission oriented projects)

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- Ensuring a top-level education & training, involving basic academic education as well as continuous professional development and capacity building is of paramount importance to create a new generation of nuclear researchers and experts able to maintain high levels of safety throughout the sector and address the challenges posed by advanced nuclear power and non-power technologies of European interest
- There is a strong and urgent need to maintain and strengthen a robust, enduring and efficient infrastructure base across the EU to underpin all aspects of research and innovation throughout the sector
- There is the need to capitalize on the European Technology Platforms SNETP- NUGENIA, -ESNII, -NC2I as well as ENEN as for E&T. ETPs are very important to foster and strengthen collaboration between research/academic institutes and industry
- International cooperation and synergies with initiatives launched by other international agencies like NI2050 & NEST by OECD-NEA, ICERR and E&T networks by IAEA, GIF task forces on infrastructure and E&T have to be fostered and strengthened as well

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- There are significant cross-cutting benefits and synergies that can be realised between fission/fusion/non-nuclear (e.g. materials) energy research programmes, as fusion evolves from activities focused on basic plasma physics to ones focused more on technology and safety-related aspects

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https://doi.org/10.1051/epjn/2019003

Available online at:
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Innovative Technologies in Training and Education for Maintenance Team of NPPs

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Abstract

Many industries, such as nuclear power plants, chemical industry, oil and gas industry have dangerous working environments and hazardous conditions for employees. Maintenance, inspection and decommissioning activities in these safety-critical areas mean a serious risk, downtime is a significant financial loss. The Virtual Reality Training Platform is reflecting on this shortcoming, by providing the possibility for maintenance workers to be trained and prepared for unexpected scenarios, and to learn complex maintenance protocols without being exposed to unnecessary danger, like high temperature, radiation, etc. Employees can have training for equipment maintenance, dismantling of facilities at closed NPP Units. One of the most significant and unique added value of the immersive virtual reality solution is that the operator can experience lifelike emergencies (detonation, shutdown) under psychological pressure, while all of the physiology indicators can be monitored like eye-tracking. Users can work together anywhere in the world. A huge financial outage in industrial production is the preparation and maintenance downtime, which can be significantly reduced by the Virtual Training platform. This method can increase the accuracy, safety, reliability, and accountability of the maintenance and decommissioning procedures, while operational costs can be reduced as well.

1. INTRODUCTION

In today's industry, quick response and fast execution of well-learnt procedures is critical. Many people work in factories, where circumstances can be fatal in cases. For example, nuclear power plants have spots where people can only stay minutes due the harmful health effects of radiation. Dangerous places are not only present in power plants, there are also machines operating under water or in high altitude. People who are working in these environments can get injured easily if they are not attentive enough. However, maintenance of these machines has to be done, so maintenance workers must be very efficient, fast, precise and well-trained when they have to visit these places. Even when circumstances are not dangerous, there are several machines the faulty operation of which can cause huge risk or loss of money **Error! Reference source not found.**, **Error! Reference source not found.**. These devices also have to be maintained regularly and efficiently.

Due to these facts, workers have to be trained several times and practice the movements very well before participating in real missions. Nowadays,

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most of the training is done on real copies of these machines, which are not currently operating and the only purpose of them is to help the training. Maintenance can be practiced in a very realistic way using these, however, there are also several drawbacks of the method. Ordering one more appliance can be very expensive to buy and maintain, while often requires much more space and occasionally operators as well. There is usually only one training appliance which is not flexible, so most employees can only get to use it few times if, because there are many people to train and travel costs may also be incurred.

The other problem is that while the appliance can be studied very closely, their environment cannot really be simulated even though this would be very important in many fields of application, especially when the real work has to be done in extreme circumstances. For example, firefighters can be trained how to operate water pumps and hoses efficiently but are not really able to feel the danger of situation when there are real people and real fire **Error! Reference source not found.**.

Interactive computer-based trainings are also available in many fields by now. It can be very cheap and flexible, but not close to trying a real machine, as using a keyboard or mouse cannot give the immersion needed to really memorise a procedure or series of movements.

2. VR training platform

In the Virtual Reality Training Platform developed by Bay Zoltán Nonprofit Ltd., the latest Virtual Reality technologies are used to help training of maintenance workers [FIG. ***13***: VR Trainig Platform]. It provides the possibility to practice complex working processes in advance, be prepared for unexpected situations and receive knowledge of the area safely, without any hazards. VR service can be applied for increasing the experience and knowledge of the personnel in the field of maintenance and operation in power plants, chemical industry, refinery plants and production companies. On the other hand, adequate operation training of high value machinery without imposing any risk on the real equipment state is also possible. The main purpose of the platform is decreasing human factor, assuring safer work and operation conditions and replacing expensive training centres with a safe and innovative education system with cost-effective periodic trainings.

Unlike in real appliance-based trainings, no special equipment is needed, so this solution can be cheaper and more flexible because a real machine does not have to be purchased. However, it still provides realism and precision unlike conventional computer programs and videos.

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The other big advantage of computer support is that everything can be measured precisely during the training. For example the working time of maintenance or the hardest part of the procedure can be easily detected as all data can be recorded and analysed during the training without the need for any human staff, but operators can still help employees remotely during the training if necessary and the system can be used anywhere, even at the home of each employee, regardless of the distance from the original working place.

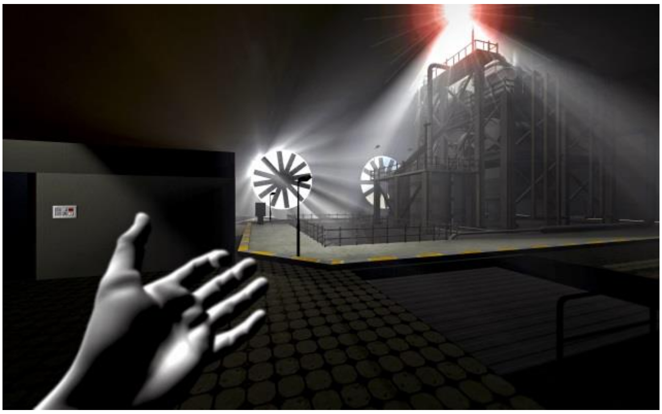

FIG. 13. VR Trainig Platform.

3. Structure of the system

The virtual training system contains key elements both on hardware and software side. Its most important part is a PC-connected VR headset – primarily Oculus Rift (https://www.oculus.com/) or HTC Vive (https://www.vive.com/) **Error! Reference source not found.**,**Error! Reference source not found.** – which is worn by the user during the training. The PC has to be powerful enough to maintain high-enough framerate (preferably 90Hz or more **Error! Reference source not found.**) while rendering virtual reality content, or else users may feel motion sickness **Error! Reference source not found.**.

VR headsets are usually used with controller interaction, but this method is not immersive enough in most cases. The main drawback is the fact that controllers are designed to control computers and cannot represent everyday actions and movements naturally **Error! Reference source not found.**. In the real life, people do not push buttons or grab joysticks to assemble or disassemble machines and they will not be able to learn or practise the real movements of the procedures if they have to do so **Error! Reference source not found.-Error! Reference source not found.**. Immersion is a critical point of virtual reality, which means that interaction

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methods also have to be as life-like and accurate as possible. For practising the assembly work, precise and latency-free (real-time) motion detection is essential. Many different devices are available on the market, however for our application, LEAP Motion (https://www.leapmotion.com/) provides the best solution **Error! Reference source not found.**, as its small sized, non-contact optical motion sensor can be fixed onto the VR headset itself and it does not disturb the free movement of the user **Error! Reference source not found.**. The sensor recognizes features of the human hand and is able to build up a skeleton using the position of the users' real hand and fingers. The software side of the platform relies on Unity game engine (https://unity.com/) **Error! Reference source not found.-Error! Reference source not found.**, using which, this hand model gets transformed to the virtual space with the help of LEAP Motion's SDK.

However, rendering the models of the user's own hands in the virtual space and capturing its motion is not enough to fully replace controllers. If the aim is not to overlap virtual objects, but to be able to touch and grab them, an interaction engine is also necessary. In the early days, we used the default gesture based model provided by LEAP SDK for this purpose, the biggest disadvantage is of which is that it does not take physical qualities of the object into account.

FIG. 14. Virtual maintance of a valve in NPP.

The user can grab the nearest object whenever the "pinch" gesture is performed. Later, we began to develop an own, more precise way for interaction, which determines the fact of grabbing considering outlines, mass and size of touchable objects and the angle of the touching fingers.

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Using this method, users can not only see their own real hand, [FIG. ***14***: Virtual maintance of a valve in NPP] but are also able to work with it confidently in virtual reality without the distraction of any other devices.

Another issue in virtual reality is getting around large virtual spaces, which is also relevant in nuclear power plant maintenance. The platform has multiple solutions for this: on the one hand, workers can use a special "walker" called Cyberith (https://www.cyberith.com/) **Error! Reference source not found.**, which uses optical flow sensors to determine direction and intensity of feet movement while users walk in place. On the other hand, the popular "teleport" mechanism can also be utilized. In this concept, users have to walk in the real area, but when a door or special barrier is reached, they get teleported to another spot, so there is no risk of outrunning the real space.

The advantage of the treadmill [Figure 3: Treadmill & SLAM] is that the operator can travel anywhere while they stay in the same position in the physical space. However, the Cyberith we use does not give full immersion in the field of simulating the principle of walking.

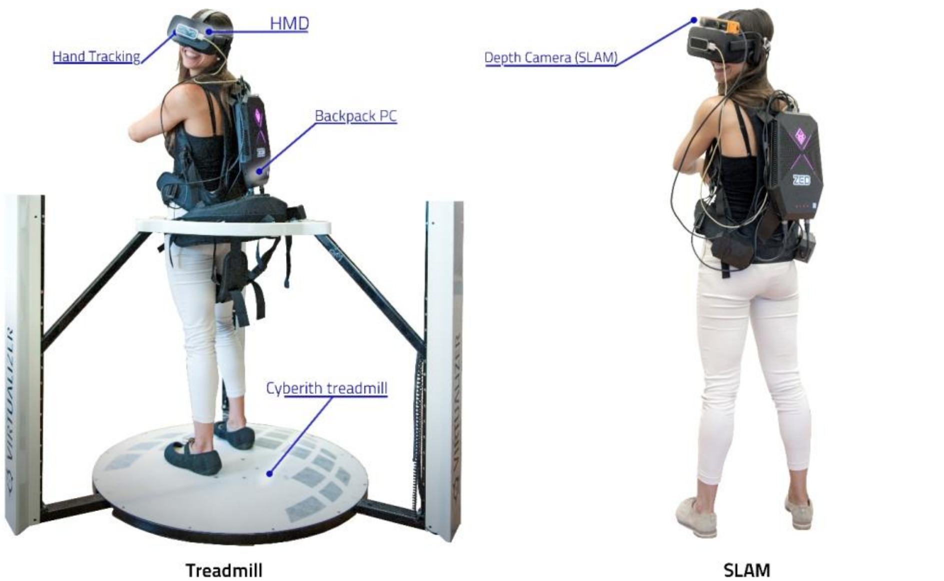

FIG.15: Treadmill & SLAM.

The step detection optical sensors do not sense the elevation of the foot, but rather a sliding motion, so this process is more like a controller: it has to be learned and accustomed to its special use. Depending on these

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artifacts, negative innervation may be developed which does not correspond to reality.

Another solution to implement motion into virtual reality is free movement. In this case, the operator walks in the physical space on their own legs like in reality and does not need to learn to walk again in virtual reality like on the treadmill *[***Error! Reference source not found.***: Treadmill & SLAM]*. This method is much closer to real spatial motion. For maximizing freedom, we used a backpack computer because it is wireless - with 2 hours of battery time - and the operator is not limited by cables. For the motion tracking, we used the Stereolabs ZED (https://www.stereolabs.com/) stereo depth-sensing camera and inertial sensor that allows us to map our environment. By implementing SLAM (Simultaneous Localization and Mapping) **Error! Reference source not found.**-**Error! Reference source not found.** algorithm for environment mapping and object and determine the actual position of the user, which is widely used in navigation and robotics besides VR and AR applications.

The disadvantage of the free movement solution used for the VR training platform is the limitation of the physical space. The boundaries of a platform set up in a room will be determined by the physical dimensions of the real environment. For this shortcoming, we implemented teleportation as a workaround.

4. Advantages in training

As stated earlier, the main purpose of the above-mentioned technologies is making training of maintenance workers more efficient and flexible. A simulation model is a great tool for training workforce because it can be done anywhere in the training room even before the production line is built. Software training with real data offers many benefits. If the control software is integrated into the simulation model, then the operator can acquire the same user interface as in real life, thereby gaining a holistic view of the production system. This allows them to study system parameters, weaknesses, operator reactions, and early problems in order to correct those.

Contrary to traditional procedure instructions and video trainings, the virtual training platform can effectively improve every moment of the practice, regardless of location and time. There is no need to build or rent expensive simulation halls, as virtually any environment can be easily built, and later, individual elements can be easily replaced and rearranged, making construction work cost-effective.

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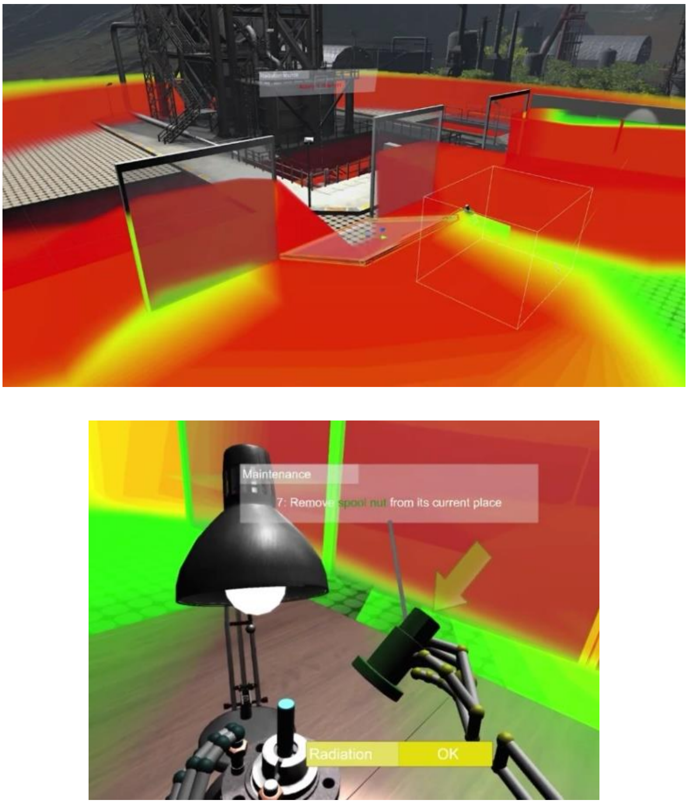

FIG. 16: Real-time radiation visualization.

Another big advantage of the platform is flexibility. The system is designed to be very easily maintainable and extensible with many different modules. Training phases, tools and the whole environment can be very easily adjusted to very different situations if needed and can be used in a wide range of industrial applications. For instance, we successfully integrated a real-time radiation calculation and visualisation module, developed by IFE **Error! Reference source not found.**. This extension can display the actual level of radiation, position of shields and the radiation source as well. A heatmap also makes it easy to distinguish dangerous and safe spots and the dose of radiation an employee would take when working in such environment [**Error! Reference source not found.**: Real-time radiation visualization] The real-time data stream makes it possible to alert the user in case of a sudden radiation increase in the facility or segments of the plant and helps finding a way to leave the working zone avoiding dangerous spots. Using this extension, nuclear decommissioning can be made not only much easier and safer, but cheaper as well.

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5. Other possible use-case scenarios

Aside from trainings, there are also some other efficient use-case scenarios of using VR, some of which we would like to introduce and discuss further.

In order for engineering teams to work in parallel phases, 3D visualization tools are needed to improve communication. The initial planning and design is always done in front of monitors, but once the base parameters of the facility and the list of objects to be placed are available, the imaginary concept can be constructed and tested in virtual reality. Rapid prototyping can be beneficial in any industry and this way, it can be way more efficient.

Using the VR platform can also be beneficial in product simulation **Error! Reference source not found.**-**Error! Reference source not found.** if the concept is constructed in virtual reality before the real construction. In this field, we would like to determine and test how our preliminary plans, flow of materials would work, whether our control principles are appropriate, the size and location of the buffer are well estimated, and where the bottlenecks are. If the data that we are working on is based on real data and comes from a similar product family or from the same versions we can turn it to our advantage in further applications. This is an iterative analysis where engineers have to examine the system from the most basic elements to determine what parameters require further analysis or changes, for example, to reduce cycle times. An important requirement is that the simulation should be able to validate our measurements and ideas, for which an easily parametric and flexible model is essential.

6. Conclusion

The introduced Virtual Reality Training Platform is a flexible framework, which has been successfully validated in nuclear industry. The platform can be adapted for several other purposes.

The more we fit a simulation platform into the application environment, the easier it is to develop and execute. The ability of virtual reality to deliver real-world images of data, objects and environments that the user can interactively influence in a realistic way opens up great opportunities for industrial applications.

This technology can be utilized in a wide range of industries (heat, water, chemical, etc.) It has great potential in Chemical, Oil- and Gas Industries where all maintenance training can be performed seamlessly in the virtual world, without disrupting the daily operation. This approach can significantly reduce cost by minimizing the outage time.

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The personal safety is guaranteed by the replacement of the dangerous working environment - high temperatures, high voltage, radiation, lack of oxygen, etc. - by Virtual Reality. Using this immersive virtual reality solution, the operator can experience lifelike emergencies under psychological pressure, and allows the operators to be properly trained to make the right decisions even in the real world. Operators need to be familiar with the layout of their working environment and the actions and activities they are expected to perform both in normal and emergency conditions. Being properly trained would ensure that the employees are prepared for any situation they may encounter at their workplace and can safely perform their duties, without delay.

Specially built training areas are hardly available and expensive to maintain. The development of a VR training platform is faster, flexible and more cost-efficient for simulating real-life emergencies

References

[1] Ródenas, J., Zarza, I., Burgos, M. C., Felipe, A., & Sánchez-Mayoral, M. L. (2004). Developing a virtual reality application for training nuclear power plant operators: setting up a database containing dose rates in the refuelling plant. Radiation Protection Dosimetry, 111(2), 173-180.
[2] Whisker, V. E., Baratta, A. J., Yerrapathruni, S., Messner, J. I., Shaw, T. S., Warren, M. E., ... & Johnson, F. T. (2003, May). Using immoof airtual environments to develop and visualize construction schedules for advanced nuclear power plants. In Proceedings of ICAPP (Vol. 3, pp. 4-7).
[3] Heldal, I., Wijkmark, H. C., & Pareto, L. (2016). Simulation and serious games for firefighter training: Challenges for effective use. NOKOBIT, 24, 12.
[4] Desai, P. R., Desai, P. N., Ajmera, K. D., & Mehta, K. (2014). A review paper on oculus rift-a virtual reality headset. arXiv preprint arXiv:1408.1173.
[5] Niehorster, D. C., Li, L., & Lappe, M. (2017). The accuracy and precision of position and orientation tracking in the HTC vive virtual reality system for scientific research. i-Perception, 8(3), 2041669517708205.
[6] Richard, P., Birebent, G., Coiffet, P., Burdea, G., Gomez, D., & Langrana, N. (1996). Effect of frame rate and force feedback on virtual object manipulation. Presence: Teleoperators & Virtual Environments, 5(1), 95-108.
[7] McCauley, M. E., & Sharkey, T. J. (1992). Cybersickness: Perception of self-motion in virtual environments. Presence: Teleoperators & Virtual Environments, 1(3), 311-318.
[8] Webb, J. S., Rogoza, B. E. T., Bristol, P. W., Higgins, J. A., Talati, S. S., Chen, Y. Y., & Konzen, N. W. (2017). U.S. Patent No. 9,678,566. Washington, DC: U.S. Patent and Trademark Office.
[9] Motion, L. (2015). Leap motion. San Francisco, CA, USA.
[10] Bowman, D. A., & McMahan, R. P. (2007). Virtual reality: how much immersion is enough?. Computer, 40(7), 36-43.
[11] Khademi, M., Mousavi Hondori, H., McKenzie, A., Dodakian, L., Lopes, C. V., & Cramer, S. C. (2014, April). Free-hand interaction with leap motion controller for stroke rehabilitation. In Proceedings of the extended abstracts

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Available online at:
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of the 32nd annual ACM conference on Human factors in computing systems (pp. 1663-1668). ACM.
[12] Ryan, M. L. (1999). Immersion vs. interactivity: Virtual reality and literary theory. SubStance, 28(2), 110-137.
[13] Hilfert, T., & König, M. (2016). Low-cost virtual reality environment for engineering and construction. Visualization in Engineering, 4(1), 2.
[14] Jerald, J., Giokaris, P., Woodall, D., Hartbolt, A., Chandak, A., & Kuntz, S. (2014, March). Developing virtual reality applications with Unity. In 2014 IEEE Virtual Reality (VR) (pp. 1-3). IEEE.
[15] Cakmak, T., & Hager, H. (2014, July). Cyberith virtualizer: a locomotion device for virtual reality. In ACM SIGGRAPH 2014 Emerging Technologies (p. 6). ACM.
[16] Engel, J., Stückler, J., & Cremers, D. (2015, September). Large-scale direct SLAM with stereo cameras. In 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (pp. 1935-1942). IEEE.
[17] Gupta, T., & Li, H. (2017, September). Indoor mapping for smart cities—An affordable approach: Using Kinect Sensor and ZED stereo camera. In 2017 International Conference on Indoor Positioning and Indoor Navigation (IPIN) (pp. 1-8). IEEE.
[18] Szőke, I., Louka, M. N., Bryntesen, T. R., Bratteli, J., Edvardsen, S. T., RøEitrheim, K. K., & Bodor, K. (2014). Real-time 3D radiation risk assessment supporting simulation of work in nuclear environments. Journal of Radiological Protection, 34(2), 389.
[19] Mujber, T. S., Szecsi, T., & Hashmi, M. S. (2004). Virtual reality applications in manufacturing process simulation. Journal of materials processing technology, 155, 1834-1838.
[20] Ottosson, S. (2002). Virtual reality in the product development process. Journal of Engineering Design, 13(2), 159-172

EPJ Nuclear Sci. Technol. 5, 7 (2019)

https://doi.org/10.1051/epjn/2019003

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Cite this article as: Jean-Paul Crocombette, Christian Van Wambeke, Quick calculation of damage for ion irradiation: implementation in Iradina and comparisons to SRIM, EPJ Nuclear Sci. Technol. 5, 7 (2019)

FISA 2019 PHD AWARDS

EPJ Nuclear Sci. Technol. 5, 7 (2019)
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https://doi.org/10.1051/epjn/2019003

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3D Convolutional and Recurrent Neural Networks for Reactor Perturbation Unfolding and Anomaly Detection

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Abstract

With Europe's ageing fleet of nuclear reactors operating closer to their safety limits, the monitoring of such reactors through complex models has become of great interest to maintain a high level of availability and safety. Therefore, we propose an extended Deep Learning framework as part of the CORTEX Horizon 2020 EU project for the unfolding of reactor transfer functions from induced neutron noise sources. The unfolding allows for the identification and localisation of reactor core perturbation sources from neutron detector readings in Pressurised Water Reactors. A 3D Convolutional Neural Network (3D-CNN) and Long Short-Term Memory (LSTM) Recurrent Neural Network (RNN) have been presented, each to study the signals presented in frequency and time domain respectively. The proposed approach achieves state-of-the-art results with the classification of perturbation type in the frequency domain reaching 99.89% accuracy and localisation of the classified perturbation source being regressed to 0.2902 Mean Absolute Error (MAE).

1. Introduction

The early detection, classification, and localisation of anomalies within the reactors' core is vital to ensure the safe and efficient operation of the increasingly aging fleet of Europe's reactors. Monitoring of these reactors at nominal conditions provides vital and valuable insights into the functional dynamics of the core, consequently allowing for early identification of anomalies. Analysis of the core operation is achieved through non-intrusive measuring of neutron flux around their mean values from in-core and ex-core detectors. These fluctuations more commonly referred to as noise are induced primarily from turbulent characteristics in the coolant flow in the core, coolant boiling, or mechanical vibrations of reactor's internal components.

Given detailed descriptions of the reactor core geometry, properties of physical perturbations, and probabilities of neutron interactions, by using a Green's function as the reactor transfer function, simulations can be constructed to show the effect of the neutron noise. Green's function holds the relationship between a locally induced perturbation and the response of the neutron flux within the core, therefore, the inversion of this function from noise readings can localise and classify such induced perturbations. This inversion known as the backwards problem or unfolding is trivial given

EPJ Nuclear Sci. Technol. 5, 7 (2019)
© J.-P. Crocombette and C. Van Wambeke, published by EDP Sciences, 2019
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measurements at every position within the core, however, the limited number of in-core and ex-core detectors makes it a complex challenge [1].

Machine learning (ML) is a data analytical process for the approximation of functions mapping a set of inputs to outputs. Therefore, the use of ML to approximate such reactor functions given limited detector readings is advantageous, learning high and low-level patterns given substantial training examples. This work presents an extended 3D-Convolutional and Recurrent neural network approach to unfold the reactor transfer function and classify induced perturbation types and their source locations in both time and frequency domains.

2. Related Work

The application of ML approaches in the field of nuclear safety has been of recent scientific interest, with nuclear energy essential to meeting fast changing climate goals. The ML community has been keen on predicting climate change [2] utilising a variety of approaches across all energy sectors. Nuclear energy relies on safety and availability to achieve such goals, and many recent works have been proposed to ensure this.

In [3] the authors utilised deep convolutional neural networks and Naïve-Bayes approaches for vision-based crack detection for reactor component surfaces from video sequences. A diagnosis system monitoring the condition of sensors using auto-associative kernel regression and sequential probability was proposed in [4]. Deep rectifier neural networks were implemented in [5] for the accident or transient scenario identification of pressurised water reactors (PWR), whereas others solved similar problem employing artificial neural networks improving condition-based maintenance [6]. Further ML approaches were implemented by [7] in the form of Adaptive Neuro-Fuzzy Inference System (ANFIS) for the prediction of critical heat flux. For unfolding, ANFIS approaches have also been utilised for the localisation of simulated induced neutron noise sources in VVER-100 rectors, given neutron pulse height distributions as training input [8-9].

Work proposed in [10] unfolds reactor transfer functions by the means of CNNs from simulated neutron noise readings in the frequency domain at differing perturbation types and frequencies. Classification and localisation of the perturbations had been achieved with low error by the means of a 2D-CNN. The localisation of the perturbation source was achieved through the spatial splitting of the core volume into 12 and 48 subsections for classification of source perturbation belonging to a particular subsection. Furthermore, an increased unfolding resolution for localisation was implemented, utilising the extracted latent variables from the CNN and clustering. [11] proposed a 3D-CNN approach to combat the limitations of the 2D implementation in [10] from the loss of spatial information through

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the conversion of the 3D volume into a 2D input. Moreover, [11] included the classification of time domain signals processed to extract temporal information via RNNs. This work extends the approaches previously developed in [10] and [11] to larger, more complex simulation scenarios, including the localisation of perturbations in the time domain.

3. Simulated Scenarios and Data Pre-Processing

The process of training ML models requires large amounts of training data, representing instances for which known perturbations are assumed and the corresponding induced neutron noise readings are estimated. The known data allows the system to learn the function mapping detector readings to their classification and origin, i.e. transfer function inversion, or unfolding. To obtain this amount of training data it is necessary to simulate scenarios to practically provide enough examples of differing anomaly types and source locations for effective unfolding. To achieve this, simulations determining the reactor transfer function or Green's function, providing detector readings of the induced neutron noise of a given perturbation scenarios for pressurised water reactors (PWR) have been employed in both the time and frequency domain.

3.1. Frequency Domain

Modelling of fluctuations in neutron flux given known perturbations in the frequency domain was achieved through the CORE SIM [12] reactor physics codes, generating neutron detector readings of the induced neutron noise in a PWR for five perturbation scenarios. CORE SIM models the effects of a noise source for a three-dimensional reactor core, of cylindrical shape in Cartesian geometry for a reactor transfer function – considered to be the Green's function of the system – capturing the response of the fluctuations of the induced neutron flux from known perturbation distributions. The Green's function provides a one-to-one relationship between any location of perturbation and the response of the neutron flux at any position within the core. CORE SIM models a PWR with a radial core of size 15x15 fuel assemblies, utilising a fine volumetric mesh of 32x32x34 voxels modelling sub-assembly response, including boundary sources. For further details, consult the CORE SIM user manual [13],[12].

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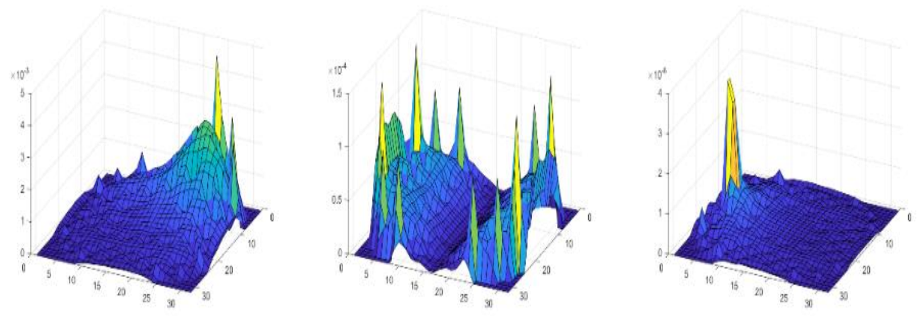

FIG. 1. Examples of the amplitude induced neutron flux in the frequency domain for a single azimuthal slice on the 10th axial plane. Left: Absorber of Variable Strength. Middle: Core Barrel Vibration - Right: Vibrating Fuel Assembly, cantilevered.

CORE SIM provides five perturbations scenarios in 34 frequencies (0.1-1.0Hz with a step of 0.1Hz and 1.0-25.0Hz with a step of 1.0Hz) each with two energy groups, i.e. high and low energy spectrum, referred to as Fast and Thermal groups respectively. The five scenarios include: Absorber of Variable Strength, the perturbation of the thermal macroscopic absorption cross-section; Axial-Travelling Perturbations, perturbation of the coolant at the velocity of the coolant flow; Fuel Assembly Vibrations, vibration of a fuel assembly in the x- and/or y-direction for differing modes cantilevered beam, simply supported for the first mode (0.8-4.0Hz), simply supported in the second mode (5.0-10.0Hz), and cantilevered beam and simply supported for both modes; Control Rod Vibrations, vibration of a one-dimensional structure along the z-direction vibrating perpendicularly to the two-dimensional (x,y) plane; Core Barrel Vibrations, perpendicular or beam mode of vibration in both the in-phase and out-of-phase modes. Examples of these perturbations can be seen in FIG. ***1*** for an axial cross section of the core volume.

Data Pre-Processing

The signals produced are complex 3D volumes of the size of the fine volumetric mesh (32x32x34 voxels), representing the induced neutron noise at every point within the core volume for a given perturbation originating from a specific positional coordinate within the core (i, j, k). The signal volumes are provided as the response in both fast and thermal groups, however, for our experimentation only the thermal group is utilised due to neutron detectors being more sensitive to thermal neutrons. The dataset is comprised of 34 frequencies each containing a minimum of 106176 data examples across all scenarios, and have been split into

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training, validation and testing sets via frequency and source location per scenario.

To mimic the signals from real plant detectors, a pre-determined number of voxel locations have been selected from the whole 32x32x34 volume to emulate the number of detectors within the simulated core. In our case 48 in-core and 8 ex-core detectors have been used from their volumetric positions for the modelled core layout. Furthermore, to emulate reality, the Auto-Power Spectral Densities (APSD) and Cross-Power Spectral Densities (CPSD) for the simulated signals have been calculated to coincide with real plant readings. Additionally, to demonstrate the robustness of the proposed network white Gaussian noise has been added to the signals in two signal-to-noise ratios (SNR), SNR=3 and SNR=1. Finally, as Deep Neural Networks (DNNs) currently cannot easily implement complex signals, each of the complex 3D volumes is decomposed to its amplitude and phase. The now two volumes are concatenated together channel-wise to form a 2x32x32x34 volume.

3.2. Time Domain

The determination of the reactor transfer function in the time domain was employed by the Simulate-3K (S3K) algorithm [14], modelling 48 in-core and 8 ex-core neutron detectors for the four-loop, Westinghouse, PWR mixed core of the OECD/NEA transient benchmark. S3K has been utilised to perform 27 different scenarios comprised of 6 perturbation settings and their combinations: Fuel Assembly Vibration of the central 5x5 cluster, vibrating synchronously in the x- or y-direction at a frequency of 1.5Hz (sine wave) or random (white noise); Fluctuations of the Coolant Flow, at ±1% from the relative mean amplitude; Fluctuations of the Coolant Temperature, at ±1ºC from the mean value of 286.7 ºC. These perturbations distributions have been performed with core operating conditions similar to the aforementioned frequency domain model.

S3K simulates each of the scenarios with a duration of 100 seconds sampled at 0.01 time steps for each of the 48 in-core and 8 ex-core detectors. The detectors are positioned at 8 azimuthal locations at 6 axial levels for in-core and distributed at 4 azimuthal locations at 2 different axial locations for the ex-core. In addition to the above classification scenarios, individual fuel assembly vibrations for all 193 azimuthal locations within the core have been modelled for 5 different scenarios of 4 perturbation settings including combinations of the 4: Fuel Assembly Vibration in the x-direction at a frequency of 1.5Hz (sine wave) or random (white noise); Fluctuations of the Coolant Flow, at ±1% from the mean value; Fluctuations of the Coolant Temperature, at ±1ºC from the mean value of 286.7 ºC. These scenarios have been experimented for the classification and localisation of

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the perturbing fuel assembly. For further technical details on S3K refer to the user manual [14].

Data Pre-Processing

The signals produced by S3K are presented as 10001-dimensional vectors per each of the 56 detectors for each scenario, representing the neutron readings of the induced neutron flux. Due to the limited number of data samples available, data augmentation was performed to increase the number of samples per detector per scenario, and to reduce the large input size into the DNN. To achieve this a sliding window of width 100 time-steps and stride 25 was used to represent a 1 second input to the network, this produced the vector $x \in \mathbb{R}^{396\times100}$ per detector. Furthermore, splitting the data into training, validation, and testing sets has been accomplished via the position of the detector, this means specific detector locations have been split into differing sets to the description in FIG. 2 per axial position of the detectors. Finally, to further test the robustness of the proposed networks, white Gaussian noise has been added to the signals at two SNRs, SNR=5 and 10.

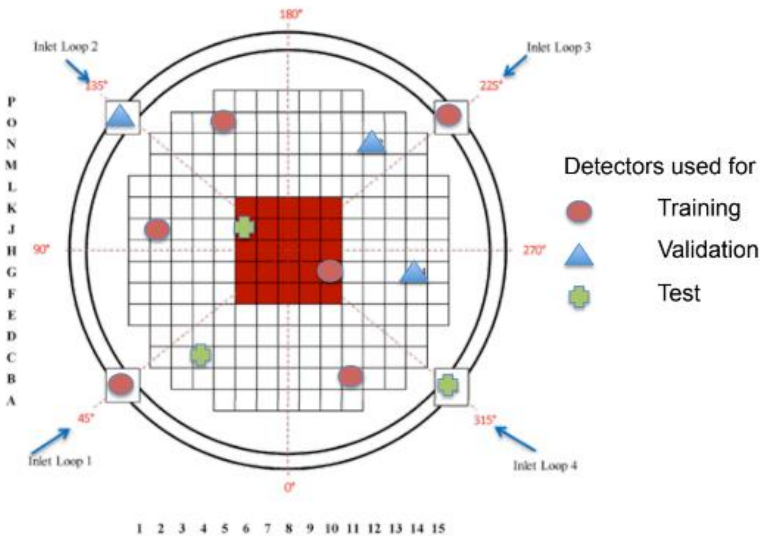

FIG. 2. Modelled core layout with 8 in-core and 4 ex-core detector locations shown for one axial plane. Corresponding train, test and validation detector splits shown, with central 5x5 FA cluster shown in red.

Additionally, for the localisation of fuel assembly vibrations, the same sub-sampling process has been undertaken; however, all 56 detectors for a 1 second sample are considered to be one input into the network. Therefore,

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the split of data has been achieved through the source location of the vibrating fuel assembly, ensuring the same assembly is not present between sets. The same process of applying white Gaussian noise have also been applied to study the effect on the network at SNR=3 and SNR=1, at higher levels of noise, due to the added robustness of utilising all possible 56 detectors as input.

4. Approach

ML and more specifically Deep Learning (DL) are a set of powerful algorithmic approaches for data analytics and pattern recognition, applying iteratively learnt knowledge to unseen data for decision making tasks without being explicitly programmed. DL is a subset of ML, utilising multiple stacked layers of Artificial Neural Networks (ANN) – inspired by biological neurons – to extract varying levels of information, hence the term deep. The proposed approaches utilise modern deep learning techniques and architectures extracting valuable pattern information from the input signals to iteratively learn the inverse of the reactor transfer functions.

4.1. 3D Convolutional Neural Network

Convolutional Neural Networks (CNNs) [15] are specialised ANNs designed for spatial feature extraction from data with known grid-like topologies, i.e. images. CNNs replace the traditional matrix multiplication of ANNs with the convolution operation extracting spatial features. Moreover, improving efficiency with the capability of learning coarse to fine features through the addition of more CNN layers, extracting complex hierarchical concepts from such features. Convolutional layers utilise a set of kernels, learning a corresponding number of filters that to capture these spatial patterns pertaining to the given input. Formally, computing the activation of a convolutional layer ℓ and feature-map f at positions i, j, k is given by

$$a_{i,j,k}^{[\ell,f]} = \phi(n_{i,j,k}^{[\ell,f]} + b^{[\ell,f]}) \quad (1)$$

where ϕ is a non-linear activation function such as Rectified Linear Units (ReLU: $f(x) = max(0, x)$) and b is a learnt bias $n_{i,j,k}^{[\ell]}$ is given by

$$n_{i,j,k}^{[\ell]} = \sum_{x=0}^{X-1}\sum_{y=0}^{Y-1}\sum_{z=0}^{Z-1} W_{x,y,z}^{[\ell]} \cdot A_{i+x,j+y,k+z}^{[\ell-1]} \quad (2)$$

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where $W^{[\ell]}$ is a kernel of learnt weights in layer ℓ with dimensions $X \times Y \times Z$, convolved with the activations from the previous layer $W^{[\ell]} * A^{[\ell-1]}$. This produces a weighted sum per location of all points within a kernels receptive field of the previous layers' activations. Visual examples of the features learnt via the convolution operation can be seen in FIG. 4.

Given the volumetric nature of the signals in the frequency domain and the task of localisation, it is necessary to obtain spatial relationships and patterns within the data volume. Therefore, this work proposes a modified, densely-connected, 3D-CNN for the volumetric feature extraction of simulated neutron detector readings seen depicted in FIG. 3.

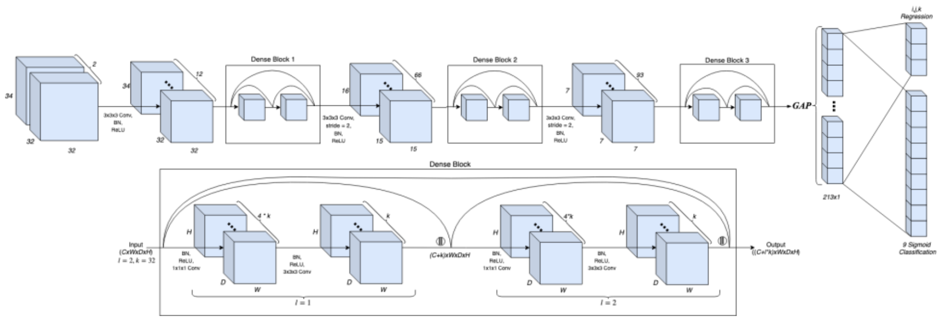

FIG. 3. The proposed Densely-connected 3D CNN architecture, depicting an example dense block of 2 layers and growth rate of 32. The Fully-connected and output layers can be seen right of the GAP, each unit represents a classification perturbation type or the source (i,j,k) location to be regressed.

The network depicted in Fig. 3. shows the architectural construction of the 3D CNN, comprised of three dense blocks modified from the 2D variant to allow for the 3D volumetric input. Dense blocks [16] are an DNN architectural design, utilising several CNN developments, with its main advantage being the use of dense connections. These connections allow for a greater flow of information between layers during the forward and backward pass of the backpropagation procedure, resulting in the reduction of vanishing gradients and achieving better performance. These connections are simply concatenations, where the ℓ^{th} hidden layer H_ℓ receives as input the feature-maps all preceding layers within that block.

$$X_\ell = H_\ell([X_0, X_1, \ldots, X_{\ell-1}]) \tag{3}$$

In addition to the dense connections, the network employs 1x1x1 kernel convolutions with stride 1 for the reduction in feature dimensionality following dense connections, furthermore, 1x1x1 kernels reduce network

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parameters whilst increasing network complexity, further assisting the parameter large 3D convolution operation [17]. The dense blocks each contain $l = 20$ layers with growth rate of $k = 6$, for further details please refer to [16]. All convolutional layers are followed by the commonplace procedure: convolutional layer → Batch Normalization (BN) → and ReLU activation. BN normalises the activations output by the convolutional layer improving network stability, ReLU is a non-linear activation function with sparse activation, further assisting in the reduction of vanishing gradients. Furthermore, the proposed network replaces the pooling operation with strided convolutions for dimensionality reduction, retaining spatial structural information from the input vital for the localisation of perturbation sources.

The last convolutional layer of the network outputs a representational feature vector of the input of size 256 via Global Average Pooling (GAP) layer [17], fully connected to two output layers for perturbation classification and localisation. GAP directly outputs the spatial average over the feature maps, resulting in a vector $V \in \mathbb{R}^m$ where m is the number of feature maps. The output layer for classification is comprised of 9 non-linear, sigmoid units each for the occurrence of the individual perturbation types (nine types as modes of fuel assembly vibration are considered as classes of perturbation). For localisation three linear units have been employed each representing the (i, j, k) coordinates of the perturbation source to be regressed.

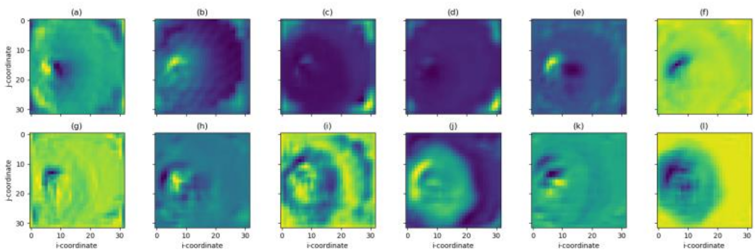

FIG. 4. Sample of 12 learnt feature-maps from the output of first dense block for the input of vibrating fuel assembly at (8,16) given all possible detectors. Visually depicting how the differing layers highlight different features of the image. (a) shows a peak at the source of vibration, (d) the response on the core barrel, (j) the noise dissipating throughout the core.

Training the network has been achieved via implementing the multi-task loss approach from [11], minimising the weighted sum of losses per task (classification and localisation) with a weight coefficient identifying the impact each tasks loss in the training procedure. For classification the network aims to minimise the negative log-likelihood (NLL)

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$$NLL = -\frac{1}{N}\sum_{i=1}^{N} y_i \cdot \log(\hat{y}_i) + (1 + y_i) \cdot \log(1 - \hat{y}_i) \tag{4}$$

and for localisation regression, minimises the L2 loss, or mean squared error (MSE)

$$MSE = \frac{1}{N}\sum_{i=1}^{N} \lVert y_i - \hat{y}_i \rVert^2 \tag{5}$$

where y_i and $\hat{y}_i$ are the true and predicted values of the network for N number of examples. As previously alluded the 3D CNN network is trained minimising a weighted sum of losses

$$\mathcal{L}(X; \boldsymbol{W}, \lambda_1, \lambda_2) = -\frac{1}{N}\sum_{i=1}^{N}\left[\frac{\lambda_1}{P}\sum_{p=1}^{P}\left[y_1^p \cdot \log(\hat{y}_1^p) + (1 + y_1^p) \cdot \log(1 - \hat{y}_1^p)\right] + \frac{\lambda_2}{C}\sum_{c=1}^{C} \lVert y_2^c - \hat{y}_2^c \rVert^2\right]_i \tag{6}$$

where P and C are the number of perturbation classes and source location coordinates respectively, λ_1 and λ_2 are the manually tuned hyper-parameter weight coefficients for each task loss, classification and localisation regressing respectively. This objective is minimised given X as input data with respect to $\boldsymbol{W}$ parameters (weights and biases).

4.2. Long Short-Term Memory, Recurrent Neural Network

Time domain signals hold temporal information within their sequential structure, therefore, a differing approach to previously described is necessary to capture these time-dependent features. To more appropriately capture the relationships within the detector signals, Recurrent Neural Networks (RNN) have been employed. RNNs utilise recurrence to allow information about previous time-steps to persist within the network informing current and future time-step cells across the sequence. RNNs in principle formulate a non-linear output A_t from both the input data x_t at that given time-step and the activation of the previous timesteps cell A_{t-1}, where ϕ is a non-linear activation function such as hyperbolic tangent (tanh):

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$$A_t = \phi(x_t, A_{t-1}) \tag{7}$$

Long Short-Term Memory (LSTM) [18], a variation of RNNs have been incorporated in this work for their ability to learn long term dependencies across long sequences, ideal for the 100 time-step sequences in question. It achieves this ability with the use of memory gates, regulating and learning how much to 'remember' from previous cell states and how much to contribute from the current data input. Initially, the forget gate determines what to remember from the previous cell state C_{t-1} given activation A_{t-1}. To decide what new information will be added to the current cell state, an input gate i_t and candidate values $\tilde{C}_t$ are generated.

$$\begin{aligned} f_t &= \sigma(\mathbf{W}_f \cdot [A_{t-1,} x_t] + b_f) \\ i_t &= \sigma(\mathbf{W}_i \cdot [A_{t-1,} x_t] + b_i) \\ \tilde{C}_t &= \tanh(\mathbf{W}_C \cdot [A_{t-1,} x_t] + b_C) \\ C_t &= f_t \odot C_{t-1} + i_t \odot \tilde{C}_t \end{aligned} \tag{8}$$

The outputs of these gates are combined to create an update the previous cell state to the cell state C_t via the forgetting and updating previously computed through learnt weights. The output gate is employed to control what should be output from the newly computed cell states, outputting a non-linear activation A_t to the subsequent cells.

$$\begin{aligned} o_t &= \sigma(\mathbf{W}_o \cdot [A_{t-1,} x_t] + b_o) \\ A_t &= o_t \odot \tanh(C_t) \end{aligned} \tag{9}$$

Further details of the intuition of LSTMs can be found in [18], with the above process visually depicted in FiIG. ***5*** within each of the LSTM cells.

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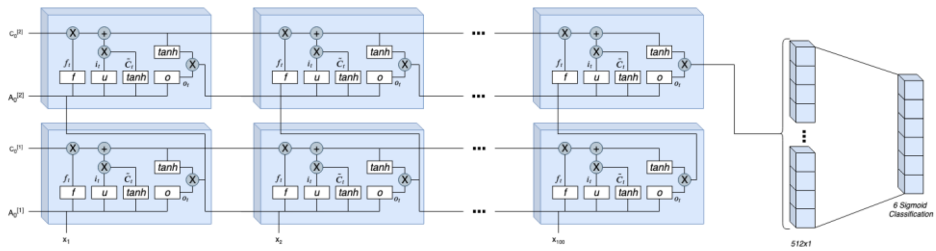

FiIG. 5. LSTM RNN architecture proposed for the classification task, outputting a 512-dimensional representational vector of the input to a 6-unit classification layer. The LSTM units take in input from the bottom, x_t, with all gates depicted in each LSTM cell.

The network proposed solely for the classification task incorporates a LSTM network comprised of 2 stacked layers. Each cell within those layers contains 512 units, outputting a 512-dimensional feature representation vector of the single sensor input for 1 second, depicted in FiIG. ***5***. This network outputs to 6 non-linear sigmoid units for the classification of the presence of individual perturbations from one detector reading. Dropout [19] of 25% drop probability, has been employed in the LSTM network regularising the effects of overfitting, setting a percentage of the unit activations to zero, limiting the networks learning capacity. The LSTM network has been trained to minimise the negative log-likelihood with respect to the parameters $\mathbf{W}$ and input x as noted in (6).

Localising vibrating fuel assemblies has been achieved employing the same core LSTM architecture as aforementioned, with the addition of a linear output layer, fully connected to the 512-dimensional representation vector for the regression of azimuthal coordinates. The training of this network has been achieved by minimizing the weighted sum of each loss per task, as to the definition in (6).

5. Experimental Results

5.2. Frequency Domain

The subsequent experiments show the results of reactor transfer function unfolding for the classification and localisation of induced perturbations given the neutron flux from simulated neutron detectors in the frequency domain from the proposed densely connected 3D CNN. The experiments have been implemented utilising the Pytorch numerical computation library trained via backpropagation, minimising the multi-task loss criterion in 4.1 with the Adam optimizer with its proposed parameters as in [20]. A batch

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size of 32 has been used, trained on an 8-core, 16-thread Intel CPU system, with 4 Nvidia 1080ti GPUs and 94GB of RAM, each model being trained 3 times and the mean and standard deviation being taken as the result.

Two experiments were conducted on the volumetric signals, the first using different sized splits of training, validation, and testing data to more appropriately represent the limited amount of data available from real plant readings, the subsequent results can be seen in Table 2. Furthermore, the results from the utilisation of detector readings from all possible voxel positions within the reactor core and only 48 in-core detectors are also shown, where the 48 in-core detectors are located corresponding to the layout of the core modelled in 0. For the latter experiment, the volumetric signals were corrupted with white Gaussian noise, as described *in Data Pre-Processing* of 0 to test the robustness of the proposed system in adverse conditions.

Table 2. Results of the proposed 3D-CNN for the classification and localisation of perturbation type and source location *(i,j,k)*. Mean and standard deviation of 3 runs.

3D-CNN Results of Classification and Localisation					
Sensors	**Train / Valid / Test (%)**	**Classification**		**Localisation**	
		Accuracy (%)	**F1-Score**	**MAE**	**MSE**
All	70 / 15 / 15	99.94 ± 0.051	0.9344 ± 0.004	0.1435 ± 0.011	0.0342 ± 0.008
48 In-Core	70 / 15 / 15	99.89 ± 0.010	0.9311 ± 0.001	0.2902 ± 0.011	0.3072 ± 0.014
48 In-Core	25 / 15 / 60	99.68 ± 0.025	0.9149 ± 0.002	0.3978 ± 0.017	0.6407 ± 0.052
48 In-Core	15 / 25 / 60	99.56 ± 0.061	0.9141 ± 0.003	0.4858 ± 0.017	0.7727 ± 0.006

The results in Table 2 show that the proposed 3D CNN models perform highly in the classification task across all testing splits, with 99.89 ± 0.010% accuracy in the best case and 99.56 ± 0.061% in the worst, respectively achieving an F1-score of 0.9311 ± 0.001 and 0.9141 ± 0.003. F1-score is an alternative measure of accuracy of prediction and target, as a function of precision and recall

$$\mathrm{F1\ Score} = 2 \times \frac{\mathrm{Precision} \times \mathrm{Recall}}{\mathrm{Precision} + \mathrm{Recall}} \tag{10}$$

where

EPJ Nuclear Sci. Technol. 5, 7 (2019)
© J.-P. Crocombette and C. Van Wambeke, published by EDP Sciences, 2019
https://doi.org/10.1051/epjn/2019003

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$$\text{Precision} = \frac{\text{True Positive}}{\text{True Positive} + \text{False Positive}} \quad \text{Recall} = \frac{\text{True Positive}}{\text{True Positive} + \text{False Negative}} \tag{11}$$

computed from the confusion matrix of predicted values of the network and true values of the data. F1-score lies within the range [0.0,1.0] where 1 is perfect precision and recall. The regression results of the perturbation source coordinates observed in Table 2 show low error was achieved, with a best case of 0.2902 ± 0.011 and 0.3072 ± 0.014 for the mean absolute error (MAE) and mean squared error (MSE) respectively. In relation to the core volume, this is approximately 4cm localisation error in an 4m x 4m x 4m reactor core utilising only 48 detectors. **Error! Reference source not found.** shows the results with the addition of singal corruption of the volumetric signals, with a worst case of 99.81 ± 0.036% accuracy, 0.9225 ± 0.002 F1-score and 0.3709 ± 0.020 MAE for classification and localisation respectively, demonstrating the robustness of the proposed approach with minimal deviation from the best performance of no corruption.

Table 3. Results of the proposed 3D-CNN for the classification and localisation of perturbation type and source location *(i,j,k)* with the corruption of input signals at SNR=3 and SNR=1.

3D-CNN Results of Classification and Localisation with the addition of noise.					
Noise	**Train / Valid / Test (%)**	**Classification**		**Localisation**	
		Accuracy (%)	**F1-Score**	**MAE**	**MSE**
No Noise	70 / 15 / 15	99.89 ± 0.010	0.9311 ± 0.001	0.2902 ± 0.011	0.3072 ± 0.014
SNR = 3	70 / 15 / 15	99.85 ± 0.006	0.9231 ± 0.001	0.3456 ± 0.016	0.4905 ± 0.011
SNR = 1	70 / 15 / 15	99.81 ± 0.036	0.9225 ± 0.002	0.3709 ± 0.020	0.5185 ± 0.017

5.2. Time Domain

Experimentation in the time domain for the unfolding of the reactor transfer function for the classification of perturbation type has been achieved via individual neutron detector measurements as described in *Data Pre-Processing* of 0. **Error! Reference source not found.** displays the results of the one second samples for the 27 scenarios of 6 perturbation settings under different SNRs of signal noise corruption. The finalised results are the mean and standard deviations of 3 training runs, trained via backpropagation with the RMSprop optimizer [20] with default settings and learning rate of 0.0001, and utilising a batch size of 64. The results show that given just 1 second readings from one neutron detector our approach can accurately classify the perturbation type with a best case of 96.41 ±

EPJ Nuclear Sci. Technol. 5, 7 (2019)
© J.-P. Crocombette and C. Van Wambeke, published by EDP Sciences, 2019
https://doi.org/10.1051/epjn/2019003

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0.021% accuracy, the addition of noise has shown that although performance degrades, the system is robust given such minimal data input.

Table 4. Classification of perturbation type in the time domain under differing levels of input signal noise corruption from induvial detector inputs.

LSTM Classification Results		
Noise	**Accuracy (%)**	**F1-Score**
Clean Signal	96.84 ±0.491	0.9342 ±0.003
SNR = 10	91.88 ±0.254	0.8107 ±0.007
SNR = 5	88.87±0.279	0.7469 ±0.006

Localisation of vibrating fuel assembly source takes a similar approach utilising the same training procedure except for the minimisation criterion, replacing with the multi-task loss in (6). Additionally, all 56 detectors have been utilised – compared to the previous experiment of individual detectors – to obtain spatial information between the detectors to infer the perturbing fuel assembly location. Corrupting the signals with white Gaussian noise has also been applied to test the robustness of the proposed approach, the resulting error of localisation can be seen in **Error! Reference source not found.**. Localisation in the time domain has been achieved with low localisation error with a worst case of 1.2304 ± 0.102 and 3.2340 ± 0.612 under SNR=1, and a best of 1.0737 ± 0.006 and 2.3682 ± 0.065 for MAE and MSE respectively.

Table 5. Localisation of the coordinates of a vibrating fuel assembly *(i,j)*, in the time-domain utilising the proposed LSTM architecture, under input signal corruption. Mean and standard deviation of 3 runs.

LSTM Classification and Localisation Results				
Noise	**Classification**		**Localisation**	
	Accuracy (%)	**F1-Score**	**MAE**	**MSE**
Clean Signal	99.89 ±0.396	0.9976 ±0.003	1.0737 ±0.006	2.3682 ±0.065
SNR = 3	99.87 ±0.032	0.9980 ±0.001	1.1191 ±0.008	2.7316 ±0.006
SNR = 1	99.46 ±0.318	0.9962 ±0.004	1.2304 ±0.102	3.2340 ±0.612

6. Conclusions and Future Work

This work proposed an extended approach to the unfolding of reactor transfer functions for the classification and localisation of reactor core perturbations from neutron detector readings produced by simulated core models. The proposed models accurately classify perturbation types and

EPJ Nuclear Sci. Technol. 5, 7 (2019)
© J.-P. Crocombette and C. Van Wambeke, published by EDP Sciences, 2019
https://doi.org/10.1051/epjn/2019003

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source locations in the time and frequency domain, with extended and more complex simulated perturbation scenarios than previous work [11,12]. Our approach outperforms previous approaches for the same task localising such perturbations to a finer voxel mesh and with fewer detectors available, i.e. 48 in-core detectors for a 32x32x34 core volume.

Our experiments further solidify the applicability and capability of deep learning approaches in the domain of nuclear reactor anomaly detection, specifically for the non-trivial task of reactor transfer function unfolding given very spare neutron flux detector readings. We will continue to extend our approaches to localising and classifying large combinations of perturbations simultaneously. Furthermore, investigations will be made to apply our model to real plant data providing further validation of the capability of our approach for on-line anomaly detection.

Acknowledgements

*The research conducted was made possible through funding from the Euratom research and training programme 2014-2018 under grant agreement No 754316 for the **'CORe Monitoring Techniques and EXperimental Validation and Demonstration (CORTEX)' Horizon 2020 project**, 2017-2021. We would like to thank the Chalmers University of Technology, particularly Dr C. Demaziere, Dr P. Vinai, Dr A. Milonakis and the Paul Scherrer Institute, particularly Dr A. Dokhane and Dr V. Verma for providing the frequency and domain data respectively, for assisting us with their understanding and for collaborating with us in the analysis process.*

References

[1] C. Demazière et al., Overview of the CORTEX project, Proc. Int. Conf. Physics of Reactors – Reactor Physics paving the way towards more efficient systems (PHYSOR2018), Cancun, Mexico, April 22-26, 2018 (2018).
[2] D. Rolnick, et al. Tackling Climate Change with Machine Learning. arXiv preprint arXiv:1906.05433, (2019).
[3] F.C. Chen, and M.R. Jahanshahi, N NB-CNN: deep learning-based crack detection using convolutional neural network and Naïve Bayes data fusion. IEEE Transactions on Industrial Electronics, 65(5), pp. 4392-4400 (2017).
[4] W. Li, et al., Design of comprehensive diagnosis system in nuclear power plant. Ann. Nucl. Energy, 109, pp. 92-102, (2017).
[5] M.C. dos Santos, et al., Deep rectifier neural network applied to the accident identification problem in a PWR nuclear power plant Ann. Nucl. Energy, 133, pp.400-408, (2019).
[6] R.M. Ayo-Imoru, and A.C. Cilliers, Continuous machine learning for abnormality identification to aid condition-based maintenance in nuclear power plant. Ann. Nucl. Energy, 118, pp.61-70, (2018).
[7] S. Zaferanlouei, et al., Prediction of critical heat flux using anfis. Ann. Nucl. Energy, 37(6), pp. 813–821, (2010).

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https://doi.org/10.1051/epjn/2019003

Available online at:
https://www.epj-n.org

[8] S.A. Hosseini, and I.E.P. Afrakoti, Neutron noise source reconstruction using the adaptive neuro-fuzzy inference system (anfis) in the vver-1000 reactor core. Ann. Nucl. Energy, 105, pp. 36–44, (2017).
[9] S.A. Hosseini, and I.E.P. Afrakoti, Evaluation of a new neutron energy spectrum unfolding code based on an Adaptive Neuro-Fuzzy Inference System (ANFIS). Journal of radiation research, 59(4), pp.436-441, (2018).
[10] F. Calivà F et al., A deep learning approach to anomaly detection in nuclear reactors. Proc. 2018 Int. Joint Conf. Neural Networks (IJCNN2018), Rio de Janeiro, Brazil, July 8-13, 2018 (2018).
[11] F. De Sousa Ribeiro et al., Towards a deep unified framework for nuclear reactor perturbation analysis. Proc. IEEE Symposium Series on Computational Intelligence (SSCI 2018), Bengaluru, India, November 18-21, (2018).
[12] C. Demazière, Core sim: a multi-purpose neutronic tool for research and education. Ann. Nucl. Energy, 38(12):2698–2718, (2011).
[13] C. Demazière, User's manual of the core sim neutronic tool. Technical report, Chalmers University of Technology, (2011).
[14] G. Grandi, et al. Simulate-3k models and methodology. SSP-98013, 6, (2006).
[15] Y. LeCun, et al., Generalization and network design strategies. Connectionism in perspective, pp. 143–155, (1989).
[16] G. Huang, et al., Densely connected convolutional networks. Proc. IEEE Conf. on computer vision & pattern recognition, Honolulu, Hawaii, USA, July 22-26, 2017 (2017).
[17] M. Lin, et al., Network in Network. arXiv preprint arXiv:1312.4400, (2013).
[18] S. Hochreiter, and J. Schmidhuber, Long short-term memory. Neural computation, 9(8), pp. 1735–1780, (1997).
[19] N. Srivastava, et al., Dropout: a simple way to prevent neural networks from overfitting. The journal of machine learning research, 15(1), pp. 1929-1958, (2014).
[20] D.P. Kingma, and J. Ba, Adam: A method for stochastic optimization. arXiv preprint arXiv:1412.6980, (2014).

Cite this article as: Jean-Paul Crocombette, Christian Van Wambeke, Quick calculation of damage for ion irradiation: implementation in Iradina and comparisons to SRIM, EPJ Nuclear Sci. Technol. 5, 7 (2019)

EPJ Nuclear Sci. Technol. 5, 7 (2019)

https://doi.org/10.1051/epjn/2019003

Available online at:
https://www.epj-n.org

Stability studies of GANEX system under different irradiation conditions

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Abstract

To demonstrate the robustness of extraction systems against radiolytic degradation is nowadays one of the limiting points to ensure a safe and stable operation for advanced nuclear fuel strategies. In this paper, is addressed the stability of one of most promising extractants (TODGA, N,N,N´,N´-tetraoctyldiglycolamide) but also the importance of designing realistic model to simulate and study the degradation of the systems. For that, new irradiations experiments were carried out where mixture between phases and the oxygen content have been taken into account. Extraction behaviour and composition of the organic phases after γ-irradiation have been measured and compared. Although TODGA studies are applicable to many processes currently under development, this work is focus on Grouped Actinides Extraction (GANEX) process development.

1. Introduction

In the development of more sustainable nuclear fuel cycle options, a future potential scenario involves the transition from thermal reactors to fast reactors with a closed fuel cycle to recycle actinide elements. Due to that, currently two actinides recycling scenarios are considered: the heterogeneous recycling of using a modified version of the PUREX process [1] followed by SANEX type process (Selective Actinides Extraction) [2]; and the homogeneous recycling of all actinides together, the named as GANEX concept (Grouped Actinide Extraction) [3].

The development and applicability of these extraction processes are limited by safety issues related to the resistance to radiation because they must work in continue operation in the recycling plant. For that reason, extractants like the diglicolamide TODGA (N,N,N´,N´-tetraoctyldiglycolamide), which shows promising extraction properties and a good resistant to radiation, are being used widely for these applications [1-7].

GANEX concept involves an initial U recovering (using the monoamide DEHiBA in total petroleum hydrocarbons (TPH) diluent) followed by the separation of all transuranium elements (TRU) [5]. One of the candidate

EPJ Nuclear Sci. Technol. 5, 7 (2019)
© J.-P. Crocombette and C. Van Wambeke, published by EDP Sciences, 2019
https://doi.org/10.1051/epjn/2019003

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options for the second step of GANEX concept is the so called Euro-GANEX process, where actinides and lanthanides are co-extracted from the first raffinate into an organic phase containing TODGA (N,N,N´,N´-tetraoctyldiglycolamide) and the malonamide DMDOHEMA (N,N′-dimethyl-N,N′-dioctylhexyloxyethyl malonamide) as phase modifier to increase the Pu loading capacity. From this loaded organic phase, all TRU are stripped by using a mixture of SO_3-Ph-BTP (2,6-bis(5,6-di(sulphophenyl)-1,2,4-triazin-3-yl)pyridine) and AHA (acetohydroxamic acid) [6].

Many efforts have been done in the last years to study the stability of the most relevant molecules involved in this promising process (TODGA, DMDOHEMA, SO_3-Ph-BTP, etc) [7-8]; and particularly those that are in the organic phase, expected to be recycled, like TODGA and DMDOHEMA. Nevertheless, the results are not always consistent neither comparable due to the different experimental conditions chosen. e.g., TODGA has been studied by many authors [7-11] but some authors are still discussing about the effect of nitric acid, degradation compounds formed or degradation pathways.

Sugo et al. [9] performed quantitative and qualitative studies on the radiolytic degradation of TODGA in different conditions of diluents but always irradiating only the organic phase, and they found that the G value was strongly dependent on both initial concentration and also on the solvent. Galán et al. [7] studied the radiolytic stability of TODGA solvents pre-equilibrated with 3 mol/L HNO_3 varying the composition of diluents with octanol, and they found an important decrease of its concentration, especially when TODGA is not pre-equilibrated with HNO_3. From their results, they reported that HNO3 has a protective role of TODGA during the irradiation. However, others authors such as Modolo et al. [10] and Zarzana et al. [11] concluded that the presence of the acidic aqueous phase has no obvious effect on the dose rate (d) when irradiation is performed in kerosene or dodecane. Moreover, Bruce J. Mincher [13] explains also that TODGA dose rate seems to be insensitive to the presence or absence of aqueous phases, by varying acidity and/or oxygen concentration flow during irradiation in dodecane. However must be highlighted that all experiments performed by Modolo et al. [10], Zarzana et al. [11] and Mincher et al. [13] were performed in non-polar diluents such us kerosene or dodecane where nitric acid is minimum extracted.

In addition to these studies, Peterman et al. [12] performed quantitative studies of TODGA samples irradiated in contact with HNO_3 but also in contact with SO_3-Ph-BTP aqueous phase, in static and in dynamic conditions. They concluded that the stability of TODGA and SO_3-Ph-BTP, and the general performance of the system depends strongly on the simulation of irradiation process conditions. Under their conditions the TODGA/SO_3-Ph-BTP system kept the original performance; in contrast with

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© J.-P. Crocombette and C. Van Wambeke, published by EDP Sciences, 2019
https://doi.org/10.1051/epjn/2019003

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results observed by Galán et.al [8], where the irradiation of SO3-Ph-BTP in HNO3 gave place to a degradation of 90% after 200 kGy.

Given the differences found in the literature about the radiolytic degradation of main molecules involved in Euro-GANEX process, the aim of this work is looking for the process-relevant conditions should be simulated to achieve reliable degradation models to ensure a safe and stable operation in nuclear fuel reprocessing plants. And for that, it has been explored how and why the experimental conditions affect to the ligand stability and proportions of by-products formed during irradiation. Particularly, this work shows the first studies to determinate the conditions to simulate the degradation of the organic phase from the point of view of the key step of Euro-GANEX process, the TRU stripping step. In that sense, it has been submitted to γ-irradiation samples of 0.2 mol/L TODGA in OK (odourless Kerosene) in contact with 0.5 mol/L nitric acid under different conditions. For an easy understanding of the parameters involved and a first approach to Euro-GANEX solvent, the phase modifier DMDOHEMA has been removed from the solvent. Both phases have been irradiated under a) normal air atmosphere; b) Argon atmosphere; and c) using an air sparging flow (to increase the contact between phases and the content of oxygen) conditions. After irradiation, the performance and composition of the systems have been analysed by gamma spectrometry and LC-MS respectively.

2. Experimental

2.1. Chemicals, solutions and isotopes

TODGA was synthesised at CIEMAT modifying an existing literature procedure under air and without drying solvent and glassware [14, 15]. SO_3-Ph-BTP was purchased in Technocomm Ltd. Degradation compounds I-VI have been obtained as described in previous studies [7]. The diluents were odourless kerosene (OK), purity 98%, from Alfa Aesar. All reagents were used from commercially available sources without further purification. Nitric acid, HNO_3, purchased form VWR Chemical was purified by Quartz sub-boiling distillation system (MLS-Milestone) and solutions were prepared by diluting concentrated nitric acid (65%) with ultrapure water (18 MΩ/cm). The radioactive tracer solutions of ^{241}Am(III) and ^{152}Eu(III), were obtained as MCl_3, in HCl 1 mol/L, by Isotope Products Laboratories, California (USA).

2.2. Irradiation procedure

Irradiation experiments of the different samples were performed in the Náyade irradiation facility (CIEMAT) described in detail elsewhere (Náyade facility [16]). This facility consists in a 1.2 m^2 by 4.5 m pool with 60 sources

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https://doi.org/10.1051/epjn/2019003

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of ^{60}Co, distributed in six lots with a total activity of $1.1 \cdot 10^{14}$ Bq. The irradiation container used provides homogeneous irradiation flux.

Different samples of TODGA (0.2 mol/L in OK) in contact with 0.5 mol/L HNO_3 were irradiated in glass vessels up to doses of 200 and 500 kGy at dose rates of 4.02 kGy/h, as determined by Fricke dosimetry. Samples under air atmosphere and Argon were irradiated in sealed glass vessels and for aerated samples an air sparging flow was employed. Extraction experiments (see below) using the irradiated organic phases were performed immediately after the last step of irradiation. Reference samples were kept in the laboratory during the irradiation process for control.

2.3. Extraction experiments

Extraction experiments were performed using 0.5 mL of fresh and irradiated organic phases (0.2 mol/L TODGA + in kerosene) and 0.5 mL of fresh aqueous phase (18 mmol/L SO_3-Ph-BTP in 0.5 mol/L HNO_3), spiked with 10 µL of ^{241}Am(III) and ^{152}Eu(III) in 0.5 mol/L HNO_3 (1 kBq/mL each). The phases are mixed 30 min, and after centrifugation, 0.3 mL of organic and aqueous phases were taken to for analysis of ^{241}Am and ^{152}Eu activities by gamma spectrometry. Canberra HPGe detector were used for high energy gamma spectrometry measurements, using Genie-2000 as gamma analysis software from Canberra, and gamma characteristic photopeak at 59.5 keV and 121.8 keV were analyzed for ^{241}Am and ^{152}Eu, respectively. The results are reported as distribution ratios D (DM = $[M^{3+}]_{org}/[M^{3+}]_{aq}$).

2.4. HPLC measurements

The chemical composition of the irradiated organic samples was characterised by HPLC-MS. HPLC measurements were performed by using an HPLC-MS Bruker EVOQTM (Triple Quadrupole detector) with a ACE 3 C18-PFP column (50 mm x 2.1 mm) at 40°C, using a gradient of mobile phase [(A: 0.1% HCOOH in H_2O), (B: 0.1% HCOOH in CH_3CN)]. The ionisation modes $APCI^+$ and ESI^+ were used for TODGA and TODGA degradation compounds (DC's) quantification, respectively. Samples for HPLC studies were analysed without pre-evaporation and diluted 1:30000 in HPLC grade MeOH. Calibration curves were performed by HPLC-MS for TODGA (10-1000 ppb) and each degradation compound of TODGA (1-250 ppb) and the correlation coefficient in all cases were in the range of 0.993-0.999. All measurements were repeated twice.

3. Results and discussion

The organic solvent selected as a simplified Euro-GANEX solvent (0.2 mol/L of TODGA in OK) in contact with 0.5 mol/L HNO_3 were irradiated up to 200 and 500 kGy with external ^{60}Co sources as described above. After

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https://doi.org/10.1051/epjn/2019003

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irradiation, the An stripping efficiency of the different irradiation models designed was analysed by the Ln/An distribution ratio measurements. Fresh and irradiated organic phases were contacted with the corresponding aqueous phase of Euro-GANEX system (18 mmol/L of SO_3-Ph-BTP in 0.5 mol/L HNO_3) and spiked with Am(III) and Eu(III). The evolution of the distribution ratio versus dose (Figure 1) shows a slightly reduction of DAm(III) and DEu(III) for all samples when the dose was higher than 500 kGy as could be expected from the previous TODGA stability studies. [10] In these experiments, aqueous phases containing SO_3-Ph-BTP were not irradiated, therefore their ability to keep An in the aqueous phases (DAm<<1) is not affected and the reduction of DAm as function of the dose is only attributed to the degradation of TODGA in the organic phase. Even so, the separation factor between Am(III) and Eu(III) is kept invariable in all chosen experimental conditions.

Regarding the different proposed irradiation experiments (air, Argon atmosphere and air sparging), only small differences in the distribution ratio of both metals were observed. These results pointed out that the different irradiation conditions could not affect considerably to the extraction properties of the studied system.

These results are in a good agreement with TODGA stability studies [7, 9, 10] where no significant changes in the Am and Eu distribution ratio at high irradiation dose were observed. According to these results, TODGA is hardly degraded by the radiation effect. However, TODGA systems are able to keep the An/Ln distribution ratio even after a high degradation due to some degradation products have good extraction properties maintaining the good extraction properties of the system until higher doses. Therefore, distribution ratios themselves should not be used as the only metric for ligand degradation.

Quantitative HPLC-MS measurements of TODGA have been carried out for a better understanding of results. Figure 2 shows concentrations of TODGA as function of the dose for the three experimental conditions used: air, Argon and air sparging. TODGA concentration decreases as function of doses in the same way when two phases were not mixed, just contacted (samples without sparging), they halved after 500 kGy. However, applying an air flow sparging, it means increasing the oxygen content and mixing between phases, there was a higher reduction of the concentration, 70% loss after 500 kGy. The small differences in the distributions ratios observed in Figure 1 could partially be now explained by the higher TODGA degradation in samples irradiated with air sparging. However, a complete characterization of the organic phases implies the identification and quantification of all those new species formed due to radiation. For that reason, to identify the degradation products formed during the irradiation,

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the composition of samples has been qualitative and quantitatively analysed and compared by HPLC-MS.

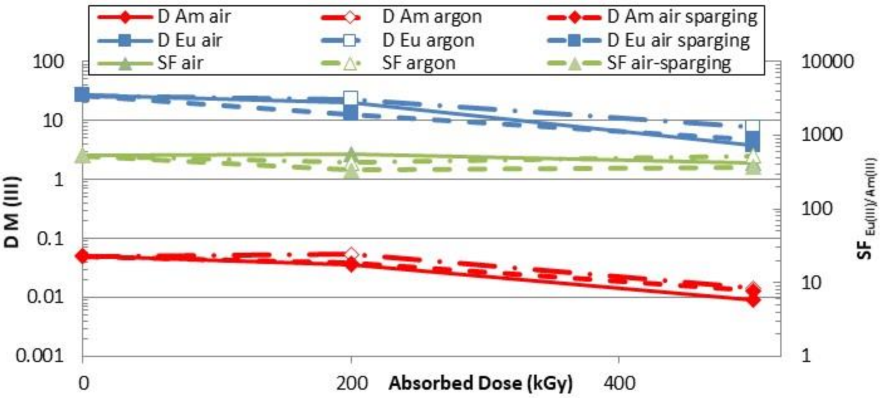

FIG. 17. Distribution ratios of Am(III) and Eu(III) as function of dose and the different irradiation conditions of the organic phase: air, Argon and air sparging. Organic phases: fresh or irradiated 0.2 mol/L TODGA in OK. Aqueous phases: fresh 18 mmol SO3-Ph-BTP in 0.5 mol/L HNO_3. Spiked with ^{241}Am(III) and ^{152}Eu(III) (1 kBq/mL each).

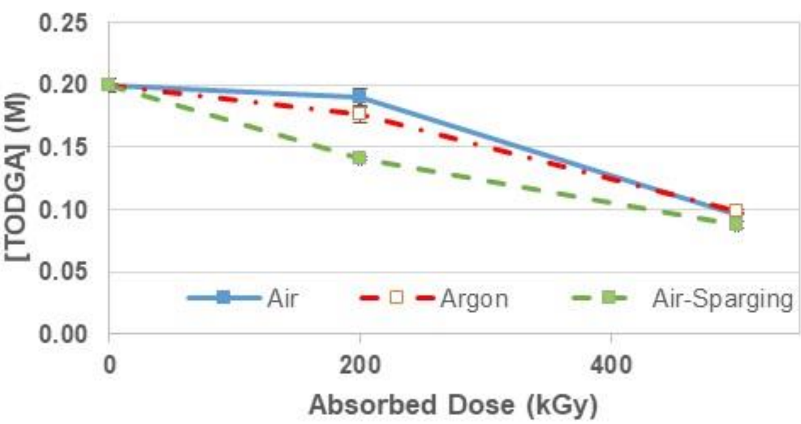

FIG. 18 Concentration of TODGA as function of the dose for 0.2 mol/L TODGA irradiated in contact 0.5 mol/L HNO_3.

Figure 3 shows qualitative HPLC-MS chromatograms of a fresh TODGA solvent and irradiated solvents up to 500 kGy in contact with HNO3 under different experimental conditions. In TODGA reference system (0 kGy), DCs

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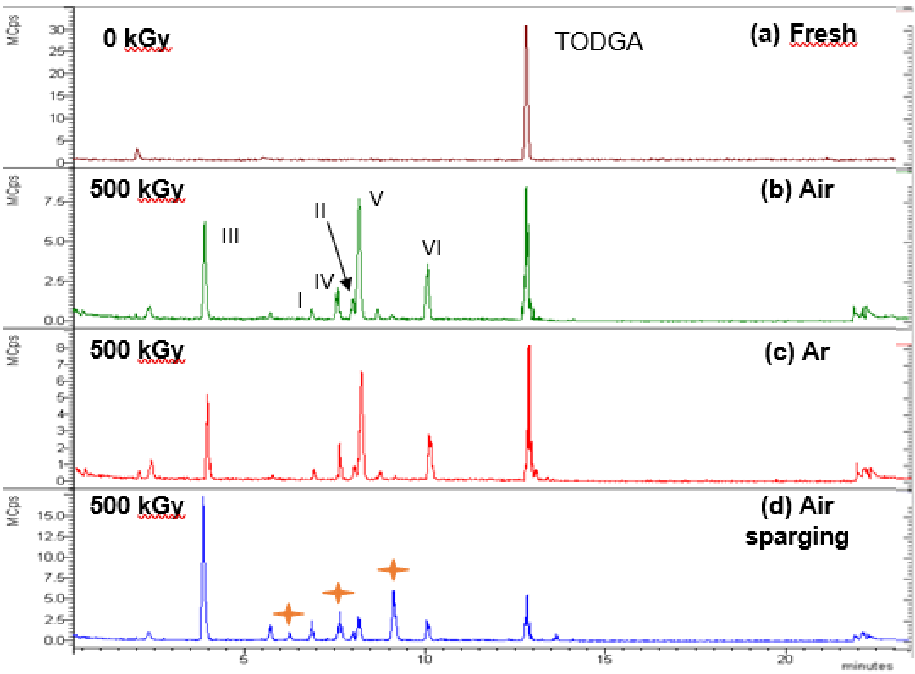
have not been observed (Figure 3a). Results observed for TODGA systems irradiated up to 500KGy in presence of air and Argon atmosphere (Figure 3b and Figure 3c) are in agreement with the literature [7, 9, 17], 9 typical TODGA DCs and in the expected proportion were identified (Figure 4). However, in the irradiated system using an air flow sparging (Figure 3d) different proportions of TODGA DCs and new signals corresponding to three possible unidentified TODGA DCs (m/z = 434.1, r.t = 6.26 min; m/z = 476.1, r.t = 7.66 min; and m/z = 518.1, r.t = 9.13 min) have been detected. Therefore, air sparging flow changes the dominant degradation pathway due to different proportion of DCs and new possible unidentified TODGA DCs are observed. This fact should be taken into account in future stability studies for process development.



(a) Fresh

FIG. 19. HPLC-MS chromatograms of TODGA solvents a) fresh as reference material, b) in presence of air irradiated up to 500 kGy, c) in presence of Argon irradiated up to 500 kGy and d) air flow sparging irradiated up to 500 kGy all of them in contact with 0.5 mol/L HNO_3.

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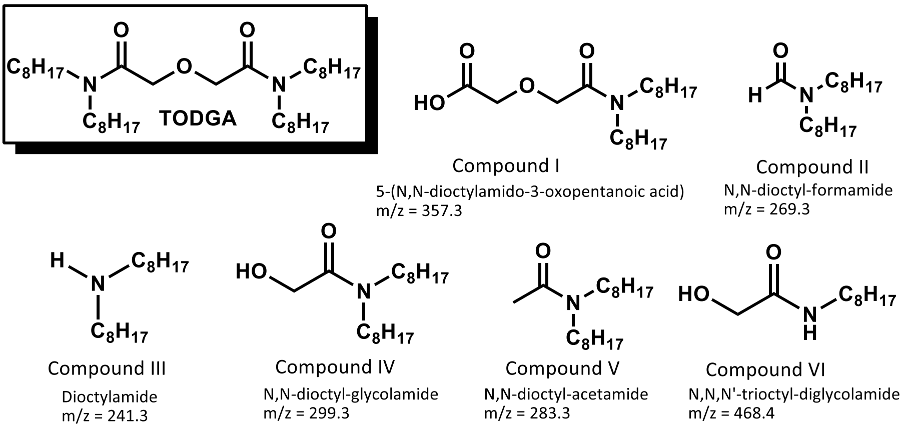

FIG. 20. Structures of TODGA and its main radiolytic degradation products.

Figure 5 shows the plausible structures assigned to the signals analysed by HPLC-MS for the new possible TODGA DCs, corresponding to m/z 518 and 476 respectively. Anyhow, deepest studies are needed to corroborate these hypothetical structures as TODGA degradation compounds.

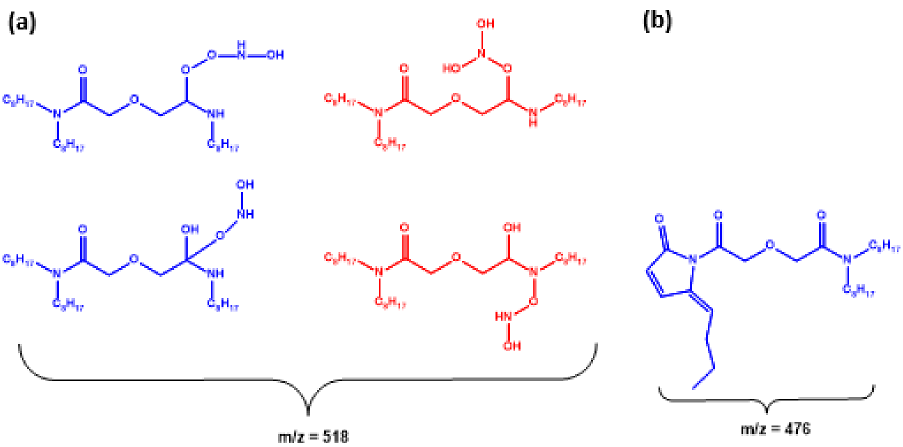

FIG. 21 Hypothetical structure of new possible TODGA degradation compounds corresponding to a) m/z 518 and b) m/z 476.

To assess the different proportions of TODGA DCs identified in the Figure 3, the quantification of the 6 main known DCs (I-VI) observed by HPLC-MS

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was carried out. Calibration curves were performed by HPLC-MS for each TODGA DCs and the concentration of all of them was calculated.

It is known that the weakest bonds of TODGA due to the radiation effect are C-O and N-C [7, 9, 11, 17], giving place to DC IV, V and VI. As it can be expected, after 200 kGy the TODGA degradation is not relevant and therefore the difference in DCs formed are negligible. However, after 500 kGy, where 50% of the initial TODGA concentration has been degraded, it can be observed different results between samples irradiated in contact (air and Argon atmosphere) and those mixed by air flow sparging. Data show that the concentration of DCs I and III increased, it means the rupture of N-CO bonds is higher; meanwhile there is a reduction in the concentration of CDs V and VI (Figure 4). When TODGA is degraded by C-O bond, the concentration of DCs IV and V should be similar, but DC IV can be also broken into DC V due to the effect of radiolysis. Therefore, the reduction observed for DC V could be attributed to oxidations or recombination that it has not been identified yet. The new proposed degradation compounds are identified when there is a higher oxygen content in the system, and it could be formed by oxidative conditions. This oxidative condition could explain why it has been observed a reduction in the concentration of CD VI to favour the formation of compounds I and III, but also, they are in good agreement with a higher oxidation of DC III when air sparging condition is used.

As can be seen in Figure 2, air flow increases TODGA degradation after 500 kGy, although differences are not too important to the performance of the system it is compared with the other conditions employed. In fact, those differences are not reflected in the behaviour of the system since samples irradiated with air sparging shows a similar DEu(III) for the three model of irradiation tested at 500 kGy (Figure 1), continue showing an excellent separation of actinides and lanthanides in the conditions employed. However, the different proportion of DCs formed using air sparging condition is a very important observation because the different DCs and their accumulations could affect the extraction properties of the system in the long term, due to its individual extraction properties.

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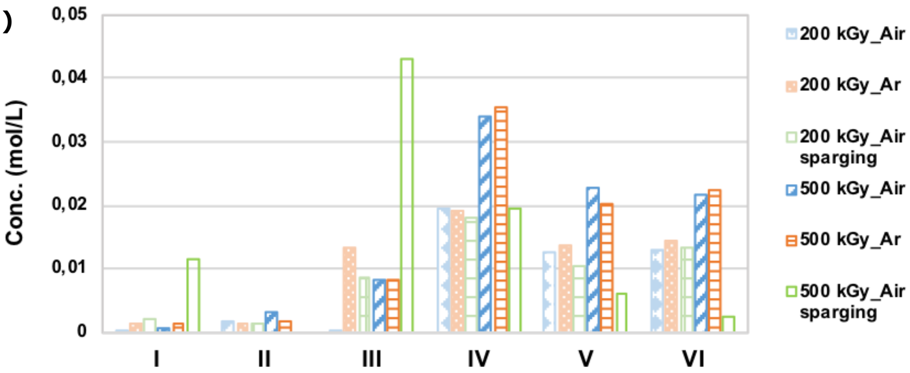

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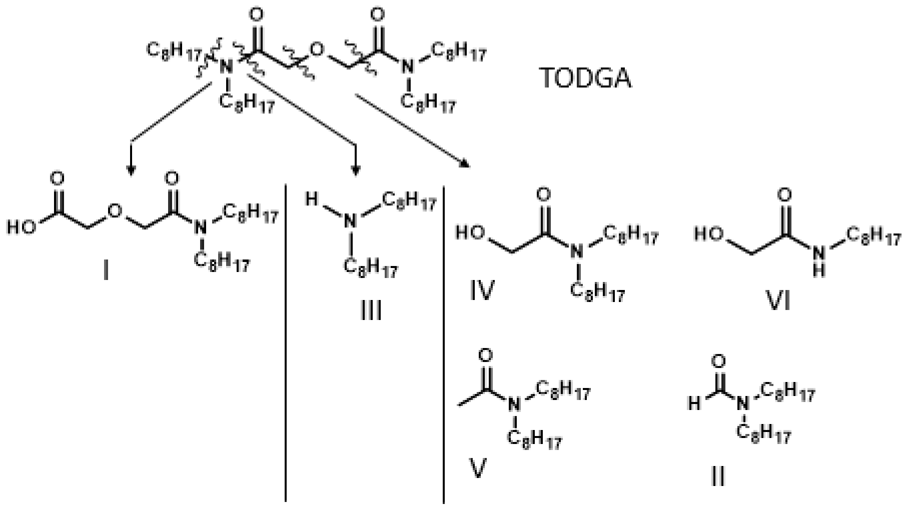

FIG. 22 a) HPLC-MS quantitative studies of different TODGA degradation compounds at different experimental conditions: air, Argon, air sparging for 0.2 mol/L TODGA in OK irradiated in contact with 0.5 mol/L HNO_3. b) Structure of TODGA and its radiolytic pathway to produce DCs I, III, IV, V and VI.

As can be seen in Figure 2, air flow increases TODGA degradation after 500 kGy, although differences are not too important to the performance of the system it is compared with the other conditions employed. In fact, those differences are not reflected in the behaviour of the system since samples irradiated with air sparging shows a similar DEu(III) for the three model of irradiation tested at 500 kGy (Figure 1), continue showing an excellent separation of actinides and lanthanides in the conditions employed. However, the different proportion of DCs formed using air sparging

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condition is a very important observation because the different DCs and their accumulations could affect the extraction properties of the system in the long term, due to its individual extraction properties.

4. Conclusions

The effects of ^{60}Co γ-radiation on TODGA-based solvents under different irradiation conditions to reach realistic model of radiolysis simulations by experiments as simple as possible have been investigated. Direct radiolysis of extractants is much less statistically probable than its indirect radiolysis through diluents, which are more abundant in solution. For that reason, the oxygen content and the present of radicals from water radiolysis have been selected as the experimental conditions to explore the degradation of TODGA in contact with HNO_3. For that, experiments under air or Argon atmosphere, and using an air sparging flow to increase the mixture between phases have been analysed. The results for a simplify GANEX system after a moderate dose, 500 kGy, show that organic TODGA-solvent maintained the separation between actinides and lanthanides in all cases. However, in the case of experiments performed in presence of air flow sparging, TODGA concentration decreased to 70% of the initial concentration, as result of a higher degradation than experiments performed under air and Argon atmosphere where phases were not mixed, just contacted (50%).

Moreover, from qualitative studies performed by LC-MS, the expected 9 TODGA DCs were observed in all irradiation studied of this work. Besides, it has been observed the presence of new possible TODGA DCs when air sparging was used, pointing out to a change in the degradation pathway. The quantification of the TODGA known DCs confirmed this hypothesis. When air was bubbled, compounds form due to N-CO bond rupture increased their concentration, DCs I and III; meanwhile a reduction in the concentration of CDs V and VI was observed.

These results illustrate that an Argon atmosphere has the same effect on TODGA-solvent in static irradiation conditions as air atmosphere. Changes observed by using an air sparging flow could be due to a higher content of oxygen, since oxygen is reacting into the radiolysis process, but also due to the presence of radicals produced from water radiolysis. Hence, from the point of view of TODGA-solvent, Euro-GANEX stability studies should be performed by simulating both phases by increasing contact between them. In this work we have learned that extended studies are necessary to going on to the identification of the relevant process conditions for a realistic simulation of long-term behaviour of advanced nuclear fuel extraction systems.

Acknowledgements

This work has been developed under the framework of the European GENIORS Project (Contract n: 730227) and CIEMAT-ENRESA collaboration agreement (SOPSEP project, Contract n: 0079000269).

References

[1] Taylor, R., "Reprocessing and recycling of spent nuclear fuel". Ed. Elsevier. 2015

[2] Wilden, A., et al. "Laboratory-scale counter-current centrifugal contactor demonstration of an innovative-SANEX process using a water soluble BTP." Solvent Extraction and Ion Exchange 33.2 (2015): 91-108.

[3] Adnet, J. M, et al. "Development of new hydrometallurgical processes for actinide recovery: GANEX concept." Proceedings of GLOBAL. 2005.

[4] Whittaker, D., et al. "Applications of diglycolamide based solvent extraction processes in spent nuclear fuel reprocessing, part 1: TODGA." Solvent Extraction and Ion Exchange 36.3 (2018): 223-256.

[5] Bell, K., et al. "Progress towards the development of a new GANEX process." Procedia Chemistry 7 (2012): 392-397.

[6] Taylor, R., et al. "The EURO-GANEX process: current status of flowsheet development and process safety studies." Procedia Chemistry 21 (2016): 524-529.

[7] Galán, H., et al. "Radiolytic stability of TODGA: characterization of degraded samples under different experimental conditions." Procedia Chemistry 7 (2012): 195-201.

[8] Galán, H., et al. "Stability and recyclability of SO3-Ph-BTP for i-SANEX process development." Proc. Internat. Solvent Extr. Conf.(ISEC 2014). 2014.

[9] Sugo, Y., Sasaki Y., and Tachimori, S. "Studies on hydrolysis and radiolysis of N, N, N′, N′-tetraoctyl-3-oxapentane-1, 5-diamide." Radiochimica Acta 90.3 (2002): 161-165.

[10] Modolo, G., et al. "Development of a TODGA based process for partitioning of actinides from a PUREX raffinate Part I: Batch extraction optimization studies and stability tests." Solvent Extraction and Ion Exchange 25.6 (2007): 703-721.

[11] Zarzana, C. A., et al. "A comparison of the γ-radiolysis of TODGA and T (EH) DGA using UHPLC-ESI-MS analysis." Solvent Extraction and Ion Exchange 33.5 (2015): 431-447

[12] Peterman, D., et al. "Performance of an i-SANEX system based on a water-soluble BTP under continuous irradiation in a γ-radiolysis test loop." Industrial & Engineering Chemistry Research 55.39 (2016): 10427-10435.

[13] Mincher, B. J. "The effects of radiation chemistry on radiochemistry: when unpaired electrons defy great expectations." Journal of Radioanalytical and Nuclear Chemistry 316.2 (2018): 799-804.

[14] Horwitz, E. P., et al. "Novel extraction of chromatographic resins based on tetraalkyldiglycolamides: characterization and potential applications." Solvent extraction and ion exchange 23.3 (2005): 319-344.

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Available online at:
https://www.epj-n.org

[15] de Mendoza J., Durana A., Camafort B., Espartero, A.G., Galán H., Núñez A. TODGA Industrial Scale-Up Report ACSEPT FP7-CP-2007-211 267; 2009.
[16] http://fusionwiki.ciemat.es/wiki/LNF:Technology#NAYADE_Co-60_irradiation_facility
[17] Mincher, B. J., Modolo G., and Mezyk S. P.. "The effects of radiation chemistry on solvent extraction 3: a review of actinide and lanthanide extraction." Solvent Extraction and Ion Exchange 27.5-6 (2009): 579-606.

Cite this article as: Jean-Paul Crocombette, Christian Van Wambeke, Quick calculation of damage for ion irradiation: implementation in Iradina and comparisons to SRIM, EPJ Nuclear Sci. Technol. 5, 7 (2019)

A FREQUENCY-DOMAIN REACTOR NEUTRON NOISE SIMULATOR BASED ON A DISCRETE ORDINATES METHOD

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Abstract

The neutron flux measured in a nuclear reactor is characterized by fluctuations around a main trend. These fluctuations are known as reactor neutron noise, and they may allow to identify anomalies in the reactor core. In this context the CORTEX – COre monitoring Techniques and EXperimental validation and demonstration project, supported by the European Commission, aims at studying reactor neutron noise induced by different types of perturbations (e.g. vibrations of reactor components), and developing core monitoring techniques from the analysis of reactor neutron noise.

When simulating reactor neutron noise, the reactor transfer function is needed. The reactor transfer function describes the system response to possible perturbations, and it can be modelled with the neutron transport equation. Most of the past work in this area relies on neutron diffusion theory. However, recent efforts focus on advanced computational capabilities that can provide more detailed insights into neutron noise problems and be used to assess the limitations of the diffusion approach.

In the CORTEX project, Chalmers University of Technology is building a neutron noise simulator with a high-order approximation of the neutron transport equation. The equations are discretized according to a finite difference scheme for the spatial variable, a discrete ordinates approximation for the angle, and a multi-group formalism for the neutron energy. The simulation consists of two steps. The first step solves the criticality problem and calculates the static neutron flux. The second step determines the neutron noise in the frequency domain with respect to the prescribed neutron noise source and the static neutron flux previously estimated.

The numerical solution of the equations is obtained from an iterative procedure. This is a computationally intensive task because a converged solution may require a very large number of iterations. A crucial factor in the reduction of the iterations is the implementation of a technique for the acceleration of the algorithm. For static calculations, methods such as the Diffusion Synthetic Acceleration (DSA) have been widely investigated. To some extent, these techniques have also been applied to time-dependent problems. On the other hand, no study on acceleration of neutron noise calculations in the frequency domain have been reported in the open literature. The current work also explores the extension of DSA method to the case of frequency-domain neutron noise simulations.

The convergence rate of the algorithm is investigated. The numerical performance agrees well with the results of the theoretical Fourier analysis. The study of the convergence also shows the acceleration effect obtained from the DSA method in the neutron noise calculations.

Results from the simulation of a localized neutron noise source based on a heterogeneous two-dimensional configuration is also presented. The system response to the perturbation follows a point-kinetic behavior, which is expected as the size of the simulated system is relatively small.

FISA 2019 PROJECT AWARD

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© J.-P. Crocombette and C. Van Wambeke, published by EDP Sciences, 2019
https://doi.org/10.1051/epjn/2019003

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SESAME Project: Advancements in Liquid Metal Thermal Hydraulics Experiments and Simulations

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Abstract

Liquid metal cooled reactors are envisaged to play an important role in the future of nuclear energy production because of their possibility to use natural resources efficiently and to reduce the volume and lifetime of nuclear waste. Sodium and Liquid lead (-alloys) are considered the short and long term solution respectively, as coolant in GEN-IV reactor. Thermal-hydraulics of liquid metals plays a key role in the design and safety assessments of these reactors. Therefore, this is the main topic of a large European collaborative program (the Horizon 2020 SESAME) sponsored by the European Commission. This paper will present the progress in the project with respect to liquid metal cooled reactor thermal-hydraulics (liquid metal heat transfer, fuel assembly thermal-hydraulics, pool thermal-hydraulics, and system thermal-hydraulics). New reference data, both experimental and high-fidelity numerical data is being generated. And finally, when considering the system scale, the purpose is to validate and improve system thermal-hydraulics models and codes, but also to further develop and validate multi-scale approaches under development.

1. Introduction

The European Sustainable Nuclear Industry Initiative (ESNII) aims at industrial application of fast reactor technology for a sustainable nuclear energy production [1]. In 2015, four demonstration projects gave a promising outlook in Europe, see figure 1. The ASTRID industrial prototype aims at confirmation of long-term innovation options for the development of SFR technology, for the fuel cycle and for waste management [2]. ALFRED is a program targeting the construction of a Lead cooled Fast Reactor (LFR) demonstrator in Central/Eastern Europe. Currently, Romania is proposed as the host country for ALFRED [3]. MYRRHA is a multipurpose fast neutron spectrum irradiation facility proposed to operate as a European large research infrastructure, and to serve as experimental pilot plant for

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the lead technology [4]. Furthermore, MYRRHA should serve as a technological system for waste transmutation demonstration and as an irradiation facility for material and fuel in support of the liquid metal fast reactor systems. Finally, SEALER is a small lead cooled reactor, which is currently under development by the Swedish company LeadCold. This reactor ensures reliable and safe production of power for sites where evacuation can never be an option. Their main target is deployment in Canadian arctic communities, which remain disconnected from national power grids and road networks [5]. Except for the SEALER concept, the reactors under consideration have been described in IAEA [6] and the IAEA booklet on the status of fast reactor designs and concepts [7].

Thermal-hydraulics of liquid metal cooled reactors is considered one of the key scientific subjects in the design and safety analysis. Thermal-hydraulic issues for fast reactors have been identified and reported in [8-16]. To solve thermal-hydraulic issues, nuclear engineers apply analytical and empirical correlations, system thermal hydraulics (STH) codes, or sub-channel codes. Additionally, Computational Fluid Dynamics (CFD) techniques are becoming more and more integrated in the daily practice of the thermal-hydraulics researchers and designers.

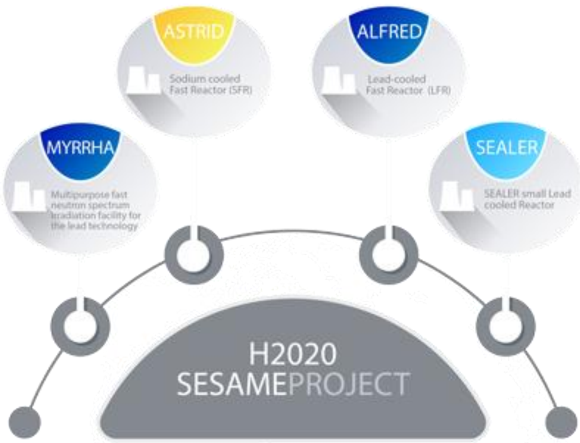

FIG. 23: European liquid metal cooled reactor demonstration projects.

To advance progress in this field, the collaborative Horizon 2020 thermal hydraulic Simulations and Experiments for the Safety Assessment of MEtal cooled reactors (SESAME) project, sponsored by the European Commission, was initialized in 2015 with duration of 4 years. This project ended in 2019.

One of the main deliverables of this international project was a textbook titled 'Thermal Hydraulics Aspects of Liquid Metal Cooled Nuclear Reactors', [17].

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23 European institutes and US partners were involved in the project (see FIG. ***23***) with about 100 researchers and 916 PMs of work.

SESAME Partners

FIG. 24. SESAME partners.

2. Liquid metal heat transfer

A relevant feature in the safety analysis of liquid metal nuclear reactors is the numerical modelling of turbulent heat transfer over the complete range from natural and mixed convection to forced convection regimes. Current engineering tools apply statistical turbulence closures and adopt the concept of the Reynolds analogy in the determination of the turbulent Prandtl number. This analogy is valid mainly for forced convective flows with a Prandtl number of order of unity. As regard the use of liquid metal, this concept is not applicable, and robust engineering turbulence models are required. This is especially true for the simulation of large pool reactors where all flow regimes may occur simultaneously. Thus, an engineering model is required which can deal with all flow regimes at the same time. Promising routes for improvement have been identified and tested on relevant available geometrically simple test cases in [18]. An update of the ongoing model evaluation and development is reported in [19].

The extension of the validation base for flow separation, jets, mixed convection and a rod bundle represent one of the main topics of the SESAME project. An overview of experimental and numerical activities performed, is presented in FIG. 25. In [20], new reference data from open literature on a backward facing step was used. It shows encouraging results for the AHFM-NRG model for turbulent heat transport coupled to an isotropic linear model for momentum. The same authors explain in [21] that they have extended their turbulent heat flux model to the use of an anisotropic non-linear model for momentum. They tested it for different scenarios like the flow between two flat plates, impinging jet case from the

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project and for a bare rod bundle case for which reference data was available from other projects and open literature. In [22], an assessment of a variety of promising models is made with respect to the impinging jet case also used in [21]. Apart from the Reynolds analogy, three different advanced models have been employed: an implicit and explicit AHFM model and the so-called Kays correlation. Limitations of the Reynolds analogy are clearly demonstrated while, all advanced models show reasonable behaviour for this forced convection case. However, they are all based on an isotropic linear model for momentum, and it is concluded that expansion to an anisotropic non-linear model (as in [21]) could clearly bring added value.

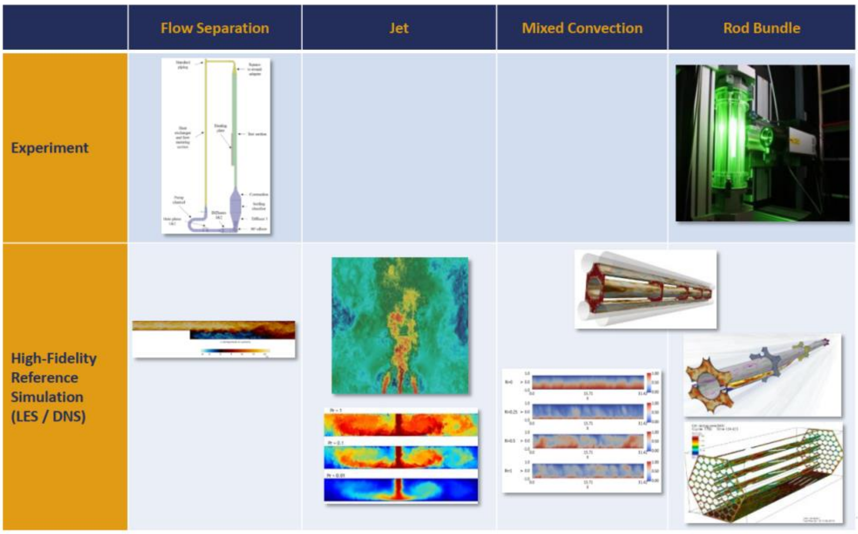

FIG. 25. Overview of reference data referred to liquid metal heat transfer.

Finally, [19] summarizes the latest developments with respect to advanced turbulent heat flux model developments. In the frame of the SESAME project, new reference data are assessed for a variety of advanced turbulent heat flux models, i.e. the second order TMBF-eq-ATHFM model, an implicit AHFM model and the AHFM-NRG. Three different sets of reference data are assessed covering the various flow regimes. For the natural convection flow regime a Rayleigh-Bernard Convection case has been considered from literature, for the mixed convection flow regime, new data from the SESAME project has been considered and for the forced convection flow regime, again the impinging jet case has been considered. Once again, the AHFM-NRG showed good results in all flow regimes. The implicit AHFM model showed good results in the forced convection regime, while it became clear that the promising second order TMBF-eq-ATHFM will need further calibration especially for applications involving non-negligible

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buoyancy effects, before definite conclusions on the performance of this model can be drawn. An extensive discussion on this work, can be found in [23].

3. Core Thermal Hydraulics

The Core Thermal Hydraulics work package, within the SESAME project was focused on the development and validation of numerical models for the thermal hydraulic simulation of liquid metals fast reactor cores. The developed models include sub-channel codes, reduced resolution CFD, coarse-grid-CFD and CFD models. New reference data were generated from the considered experiments, high fidelity numerical models and DNS. Experimental data is generated for wire-wrapped bundles, a bundle with spacers, the effect of blockage, and inter wrapper flow. All intended data was prepared and applied in the model development or in the validation of the used model.

In particular within the SESAME project, an experiment was performed for a 7-pin rod bundle using water as a simulant fluid to obtain validation data for the flow field. In addition to this, quasi-DNS simulation data was generated for a rod bundle with an infinite number of pins and LES data was generated for a 61-pin bundle. In [24], the work on validating RANS CFD methods for wire-wrapped fuel assemblies is summarized. It is concluded that validation efforts up to now indicate that an accuracy within 12.5% for engineering RANS models should be feasible for all bundle sizes and all parameters checked. It is also noted that this value has to be considered as preliminary. Important steps in the validation strategy are missing, i.e. validation for large scale bundles both for the hydraulic field as well as for the thermal field. Furthermore, it is important to realize that all of the applied thermal validation simulations have used the standard Reynolds analogy with a constant turbulent Prandtl number approach and as such there is room for improvement.

Concerning grid spaced fuel assemblies, new data to support the ALFRED reactor fuel assembly design has been produced by performing experiments in a liquid metal rod bundle with and without blockages (FIG. ***26***). These experiments have been described in detail by [25]. Simulations have been performed for these experiments also. The simulations for the unblocked bundle show a good comparison with the experimental data with differences less than 10%. The simulations for the blocked bundle also show a reasonable comparison (on average in the order of 15%), except for the prediction of the wake region behind the blockage [26]. Simulations were performed using a reduced resolution RANS approach to allow scaling up to a complete ALFRED fuel assembly at reasonable computational costs. The errors involved in using a reduced resolution technique were a priori

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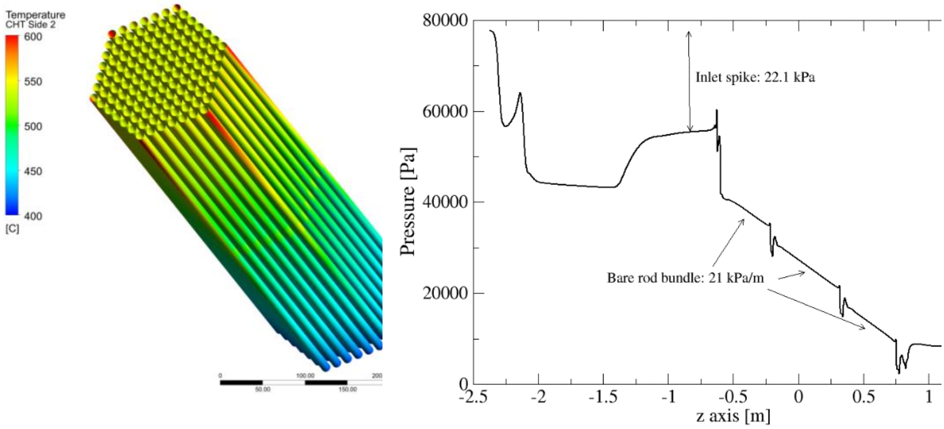
determined by comparison to RANS results and by comparing to experiments.



(*a*) (*b*)

FIG. 26. Clad temperature distribution (a) and Cross-section averaged pressure distribution along the streamwise direction (b): unperturbed case (ALFRED fuel assembly)

The interaction of turbulent flow with the fuel pins (flow induced vibrations in a fuel assembly) was experimentally investigated in a seven pin bare rod bundle using water as coolant (SEEDS-1 experimental facility). Obtained data were used to support the development and validation of numerical approaches. Simulations were based on a URANS approach with an SST k-ω turbulence model and strongly coupled algorithms to account for the fluid-structure interaction. The frequency of the flow pulsations was reasonably well predicted. However, the results of the Fluid Structure Interaction (FSI) calculations deviated from the experiments in that they under-predicted the amplitude of the flow-induced vibrations and in that they over-predicted the respective frequency. Several possible reasons for the mismatch were identified, but will need future investigations to draw conclusion. In particular, the fixation and/or material properties of the transparent material, the stiffness of the rods, the modeling of the water filling of the rods, and dimensional tolerances of the components of the experimental set-up might play a role [27].

4. Pool Thermal Hydraulics

SESAME work package number three, deals with HLM flows in a pool configuration at different scales (FIG. ***27***). Thermal stratification and mixing phenomena were investigated in small scale apparatus like the TALL-3D

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facility [28] (Thermal-hydraulic Lead-bismuth Loop with 3D flow test section) developed at KTH (Royal Institute of Technology, Stockholm, Sweden). Solidification/remelting in buoyancy driven lead flow was performed in the SESAME-stand experimental facility by CVR (Research Centre Rez, Czech Republic). Large scale experiments were performed at ENEA Brasimone R.C. in the CIRCE (Circolazione Eutettico) refurbished with the Integral Circulation Experiment (ICE) test section and thermal stratification and flow patterns were experimentally investigated.

Experimental data were used to validate numerical approaches developed in parallel for these facilities using CFD software. These comparisons, reported in [29] and [30] show reasonable performance of the CFD models. In [29] validation of CFD was performed for the TALL facility including an elaborate sensitivity analysis. This analysis indicates that the boundary conditions (e.g. LBE mass flow rate, inlet temperature, heater power) followed by the turbulent Prandtl number and material properties (e.g. density and heat capacity of LBE) constitute the major sources of modelling uncertainty. Once the radiative heat transfer was taken into consideration, the CFD simulations reported in 0 could reproduce with good accuracy the solidification/remelting experiments performed in the SESAME-Stand facility. The CFD models of CIRCE-ICE reported in [30] reproduce the general flow and temperature patterns of the facility operating under nominal and transient conditions reasonably well. It was found that prediction of the stratification in the CIRCE-ICE pool is sensitive to the modelling of the conjugate heat transfer from the inner loop to the pool. Overall, modelling results of CIRCE-ICE served as valuable feedback to the experimentalists, resulting in changes made to the facility and a better data acquisition in follow-up experiments.

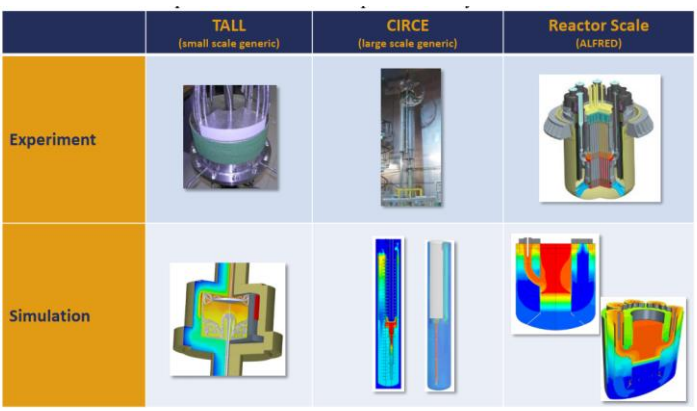

FIG. 27. Overview of experimental and numerical pool thermal hydraulic activities.

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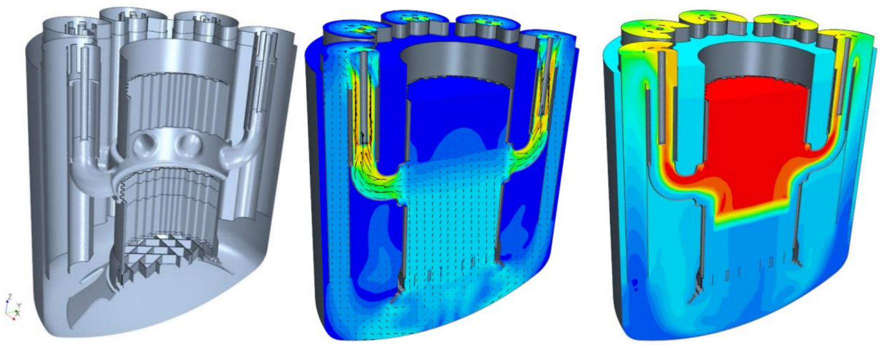
Finally, full CFD approaches are applied to the full scale ALFRED design [3], profiting from the validation efforts on the TALL and CIRCE-ICE facilities. These simulations for a full scale reactor provide designers a priori detailed insight in 3 dimensions concerning the behaviour of flow and heat transport in their design.



(a) (b) (c)

FIG. 28. ALFRED according to LEADER project. Geometry (a), velocity field (b) and temperature field (c)

5. System Thermal Hydraulics

Thermal-hydraulics simulation techniques are essential in order to simulate the behaviour of a complete PWR or BWR nuclear reactor system, i.e. primary, secondary, and/or energy conversion system. Traditionally, the analysis of such system behaviour is performed using system thermal-hydraulics codes. Mostly, such thermal-hydraulic system analyses are validated using integral design specific experiments or reactor data from prototype, test, or demonstration reactors [32]. Specifically for the purpose of application to liquid metal cooled reactors, these codes need to be updated with state-of-the-art algorithms, models and correlations. Furthermore, the validation base should be extended in order to confirm the applicability of such codes for safety analyses. Therefore, the capabilities of the existing system codes to describe a reactor transient involving complex 3D effects needs to be evaluated and validated.

In recent years, the traditional approach of using system thermal-hydraulic codes has been supplemented with new multi-scale approaches in which system thermal hydraulics codes are coupled to detailed three dimensional CFD approaches. Development of such approaches is also applicable to light water reactors [33] and was also developed for liquid metal cooled reactors [34]. However, only a limited set of validation data is available up to now

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https://doi.org/10.1051/epjn/2019003

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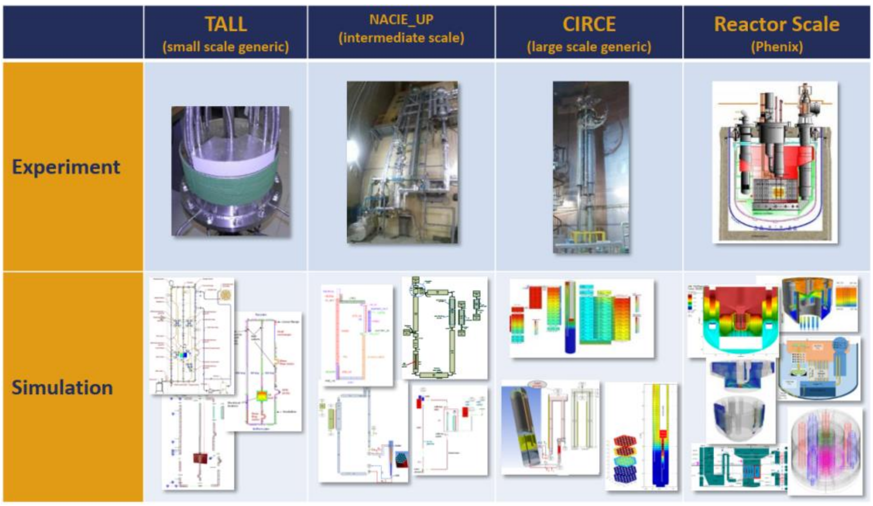
and basically limited to detailed experiments in the TALL-3D test loop. Apart from this small scale basic experiment, validation of such multi-scale approaches has also been performed by comparing to reactor scale data from the EBR-II [35] and Phénix natural circulation tests [36]. As these data relate to real operating reactor, the possibilities for instrumentation were limited.

Therefore, the WP5 of the European SESAME project aims at extending the validation base by providing reference data at different levels. An overview on the system scale experiments and simulations within the SESAME projects is provided in FiIG. ***29***. The first level of validation data was provided by small and dedicated experiments in the Swedish TALL-3D facility. At a slightly larger scale, the experiments in the NACIE-UP facility focused on the multi-scale coupling of the behaviour in the fuel assemblies and the loop system. Scaling up once again, the CIRCE facility in the so-called HERO configuration [37] was used to provide experimental validation data. Real reactor data will once again be provided from the Phénix reactor end of life tests. This time, data from the dissymmetric test is made available. This data will allow validation of the three dimensional effects to a much larger extent than the natural circulation test data which were previously used [36].



FiIG. 29. Overview of system scale experiments and simulations.

A large amount of experimental tests was performed in the TALL-3D facility [38]. Specific tests were selected for blind and open benchmark with system codes or coupled multi-scale numerical approaches. The open benchmarked results from, all available simulations compared well with the experiment. The blind benchmark demonstrated a spread of the results. In

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https://doi.org/10.1051/epjn/2019003

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fact, all possible types of transients were obtained in the simulations. An uncertainty propagation analysis was performed which provided a lot of insight. The results suggest that the current models are not capable of capturing the experimental data (even taking into account experimental uncertainties). However, the predictions are close to experimental data and do capture the character of the natural circulation instability.

The blind benchmark results on the NACIE_UP tests are reported in [39]. The simulations showed a sufficiently good agreement among the participants regarding the general behaviour of the loop in both steady state and transient conditions. The observed discrepancies in the LBE mass flow rate were mainly related to the specific parameters adopted to set the numerical model, as the pressure loss coefficients or the gas circulation model.

With respect to CIRCE-HERO, [40] reports that an interesting observation is that the two multiscale coupled models show similar overshoots in the outlet temperature of the heat exchanger. This may indicate that a particular 3D phenomenon is not captured by the STH part of the coupled model or that particular input from the experiments is missing. It is advised to investigate this further in the future. Despite the observed differences between multi-scale simulations and experiments, it is concluded that multi-scale coupled techniques provide a promising methodology that deserves further investigation and qualification to be used as a tool in the design of nuclear power plants. Because of the complexity of the phenomena involved and of the size of the physical domain, the modelling of the Phénix reactor proved to be a challenging task [41]. The best compromise has to be found between the accuracy and the computational cost. The results reported in [41] show two main issues: (i) correctly computing the thermal hydraulics of the first three minutes of the dissymmetric transient and (ii) finding the correct parameters to accurately compute the remaining 27 minutes. For the first 3 minutes of the transient, it is concluded that the intermediate heat exchangers should be included in the CFD model in order to correctly compute the momentum and stratification of the sodium leaving the intermediate heat exchangers. For the remaining 27 minutes, most participants underestimate the cooling rate. A deeper investigation of the heat losses from and the thermal inertia in the Phénix reactor is therefore recommended.

6. Conclusions

The activities and progress in support of liquid metal cooled reactor design and safety analyses performed within the European collaborative H2020 SESAME project are described in this paper.

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https://doi.org/10.1051/epjn/2019003

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The major outcomes are:

- Turbulent heat transport in liquid metal:
    - Enlargement of the reference database with new experimental and high fidelity numerical data with a focus on flow separation, jets, and rod bundle flow phenomena.
    - Further development and assessment of promising models like a second order heat flux model, implicit and explicit algebraic heat flux models and the application of the Kays correlation
- Core thermal hydraulics:
    - Creation of new experimental and high fidelity numerical data for validation of RANS models with respect to the hydraulics of the flow in wire wrapped fuel assemblies.
    - New experimental data is created for the assessment of liquid metal fuel assemblies employing grid spacers including the effects of blockages. RANS modelling approaches have been validated using these data, and subsequently these validated modelling approaches have been applied to a full scale ALFRED fuel assembly.
    - Assessment of the influence of the inter-wrapper flow through experiments and numerical analyses which have been validated using the experimental data.
    - Creation of new experimental data and parallel model development for validation of numerical models concerning flow induced vibrations in liquid metal reactor fuel assemblies.
- Pool thermal hydraulics:
    - Enlargement of the validation base for pool thermal hydraulics by creation of new experimental data using two important LBE facilities, i.e. TALL-3D and CIRCE.
    - Further development and validation of CFD tools for pool modelling.
    - Design (TALL-STS) and construction (SESAME-Stand) of new experimental facilities supporting development and validation of CFD models for solidification phenomena.
    - CFD was applied to a full scale ALFRED pool revealing some potential design improvements.
- System thermal hydraulics:
    - The validation base for liquid metal system thermal hydraulics has been enlarged with new experimental data ranging from a small generic scale, to intermediate scale and large scale experiments, and finally to real reactor scale.
    - Results of system thermal hydraulic codes and multi-scale coupled simulation tools have been compared with experimental results and in general contribute to the increase in validation of the numerical tools while at the same time

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https://doi.org/10.1051/epjn/2019003

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highlighting shortcomings on modelling as well as measurements.

Acknowledgments

The SESAME project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No. 654935.

References

[1] ESNII, 'ESNII, The European Sustainable Nuclear Industrial Initiative: Concept Paper', SNE-TP (2010)

[2] Le Coz P., Sauvage J.-F., Hamy J.-M., Jourdain V., Biaudis J.-P., Oota H., Chauveau T., Audouin P., Robertson D., Gefflot R., 'The ASTRID Project : Status and Future Prospects', FR13, Paris, France (2013).

[3] Alemberti A., Mansani L., Grasso G., Mattioli D., Roelofs F., De Bruyn D., 'The European Lead Fast Reactor strategy and the Roadmap for the Demonstrator ALFRED', FR13, Paris, France (2013).

[4] De Bruyn D. et al., 'The MYRRHA ADS project in Belgium enters the frontend engineering phase', ICAPP14, Charlotte, USA (2014).

[5] Wallenius J., Qvist S., Mickus I., Bortot S., Szakalos P., Ejenstam J., 'Design of SEALER, a very small lead-cooled reactor for commercial power production in off-grid applications', Nuclear Engineering and Design, vol. 338, p.p. 23-33 (2018).

[6] IAEA, 'Status of Fast Reactor Research and Technology Development', IAEA-Tecdoc 1631, Vienna, Austria (2012).

[7] IAEA, 2013. Status of Innovative Fast Reactor Designs and Concepts. Vienna, Austria.

[8] Roelofs F., Tichelen K. van, Tenchine D., 2013. Status and Future Challenges of Liquid Metal Cooled Reactor Thermal-hydraulics. NURETH15, Pisa, Italy.

[9] Tenchine D., 2010. Some Thermal Hydraulic Challenges in Sodium Cooled Fast Reactors. Nuclear Engineering & Design, vol. 240, p.p. 1195-1217.

[10] Akimoto H., Ohshima H., Kamide H., Nakagawa S., Ezato K., Takase K., Nakamura H., 'Thermalhydraulic research in JAEA; Issues and Future Directions', NURETH13, Kanazawa, Japan (2009).

[11] Song C.H., Kim K.K., Hahn D.H., Lee W.J., Bae Y.Y., Hong B.G., 'Thermal-Hydraulic R&Ds for Gen-III+ and Gen-IV Reactors at KAERI: Issues and Future Directions', NURETH13, Kanazawa, Japan (2009).

[12] Velusamy K., Chellapandi P., Chetal S., Raj B., 'Overview of Pool Hydraulic Design of Indian Prototype Fast Breeder Reactor', Sadhana, vol. 35, p.p. 97-128 (2010).

[13] Sienicki J., Wade D., Tzanos C., 'Thermal Hydraulic Research and Development Needs for Lead Fast Reactors', IAEA Tecdoc 1520, Theoretical and Experimental Studies of Heavy Liquid Metal Thermal Hydraulics, Karlsruhe, Germany (2003)

[14] Todreas N., 'Thermal Hydraulic Challenges in Fast Reactor Design', NURETH12, Pittsburgh, USA (2007).

[15] Roelofs F., Gopala V.R., Van Tichelen K., Cheng X., Merzari E., Pointer W.D., 'Status and Future Challenges of CFD for Liquid Metal Cooled Reactors', FR13, Paris, France (2013).

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https://doi.org/10.1051/epjn/2019003

Available online at:
https://www.epj-n.org

[16] Chellapandi P., Velusamy K., 'Thermal hydraulic issues and challenges for current and new generation FBRs', Nuclear Engineering and Design, Vol. 294, p.p. 202-225 (2015).
[17] Roelofs F. edit., 'Thermal Hydraulics Aspects of Liquid Metal Cooled Nuclear Reactors', ISBN 978-0-08-101980-1, Woodhead Publishing, Elsevier (2019).
[18] Roelofs F., Shams A., Otic I., Böttcher M., Duponcheel M., Bartosiewicz Y., Lakehal D., Baglietto E., Lardeau S., Cheng X., 'Status and perspective of turbulence heat transfer modelling for the industrial application of liquid metal flows', Nuclear Engineering & Design, vol. 290, p.p. 99-106 (2015).
[19] Shams A., De Santis A., Koloszar L., Villa-Ortiz A., Narayanan C., 'Status and Perspectives of Turbulent Heat Transfer Modelling in Low-Prandtl Fluids', SESAME International Workshop, Petten, Netherlands (2019).
[20] De Santis A., Shams A., 'Application of an algebraic turbulent heat flux model to a backward facing step flow at low Prandtl number', Annals of Nuclear Energy, vol. 117, p.p. 32-44 (2018).
[21] Shams A., De Santis A., 'Towards the accurate prediction of the turbulent flow and heat transfer in low-Prandtl fluids', International Journal of Heat and Mass Transfer, vol. 130, p.p. 290-303 (2019).
[22] De Santis A, Villa-Ortiz A., Shams A., Koloszar L., 'Modelling of a planar impinging jet at unity, moderate and low Prandtl number: Assessment of advanced RANS closures', Annals of Nuclear Energy, vol. 129, p.p. 125-145 (2019)
[23] Shams A., Roelofs F., Tiselj I., Oder J., Bartosiewicz Y., Duponcheel M., Niceno B., Guo W., Stalio E., Angeli D., Fregni A., Buckingham S, Koloszar L.K., Villa-Ortiz A., Planquart P., Narayanan C., Lakehal D., Van Tichelen K., Jäger W., Schaub T., 'A Collaborative Effort Towards the Accurate Prediction of Flow and Heat transfer in Low-Prandtl Fluids', NURETH-18, Portland, USA (2019).
[24] Roelofs F., Uitslag-Doolaard H., Dovizio D., Mikuz B., Shams A., Bertocchi F., Rohde M., Pacio J., Di Piazza I., Kennedy G., Van Tichelen K., Obabko A., Merzari E., 'Towards Validated Prediction with RANS CFD of Flow and Heat Transport in a Wire-Wrap Fuel Assembly', SESAME International Workshop, Petten, Netherlands (2019).
[25] Marinari R., Di Piazza I., Tarantino M., Martelli D., 'Temperature Profiles in the Blockage Experiment with the BFPS Test Section', SESAME International Workshop, Petten, Netherlands (2019).
[26] Mathur A., Uitslag-Doolaard H., Roelofs F., 'Reduced Resolution RANS Approach Validation to Grid Spacer Fuel Assemblies', SESAME International Workshop, Petten, Netherlands (2019).
[27] Bertocchi F., Rohde M., De Santis D., Shams A., Dolfen H., Degroote J., Vierendeels J., 'FluidStructure Interaction of a 7-rods Bundle: Benchmarking Numerical Simulations with Experimental Data', SESAME International Workshop, Petten, Netherlands (2019).
[28] Grischchencko D., Jeltsov M., Kööp K., Karbojian A., Villanueva W., Kudinov P., 'The TALL-3D facility design and commissioning tests for validation of coupled STH and CFD codes', Nuclear Engineering & Design, vol. 290, p.p. 144-153 (2015).
[29] Jeltsov M., Grishchenko D., Kudinov P., 'Validation of Star-CCM+ for liquid metal thermalhydraulics using TALL-3D experiment', Nuclear Engineering and Design, vol. 341, p.p. 306-325 (2019).

[30] Zwijsen K., Dovizio D., Moreau V., Roelofs F., 'CFD Modelling of the CIRCE Facility', SESAME International Workshop, Petten, Netherlands (2019).
[31] Profir M., Moreau V., Melichar T., `Numerical and Experimental Campains for Lead Solidification Modeling and Testing`, submitted to Nuclear Engineering and Design, June 2019
[32] Bestion D., 'System thermalhydraulics for design basis accident analysis and simulation: Status of tools and methods and direction for future R&D', Nuclear Engineering & Design, vol. 312, p.p. 12-29 (2017).
[33] Chanaron B., Ahnert C., Crouzet N., Sanchez V., Kolev N., Marchand O., Kliem S., Papukchiev A., 'Advanced multi-physics simulation for reactor safety in the framework of the NURESAFE project', Annals of Nuclear Energy, Vol. 84, p.p. 166–177 (2015).
[34] Bandini G., Polidori M., Gerschenfeld A., Pialla D., Li S., Ma W.M., Kudinov P., Jeltsov M., Kööp K., Huber K., Cheng X., Bruzzese C., Class A., Prill D., Papukchiev A., Geffray C., Macian-Juan R., Maas L., 'Assessment of systems codes and their coupling with CFD codes in thermal–hydraulic.
[35] Briggs L., Hu W., Su G.H., Vezzoni B., Del Nevo A., Zanino R., Mochizuki H., Choi C., Stempniewicz M., Zhang Y., Monti S., Sui D., Maas L., Partha Sarathy U., Petruzzi A., Ohira H., Morita K., Shin A., Rtishchev N., Truong B., 'EBR-II Passive Safety Demonstration Tests Benchmark Analyses – Phase 2', NURETH16, Chicago, USA (2015).
[36] Pialla D., Tenchine D., Li S., Gauthe P., Vasile A., Baviere R., Tauveron N., Perdu F., Maas L., Cocheme F., Huber K., Cheng X., 'Overview of the system alone and system/CFD coupled calculations of the PHENIX Natural Circulation Test within the THINS project', Nuclear Engineering & Design, vol. 290, p.p. 78-86 (2015).
[37] Martelli D., Tarantino M., Di Piazza I., 'Experimental Activity for the Investigation of Mixing and Thermal Stratification Phenomena in the CIRCE Pool Facility', ICONE24, Charlotte, USA (2016).
[38] Grishchenko D., Papukchiev A., Geffray C., Liu C., Polidori M., Kööp K., Jeltsov M., Kudinov P., 'Lessons Learned from the Blind Benchmark on Natural Circulation Instability in TALL-3D', SESAME International Workshop, Petten, Netherlands (2019).
[39] Forgione N., Angelucci M., Barone G., Polidori M., Cervone A., Di Piazza I., Gianetti F., Lorusso P., Holland T., Papukchiev A., 'Blind Simulations of NACIE-UP Experimental Tests by STH codes', ICONE26, London, UK (2018).
[40] Zwijsen K., Martelli D., Breijder P., Forgione N., Roelofs F., 'Multi-scale Modelling of the CIRCEHERO Facility', SESAME International Workshop, Petten, Netherlands (2019).
[41] Uitslag-Doolaard H., Alcaro F., Roelofs F., Wang X., Kraus A., Brunett A., Thomas J., Geffray C., Gerschenfeld A., 'Multiscale Modelling of the Phénix Dissymmetric Test Benchmark', SESAME International Workshop, Petten, Netherlands (2019).

Cite this article as: Jean-Paul Crocombette, Christian Van Wambeke, Quick calculation of damage for ion irradiation: implementation in Iradina and comparisons to SRIM, EPJ Nuclear Sci. Technol. 5, 7 (2019)

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doi: 10.2777/522041
ISBN 978-92-79-98744-1

Publications Office