SNETP
Sustainable Nuclear Energy
Technology Platform

SNETP REPORT

SNETP FORUM 2021 - Proceedings

SNETP Association

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Executive Summary

The SNETP FORUM 2021 was held on 2-4 February in a virtual format. Over 630 participants, not only from all European countries but also from Japan, USA, Canada, Ukraine, and Argentina, were actively involved during the three-day event dedicated to innovation R&D in civil nuclear fission.

The programme was designed with the help of the scientific committee of the SNETP FORUM:

- ✓ Abderrahim Al Mazouzi (EDF)
- ✓ Rob Arnold (BEIS)
- ✓ Anthony Banford (NNL)
- ✓ Didier Banner (EDF)
- ✓ Pavel Kral (UJV)
- ✓ Franck Carré (CEA)
- ✓ Marc Deffrennes (weCARE)
- ✓ Michael Fütterer (EC-JRC)
- ✓ Eric Hanus (CEA)
- ✓ Luis Herranz (CIEMAT)
- ✓ Erika Holt (VTT)
- ✓ Lorenzo Malerba (CIEMAT)
- ✓ Bruno Michel (CEA)
- ✓ Steve Napier (NIRO)
- ✓ Karl-Fredrik Nilsson (JRC)
- ✓ Nathan Paterson (Foratom)
- ✓ Paul Schuurmans (SCK-CEN)
- ✓ Ferry Roelofs (NRG)

And the organisation committee:

- ✓ Abderrahim Al Mazouzi (EDF)
- ✓ Gilles Quénéhervé (LGI)
- ✓ Clara Demange (LGI)

1. Plenary session

SNETP President, Bernard Salha (EDF), officially launched the event by welcoming the audience and presenting the SNETP Association. “We are the largest collaborative platform in Europe working in nuclear research and innovation. We gather the major R&D organisations involved in nuclear in Europe and beyond and we work together to improve nuclear efficiency, safety and performance”, he stated.

1.1. SNETP strategy

Bernard Salha gave an overview of SNETP objectives: promoting scientific excellence in nuclear research, boosting innovation, representing nuclear fission R&D in European affairs, strengthening international relations with nuclear institutions, providing solutions to industry, cooperating closely with regulators, supporting R&D infrastructure, sharing experience with European associations and engaging with civil society. “We aim to contribute to the shaping of European energy policies, especially in the nuclear field, by exchanging with relevant actors about research priorities and producing reference documents, such as the SNETP Strategic Research and Innovation Agenda (SRIA)”, he said. He also briefly presented the SNETP Pillars: ESNII on Generation IV Fast Neutron Reactor technologies, NC2I on nuclear cogeneration and NUGENIA on Generation II and III reactor technologies; and the SNETP committees, each one of them working towards a specific SNETP objective.

1.2. SNETP pillars

Following this introduction, SNETP Pillars Chairmen described the activities of NUGENIA, ESNII and NC2I. **Steve Napier (NIRO/UK), NUGENIA Chairman**, introduced the overall objectives of the pillar and presented each NUGENIA technical area focusing on the specific challenges faced. He concluded his presentation with an overview of what NUGENIA has achieved and the remaining actions. **Marc Schyns (SCK.CEN/Be), ESNII Interim Chairman**, presented the ESNII Vision Paper that will contain a mission and vision statement, an overall strategy and a list of goals and objectives. Finally, **Józef Sobolewski (NCBJ/Pl)**, NC2I Chairman, presented the mission and vision of the pillar, with a focus on nuclear cogeneration activities in Poland. A detailed vision of the three SNETP pillars will be published in April this year.

1.3. Panel discussion

The day continued with a panel session. In his introduction to this session and after welcoming the invitees, the president Bernard Salha, welcomed the opportunity to exchange views on the resilience of the nuclear sector in this historic moment both from the sanitary view point (the covid is getting even stronger nowadays) and also from the climate side. He insisted by saying “Our common goal is to provide solutions to tackle this huge challenge facing us all now and will be even more dramatic for the generations to come if we do not do anything about it right now”.

Bernard Salha pointed out that “The European nuclear industry and its R&I community have a long history of providing excellence and benefit to European citizens. Nuclear energy is indispensable in areas such as tackling climate change, as it is currently the largest single supplier of flexible, low-carbon electricity in EU and enables continuous security of supply by ensuring independence from third countries. But nuclear technology is more than just a power supplier: it plays an indispensable role in the medical sector, particularly in terms of diagnosis and treatment of cancer (thus supporting Europe’s Beating Cancer Plan), as well as in industry, space, agriculture, etc. Nuclear is also a place of innovation for new digital applications (such as artificial intelligence, block chain, IOT...) as well as for operation and security of the European electrical grid together with variable renewables and storage. By developing innovative and cross-cutting applications, nuclear serves a wide range of R&I domains which the EU is focusing on”.

He ended up his introduction saying that "SNETP, with its 120 members from industry, research centres, academia and SMEs, aims to strengthen cross-sectoral collaboration to facilitate innovation in nuclear and to support the maintenance and enhancement of skills and qualifications to address the key challenges facing the sector".

Michael Chudakov, Deputy Director General and Head of the Department of Nuclear Energy at the IAEA highlighted the role of collaborative research, innovation and development to increase the contribution of nuclear power to climate change mitigation, energy security and energy poverty alleviation. "None of this can be done without international cooperation and collaboration on innovation and R&D with key international partners", he said.

William Magwood, Director-General, OECD Nuclear Energy Agency (NEA) discussed about how the R&D community can best help the new build to be successful in the future. During his intervention he highlighted the outcome of the report the NEA published last year, Unlocking Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders: "One of the most important areas examined in this report is how digital technology can help, and when I'm asked what nuclear research can do, I say that looking at digital technologies is the single most important thing that can be done by the technical community at this point".

Sama Bilbao, Director General of the World Nuclear Association, focused her presentation on the role of nuclear energy in climate change mitigation. She compared the impact of climate change on the nuclear industry with the impact of Covid-19 on the pharmaceutical industry and asked for a paradigm and attitude change to accelerate the deployment of cost-effective nuclear technologies. Sama Bilbao also stressed the need for government support to increase innovation in the nuclear industry.

Yves Desbazeille, Director General of FORATOM, presented nuclear's contribution to Europe's economy in terms of electricity production – nuclear accounts for 50% of EU's decarbonised electricity –, and jobs creation – nuclear provides over 1 million jobs in the EU. He also gave an overview of the role for nuclear in decarbonisation: "The first objective is to ensure a proper long-term operation of the existing fleet to move towards a decarbonised future. In the long run it is also important to invest in new build with an objective of 15% nuclear generation for 2050".

Rosalinde VAN DER VLIES, Director of the Clean Planet Directorate in the European Commission's, Directorate-General for Research and Innovation, re-contextualised her intervention within the framework of the European Green Deal: "Sustainability and competitiveness issues really go hand in hand. With the European Green Deal, the European Commission (EC) has for the first time explicitly said that sustainability strategy is also our growth strategy and contributes to our competitiveness". Rosalinde VAN DER VLIES stated that strong investments in research and innovation will be required to achieve climate neutrality by 2050 and emissions reduction targets of 55% by 2030. She also highlighted a few novelties of the new Euratom work programme: "In the area of fission, our objective is to foster cross sector innovation linked to non-power applications. It will also be a priority to improve safety in fuel management, radioactive waste and decommissioning. Finally, we will also focus on having more synergies with Horizon Europe, in particular in training activities", she stated.

Nicolas Février, Director at EDF – Nuclear Engineering and New Build Projects Division – Design and Technology Branch, presented nuclear power as a low carbon energy solution for global warming mitigation. "It is very important for EDF to be a key player in the target of reaching carbon neutrality. We are convinced that nuclear, apart from being carbon free, is a dispatchable energy that is resilient, very cost-efficient and will be a pillar of the carbon neutrality we are committed to", he said. Nicolas Février also highlighted two lessons drawn from the covid crisis: Europe needs to secure its independence in a number of strategic domains, such as medicine and electricity generation; and once the crisis is solved, the development of new nuclear power plant projects will be a good way to establish a rapid economic recovery and to boost local employment.

To conclude, SNETP President shared the Association's vision to tackle climate change: "SNETP believes the best solution to fight climate change is to combine a variety of technologies, including nuclear energy and renewables emitting the lowest possible amount of greenhouse gases, to hold the increase of global temperature below 1.5 degrees by 2050, in coherence with the recommendations of many international organisations. This is a position based on scientific and technical facts which are at the heart of our Association". In this sense he called for political support, strong investments and strengthened cross sector collaboration to reach these objectives.

2. Technical sessions

The second and third days of the SNETP FORUM 2021 were dedicated to technical sessions on a variety of topics of interest for the nuclear community.

2.1. Technical session #1 – Long-term operation & construction

This technical session was moderated by Pavel Kral (UJV) and Luis Herranz (CIEMAT).

2.1.1. Scope

As it was emphasized several times during the panel discussion of the plenary session, long term operation (LTO) of nuclear power plants (NPPs) and new builds are key pillars when addressing climate challenges the world is already facing. Consistently with this view, a technical session was set up. A total of eight papers were presented and the session was attended by approximately 80 people. A number of questions were raised and responded right after each presentation, which made the session livelier and more interesting. This short excerpt highlights the main topics dealt with in the session and the main points that drew audience's attention.

2.1.2. Summary of the technical session

- **Implementation of new safety requirements in post-Fukushima period (including LTO considerations)**

J. Misak (UJV) recalled that after the Fukushima accident IAEA safety standards have been notably enhanced and brought into national regulations and best practices. The more stringent requirements apply to new builds but also to existing NPPs, if reasonably achievable, and address all stages of NPP life, including design and safety demonstration. He emphasized that the resulting safety improvements are essential for acceptance of LTO of the running NPPs and it makes all the sense to face this in a coordinated and consistent way. A number of specific points were addressed: the plant design should consider also "extended conditions", which even include severe accidents; deterministic safety analysis (uncertainties quantification included) should demonstrate independence between levels of defence and between units (if more than one in the same site) and "practical elimination" of early and large releases. A number of ideas to achieve this were discussed in his presentation: limitation of systems sharing between levels; prevention of common cause failures; independence of safety systems and safety features, with special attention to I&C and auxiliary support systems; increased margins against natural hazards of systems in charge of preventing large and early radioactive releases; robust connection points for non-permanent water sources should be an essential component of accident management; demonstration of practical elimination could result in early or large radioactive releases in the early phases of an accident. All these ideas recognise that enhancing deterministic safety analysis is a key ingredient of safety demonstration supporting LTO.

- **Hydrogen management**

N. Chaumeix (CNRS) walked the audience through combustible gas risk associated to severe accidents and its management. The first part of her presentation introduced some key phenomenological aspects that have been investigated for long time and, more specifically, within the SAMHYCO project (an in-kind project within NUGENIA/TA2) and the Mithygene project. After the presentation of the mitigation strategies considered so far for combustible gas risk mitigation, some key points related to such a strategy and recent research outcomes were briefly touched upon, with particular emphasis on combustion: the flammability limits (particularly the lower one) when gas is not quiescent and shows a level of turbulence or when gas is perturbed by droplets coming from spraying containment; and the combustion regimes under anticipated conditions (temperature, gas composition, presence of obstacles, etc.) within containment during severe accidents. At the end of the presentation, once some of the investigation findings had been shared, she pointed towards application of all the present knowledge and some more coming from the EC-AMHYCO project, which has just started and is focused on the enhancement of accident management for combustible gas risk.

- **Progress towards simulation of passive safety systems**

M. Montout (EDF) introduced the EC-PASTELS (Passive Systems: Simulating the thermal-hydraulics with experimental studies) project aimed at enhancing the ability to design and deliver innovative passive safety, with emphasis on enhancing the current capability of simulation to support the safety demonstration. Two specific passive systems are planned to be investigated: Containment Wall Condenser (CWC) and SAfety COndenser (SACO). To do so, a strategy has been developed to strengthen the existing modelling capabilities of any sort (from thermal-hydraulic system codes to multi-scale, multi-physics tools) and combine them to meet the objectives set. The experimental database to be used for this purpose will consist of experiments conducted in the HERO-2 facility (Separate Effect Tests, SETs) and the PERSEO one (Integral Tests, ITs). The final outcome of the project will be a settled simulation methodology supported through validation against the chosen tests and the necessary guidelines to correctly apply it. In addition, a roadmap to bring CWC and SACO to the level of industrial NPP readiness is planned to be delivered.

- **Materials research for LTO**

After contextualizing materials research with the present time of definition of energy systems in the EU and the key role that nuclear can play in the de-carbonisation target, C. Fazio (JRC) focused her presentation on the research activities on materials underway and/or planned at JRC, with particular emphasis on those relevant for LTO, like the RPV embrittlement (STRUMAT-LTO project). She highlighted the importance of miniature testing for surveillance programs, particularly in an LTO context, and discussed the challenges ahead when moving from macro- to micro-testing and the need to standardize practices, despite how long this process might take (more than 15 years took for small punch tests to go from R&D to a European standard). In view of these challenges (miniaturization and harmonization) for both irradiated and non-irradiated materials and the JRC capability to assess non-irradiated materials at macro- and micro-mechanical scales, a dedicated « open-access » infrastructure (RADLAB) was proposed and its potential equipment briefly described.

- **Fluid Structure Interaction: A Multi-Physics Application for Design and LTO Support**

Ferry Roelofs (NRG) presented to the audience the VIKING (Vibration ImpaKt In Nuclear power Generation) project idea, that addresses issues with vibrations induced by the coolant flows (primary, secondary, tertiary, etc…) in nuclear power plants. The collaboration focuses on two types of vibration issues, i.e. fretting in fuel assembly rod bundles and fluid elastic instability occurring in rod bundles in cross flow, e.g. in heat exchangers (steam generators). The project builds upon existing knowledge from NUGENIA and H2020 projects like CORTEX, MYRTE, and SESAME at the same time fully utilizing the existing national programs in this field. Focus on two types of vibration issues are placed: fuel assembly rod bundles and rod bundles in cross flow (e.g. in heat exchangers). The objective of VIKING is to utilize experimental data available from the partners together with reference numerical data (LES) to further develop and validate numerical engineering methods (unsteady RANS simulations, Hybrid LES-URANS simulations), or new methods like the pressure fluctuation method (PFM).

- **Perspectives and opportunities for LTO in Europe (LTO Economics)**

Andrei Goicea (Foratom) discussed in his presentation the impact of the lifetime extension of the existing nuclear fleet on the new decarbonization targets. FORATOM made its own analysis based on the impact assessments of the different communications related to decarbonisation targets. It was stressed that according to different sources (IEA or EC), the Levelized Costs of Electricity (LCOE) for LTO are the lowest among all technologies. It is also important to note, that EU-ETS carbon price will have an important impact on the decision to choose lifetime extension of existing nuclear fleet and to close fossil fuel capacity instead. Andrei concluded listing several important tasks to be done at EU level like ensuring a coherent, consistent and stable EU policy framework (including Euratom), pursuing the ambitious net-zero CO2 emissions target for the EU in 2050 and choosing the most economic and technically feasible path to achieve it, to develop and implement a strong industrial strategy to ensure that Europe maintains its technological leadership, and to support human competences development.

- **Leveraging Research and Operational Experience for Plant Upgrades and LTO at Loviisa NPP**

Harri Tuomisto (Fortum) summarized in his presention the Finish experience with LTO, that was demonstated on the Loviisa NPP. Plant performance and lifetime profile and plant modifications in reaction to accidents from TMI-2 to Fukushima were presented as well as the operating experience, dealing with internal hazards, the Severe Accident Management (SAM) program and the role of experimental and analytical research. A number of experimental facilities was built in Finland to cover the open issues in plant safety. Thanks to the design improvements the plant power uprates were possible without deteriorating plant safety parameters.

- **On-going and/or planned research in the present Spanish context**

Luis E. Herranz (CIEMAT) presented an overview of Spanish research coordinated by CEIDEN, the Spanish nuclear technology platform that gathers all actors/entities involved in the R&D of nuclear fission in the country. More than 100 public and private entities participate in CEIDEN, which represents the majority of the players in this field in Spain. In addition, there are more than 20 international collaborators. CEIDEN is not a legal entity and it organizes the work on in-kind basis. It is organized in working groups and delivers major and supported projects. The technical programme of CEIDEN is focused on technical challenges that are addressed through specific projects. The current living challenges are long-term operation, spent fuel and waste management, and new technologies. Specific projects are addressing LTO (both reactor internals and concrete ageing) and activities have been initiated on ATFs. In addition, they spend substantial resources on knowledge transfer. The main strengths of CEIDEN are its 'networking' operation model and non-profit contribution by all its members. CEIDEN conveys to the Administration and to the Spanish companies the idea that the promotion of R&D supports nuclear Spanish industrial exports, and the safe short, medium- and long-term operation of nuclear power plants.

2.1.3. Emerging project ideas

The spectrum of presentations in technical session 1 covered very well various aspects of long-term operation (LTO). From the implementation of new safety requirements in post-Fukushima period and plant modifications, over the experimental programmes and computer tools development to the LTO economics.

Regarding the new project ideas, the presentation (2.5) introduced the project idea VIKING, focused on the issues with vibrations induced by the coolant flows (primary, secondary, tertiary, etc…) in nuclear power plants. Application of fluid-structure interaction (FSI) class of computer codes to the vibration assessment and design optimization could bring substantial benefits in design and operation of fuel assemblies, heat exchangers and other relevant systems of NPP. Other presentations referred to just born projects within the last call of H2020 (AMHYCO and PASTELS). The presentation (2.4) identified some needs stemming from LTO in the domain of material research that might be addressed through international collaboration based on an "open access" to a strategic infrastructure that would be built in JRC-Petten for testing irradiated materials. It might be the case that this initiative could be integrated in a forthcoming project. Interest was raised concerning the application of Artificial Intelligence (AI) to materials research and the effect of scale when testing RPV in the decommissioning phase of the NPP.

2.2. Technical session #2 – SMRs

This session was moderated by Eric Hanus (CEA) and Rob Arnold (BEIS).

2.2.1. Scope

Technical session 2 deals with SMRs, small modular reactors that are currently experiencing growing interest worldwide. The agenda of the session allowed handling the SMRs topics from different perspectives:

- description of ongoing industrial projects like NuScale and Nuward,
- interest of countries for SMR deployment, with the example of Estonia,
- information about the ongoing Euratom-funded project Elsmor,
- focus on passive safety systems used in SMR designs with both description of experimental facility at SIET and TSO concerns through IRSN presentation,
- overview of AMR, advanced modular reactors based on gen-IV concepts, and
- presentation of even smaller micro-reactors.

The session was very popular with a large audience and lively questions and answers.

2.2.2. Summary of the technical session

- **Microreactors, an overview (Mark Davies, USNC)**

Canadian-based Ultra-Safe Nuclear Corporation (UNSC) is developing a small-scale micro modular reactor aimed at power supply to off-grid and remote locations. The aim is to develop a safe, clean, cost-effective unit that requires no refueling for 20 years. UNSC's design is based on fuel pellets consisting of ceramic encapsulated TRISO fuel particles. This is designed to provide meltdown-proof fuel that can be deployed safely and securely in Arctic conditions and allow flexible use of electricity and heat with a minimal waste burden. USNC is entering phase 2 of the design review with the CSNC and active application for an Environmental Assessment and License to Prepare Site. This schedule would allow it to bring Canada's first SMR into operation by 2026 or earlier.

- **NuwardTM (Eric Hanus, CEA)**

Eric Hanus presented the ongoing NuwardTM project, which aims at providing a 340MWe power plant including 2 reactors in a single nuclear building. The target is to replace coal-fired power plants to power remote municipalities and industrial sites and to supply networks that cannot be connected to high or medium sized reactors. The product is a combination of proven and innovative technologies that yield to the most compact reactor in the world. Details were given about the main innovations and their impact on the design and the safety demonstration. NuwardTM has an integrated architecture with primary cooling system in the pressure vessel, which significantly reduces the LOCA risk. The steam generators located inside the RPV have a plate design, which provides high efficiency heat transfer and thus compactness. The nuclear reaction is controlled by immerged mechanisms, eliminating thus the rod ejection risk. A specific RRP component is used to passively remove residual heat. The core is managed with no soluble boron avoiding clear water plug. NuwardTM development roadmap is presented: currently the project is in the conceptual design phase. EDF is leading the development together with CEA, TechnicAtome and Naval group and international cooperation is being considered.

- **Execution of first privately funded EU SMR deployment (Kalev Kallemets, Fermi Energia)**

Fermi Energia is exploring the options and drivers for an SMR build in Estonia. This is in response to an anticipated and substantial increase in the proportion and total amount of energy consumed as electricity in the Nordic and Baltic region. Much of this is seen as coming from wind, but this cannot provide the flexibility and security of energy supply and nuclear can play a substantial role in enabling this. Fermi Energia is observing the licensing and supply chain progress of other developers of small nuclear reactors and is engaging with local and national authorities in Estonia in order to develop a value proposition and dialogue with possible sites for SMR power plant deployment. The plan is to finance such a build via private capital and ownership responsibility, based on a model of disruptive technology innovation.

- **ELSMOR (Ville Tulkki, VTT)**

ELSMOR is a project funded by the Euratom 2014-18 Research and Training Programme and is aimed at investigating improved safety features, refueling and spent fuel management of Light Water SMRs. It is undertaken in collaboration with the French SMR developer consortium and is used as an early conceptual development version of the French Nuward SMR for some technology reference cases. Work demonstrated that SMR safety follows the same Defence-in-Depth principle as for larger systems but requires a greater focus on passive safety features. In addition to the investigations, the safety case methodologies and models that the project develops will be used on a chosen plant reference design in order to demonstrate their applicability for real-world cases. A stakeholder engagement programme and an international workshop are planned in order to disseminate results.

- **Passive systems and SMRs (Christophe Herer, IRSN)**

ISRN is the technical support organisation for France's Nuclear Safety Authority. Its approach to passive safety assumes that this form of safety mechanism relies on natural laws, properties of materials and internally stored energy. IRSN interprets SMRs as reactors with <1000 MW thermal output or <300 MW electrical output. Passive safety systems are already integrated into existing reactors in large nuclear power plants, but a common approach to SMRs design places a greater reliance on them than with large reactor systems. This may be because the physics of SMRs of smaller size makes passive safety systems more suitable for them than for large systems. IRSN has been increasingly involved in the study of passive safety systems and their performance in SMRs. Passive circulation and cooling is a significant area of work. IRSN is willing to develop several new experimental loops like ALCINA, HEXPO and EIPI to characterize the underlying physics.

- **Experimental support for SMR passive safety systems (Roberta Ferri, SIET)**

SIET is a company established in Italy with the primary purpose of carrying out safety tests on components and systems of nuclear power plants. Its core business focuses on thermal hydraulics, but extends to design of experimental facilities, instrumentation and product certification. The site allows testing of large components at megawatt-scale (3 facilities SPES, GEST and IETI at 7-10MW). In the area of SMRs, work has included testing of steam generator tubes (including the NuScale design) in the SPES-3 Integral test Facility. Work is not limited to LWR designs and has encompassed testing of steam generators for liquid metal cooled systems. SIET is also involved in Euratom research, including the ELSMOR project.

- **Lessons learnt from approval of NuScale SMR (Dom Claudio, NuScale)**

First Dom Claudio reminded the development of NuScale Power which was formed in 2007 to complete the design and commercialise a SMR. In 2013 NuScale was awarded over $300M in DOE funding. Now total investment is greater than US$1B. The speaker then presented the NuScale power module and components, each module being able to deliver up to 77MWe while several plant options are considered with 4, 6 and 12 modules. Regarding innovation the main features are illustrated in the management of decay power which is performed with no pumps, no external power or water. NuScale received standard design approval by NRC in 2020. Dom Claudio then focused his talk on the challenge of innovation, which requires additional regulatory work and a holistic approach in evaluating safety, and faces disincentive since approval is time and cost consuming to achieve. NuScale had to spend 8 years in pre application effort, run a comprehensive test program, analyse regulatory gap, etc. Special attention was paid to passive safety systems, containment function and core damage events. NuScale is seeking applications beyond baseload electricity like desalination or hydrogen production.

- **Nuclear: the need for radical innovation (Jacopo Buongiorno, MIT)**

The growing consensus that nuclear energy can play a major role in the decarbonisation of society needs to be accompanied by a shift in the economic models and design approach used for new nuclear plant. Jacopo Buongiorno argued for the adoption of smaller plant with higher volume manufacturing and proposed the nuclear "battery" as a solution. This is presented as a highly integrated, factory built highly transportable 1-10 MWe modular reactor system, with long-lasting fuel that is fully serviceable off-site. Such products need to be cost-competitive with natural gas boilers and licensable in locations with high population densities. These would be useable in a wider variety of applications and thus across many markets. However, avoiding cost escalation in the design process is seen as a key challenge.

- **Advanced modular reactors for UK (Zara Hodgson, NIRO)**

The UK has a legally binding obligation to reduce its net greenhouse gas emissions to zero by the year 2050. It recently released a new energy plan that includes a substantial role for low-carbon hydrogen as an energy carrier and reliance on nuclear, renewables and CCS in electricity and hydrogen generation. This also includes plans to agree on final investment for one further large nuclear plant by the mid-2020s, develop a LW- SMR design, build a demonstrator of a non-LWR SMR by the early 2030s, and build a commercially-viable fusion power plant by 2040. A dedicated Advanced Nuclear Fund will be established to support the SMR-related elements of this programme.

2.2.3. Emerging project ideas

In conjunction with TS2, a NUGENIA TA6 meeting, scheduled right before the SNETP FORUM, helped identifying some project ideas.

- A follow-up project of ELSMOR, which contributes to defining future uniform European requirements for SMR licensing. For instance, current work may lead to identifying gaps in code qualification requiring additional experimental testing in particular in the field of passive safety systems
- Thanks to their intrinsic safety performances and reduced emergency preparedness zone to site boundary, SMR are envisaged close to industrial sites and cities. It would be therefore interesting to build a proposal studying the ability of PW-SMRs to provide energy to district heating and hydrogen production through water electrolysis. Discussions are ongoing in order to submit such a proposal to the next Euratom call.
- One issue that was risen is the social acceptance of numerous SMRs being deployed closer to cities and industrial sites. Such item can be looked at with the SHARE initiative also under discussion for submitting a proposal to the next Euratom call.

2.3. Technical session #3 – Fuel Development and fuel cycle efficiency

This session was moderated by Steve Napier (NIRO) and Bruno Michel (CEA).

2.3.1. Scope

Fuel development and fuel cycle efficiency: industry stakeholders consider that the closure of the cycle, defined as the complete recycling of spent fuel requiring no new supply of natural uranium to produce electricity, is a long-term target for the sustainability of the nuclear industry. A closed cycle for Pu involving multi-recycling could be the first step towards a fully closed cycle. Developing scientific knowledge and expertise on nuclear fuel recycling, while taking into account waste reduction, environmental parameters and hypothetical accidental operations is paramount. Innovative fuels are also needed to make this recycling possible, as well as to enhance safety under various operating conditions. Fuel performance codes based on a thorough understanding of the fuel behaviour obtained by complementary post irradiation experiments, separate effect experiments and multiscale modelling are the way forward to improve the efficiency of the development of these fuels.

2.3.2. Summary of the technical session

- **Developments in Advanced Recycling and Sustainability for Future Fuel Cycle Options (Robin Taylor UK NNL)**

Robin Taylor from UK National Nuclear Laboratory (NNL) covered the drivers for optimisation of advanced recycle processes and UK's Advanced Fuel Cycle Research Programme (AFCP). The key questions the programme was asked to provide some answers to; Can we do better? Can we find 21st Century solutions for Spent Fuel recycling? How to realise the benefits by addressing the perceived problems of recycling?

The programme covered a matrix of key topics for process optimisation: process safety; sustainability; waste management and environmental impact; non-proliferation and economics

The presentation covered the following research topics: Uranium/Plutonium advanced aqueous reprocessing; heterogeneous recycling option for minor actinides; homogeneous recycling option for U and transuranic actinides together and results from NNL's Sim Plant.

In summary, AFCP is developing options that promote sustainability and de-risk deployment of Advanced Nuclear Technology by collaborating internationally, including the European projects (GENIORS, PUMMA & PATRICIA).

The advanced recycling options currently under development in UK and internationally include.

- Flexible, advanced processes that reduce costs, wastes, environmental impacts and add proliferation barriers
- Trends in separations towards single cycle concepts, use of centrifugal contactors, mixed actinide products and complexation rather than redox reactions
- Separation processes are in the TRL range 3-6 (development through to demonstration)
- Interfacing with upstream, downstream & ancillary processes is an important next step towards industrialisation

The AFCP is developing modelling tools to evaluate fuel cycle options.
- E.g. NNL Sim Plant highlights reductions in wastes and plant size achievable through R&D

- **Nuclear Data for Advanced Fuel Cycles (Allan Simpson UK NNL)**

Allan Simpson also from UK NNL covered nuclear data for Advanced Technology Fuel (ATF), developing tools for an advanced fuel cycle (FISPIN11) and nuclear data for advanced reactors.

The presentation also gave background information on the importance of nuclear data for all nuclear R&D. Nuclear data is key to all the programmes in the UK AFCP as well as international research programmes. It underpins research and development across the entire fuel cycle, as well as nuclear reactors under development and under construction. There are over 90 organisations in the UK engaged in AFCP work.

The presentation gave details of the work being carried out in support of advance LWR fuel development and the importance of nuclear data in the fuel qualification process. It identified the gaps in the existing data and the work being carried out to fill these gaps and verify and evaluate the data.

FISPIN is the UK spent fuel inventory code. Its performance is well understood for existing fuels and reactors, however inventory calculations for advanced systems may introduce greater uncertainties.

In order to start testing this, under AFCP the UK has been developing FISPIN's uncertainty handling capability, making use of the embedded uncertainty information in nuclear data, to assess the resultant uncertainties in the inventory. There is a need to understand the impact now, in order to focus work on improvements.

He concluded saying that programme elements such as Nuclear Data and Nuclear Physics relevant to the sector are vital enabling capabilities without which the UK nuclear sector cannot function.

- **Benchmark and improvement of fuel performance codes (L. Luzzi Politecnico di Milano)**

Simulation of the fuel element behaviour under irradiation involves many phenomena. Among them thermo-mechanical behaviour, irradiation/neutron flux effects, burnup/fission products effects, microstructural changes and chemical modifications. In fuel performance codes there is a high complexity to represent these multi-physics phenomena featured by different time and space scales. The computational schemes of these codes are based on numerous material behaviour and models and covers normal and off-normal irradiation loadings conditions. There are various fuel performance codes depending on the objectives and the field of the targeted application. Among these modelling options there are geometrical description (from 1D to 3D), multi-physic description (thermic, mechanics, fission gas behaviour, thermodynamics,…) and also multiscale approaches (fuel rod, fuel pellet and cladding, microstructure,…). State of the art was detailed as recent improvements obtained in the framework of several international programs. Among these significant progresses, there are inert Gas Behaviour, He production and behaviour, thermal properties of MOX and thermo-chemical aspects. The validation strategy of the FPCs is based on "separate effects" and "integral data". These experimental data are obtained from in-pile and out-of-pile tests thanks to online measurements and post irradiation/test examinations. Some results obtained in different international benchmarks were illustrated. For instance, clad external temperature and fuel rod internal pressure assessment in a LOCA accident were compared with Halden experiments in the FUMAC project. For sodium fast reactor fuels the SUPERFACT benchmark has also been carried out in the framework of the INSPYRE H2020 project. To conclude, the main ongoing challenges regarding fuel modelling, multi-physics coupling and FPCs validation were summarized.

- **An Update on the Development of FCM fuels for Micro-Modular Reactors (Mark Davies USNC)**

Mark Davies from USNC presented on the development of Fully Ceramic Micro-encapsulated Fuel (FCMF) for MMR reactors. This covered production of Triso particles through to FCM pellets, and included the development of a multi pellet Spark Plasma Sintering technique to match the production requirements of fuel for the MMS reactor

Work was underway to provide accelerated qualification of the fuel. Materials test reactors will be utilized to deliver an accelerated qualification programme. The normal and Off normal tests will be conducted at 30% and 110% lifetime burnup. 30%, which covers approximately 7 years of FOAK operation, in approximately two years from commencement of test and delivered ahead of FOAK plant assembly with 110% in approximately 4 to 5 years. Off normal testing conducted at separate facility.

The Next Steps - Executing Canada's First SMR Project.

Vendor design review with the CNSC is now entering phase 2. The agreement to site at CNL/AECL has been signed. There is an active application for an Environmental Assessment and License to Prepare Site. Partnership established with Ontario Power Generation through Global First Power to build, own and operate the plant.

This schedule will bring Canada's first SMR into operation by 2026 or earlier.

- **Future prospects in fuel development and related R&D needs (Guy Gentet FRAMATOME)**

The presentation introduced the industrial need associated to a holistic R&D program in order to improve safety for innovative fuel assembly and control rod absorber. The objectives of this R&D program are the development of a fuel multi-physics platform, accident tolerant fuel and innovative control rods. Future prospects in fuel developments for FRAMATOME concern also VVER reactors due to their growing numbers and their contribution to decarbonized energy. The main objectives associated to the fuel multi-physics platform are the improvement of safety with the increase of knowledge and the core loading optimization. The different R&D aspects to address for this are: 3D simulation of fuel assembly including Fluid Structure Interaction, coupling of FSI tools with neutron physics and inhomogeneous flow simulation. The second aspect discussed concerns simulation and experimentation for margin assessment of Accident Tolerant Fuels. For the later, R&D topics are 3D models for ballooning and fuel relocation, simplified models and fuel performance codes for industrial studies, meta model for monitoring systems and inspection/PIE techniques. Finally, the holistic R&D was described for Accident Tolerant Control Rod Absorbers with a complementary approach to the one used for fuel rods. Conclusions recalled that fuel supply for VVER is an important issue to which FRAMATOME is willing to contribute through safe, efficient and decarbonized energy production. For this FRAMATOME is ready to launch European R&D programs in the field of multi-physic core platform and advanced simulation/experimental techniques for accident tolerant fuel/absorber designs.

- **Using a basic research approach to improve fuel performance codes (Marjorie Bertolus CEA)**

One effective way to bring further insights into fuel behaviour modelling is to use a separate effect approach with a synergy between experiment and multiscale modelling. This kind of approach was developed in the F-BRIDGE FP7 project for UO_2 fuels and is now applied on $(U,Pu)O_2$ fuels in the INSPYRE project. In the latter, basic research on different physics involved in fuel behaviour is achieved and integrated in fuel performance codes through a multi-scale approach. Two examples of significant progresses obtained in the INSPYRE project were presented for thermal properties and fission gas behaviour. In the first case, the heat capacities are computed thanks to atomistic simulation in stoichiometric $(U,Pu)O_2$ as a function de Pu concentration. Through these simulations, it was possible to characterize with a high precision the Bredig transition which leads to a significant decrease of the heat capacity at high temperature. Then a macroscopic model was proposed to fit atomistic simulation results and was used in a fuel performance code in order to evaluate the impact on the fuel central temperature under a high rate power transient. It was concluded that the impact is significant and that an improvement of other properties is needed in order to reduce error compensation in codes. For the second example the Sciantix module developed for the inert gas behaviour was presented. In this approach, the objective is to have physically based constitutive equations with parameters fitted through a separate effect validation. To conclude, recent progresses achieved in the INSPYRE project were summarized and some prospects were given for non-linear mechanical behaviour.

- **IRSN Fuel + software platform to simulate fuel behaviour in accidental conditions**

The objectives of the “fuel+software platform” are to simulate the « life » of the nuclear fuel from the irradiation in the reactor until the long-term storage. The research strategy is based on three steps “Knowledge acquisition”, “Knowledge consolidation” and “Knowledge use”. The «fuel+software platform» has strong links with ongoing experimental programs such as CABRI international program (RIA), PERFROI (LOCA), DENOPI (Spent fuel pool) or SCIP. The simulation of each step of the nuclear fuel life is achieved through a suite of fuel performance codes in the framework of the «fuel+software platform». The latter addresses different scales: local, fuel rod, assembly and reactor/spent fuel pool. The «fuel+software platform» provides tools to facilitate studies for uncertainties propagation, sensitivity analysis, automatic running routines, post-processing. The «fuel+software platform» architecture is based on three main layers (computer architecture, physical model and application validation) and is interfaced with third party softwares. The codes of the «fuel+software platform» developed by IRSN are SHOWBIZ, SCANAIR, CIGALON and DRACCAR. The features of each code have been detailed; main objectives are summarized in the following. SHOWBIZ is devoted to zirconium alloy behaviour under design basis accident. The IRSN code simulate the thermo-mechanical behaviour of a fuel rod under an RIA transient. The CIGALON code estimates mechanical consequences of a fuel-coolant interaction caused by the rupture of a cladding during an RIA type test. The DRACCAR code simulates the 3D thermo-mechanical and reflooding behavior of one or more fuel rod assemblies during a loss of coolant accident (LOCA)

- **Spent Nuclear fuel - Characterisation and Evolution Until Disposal (Peter Jansson UPPSALA)**

Peter Jansson from Uppsala University gave an overview of the SFC covering the four tasks, scope and objectives and the users group. The objectives of the EURAD supported programme are:

To produce experimentally verified procedures to reliably determine the nuclide content in SNF, including realistic uncertainties, by developing characterization techniques and uncertainty quantification.

To understand the performance of SNF during prolonged storage, transport and emplacement in a deep geological repository by enhancing the capability for safety analysis of relevant operations.

To understand the behaviour of SNF and ageing effects under normal and postulated accident scenarios until disposal, in order to identify relevant or typical bounding cases and to contribute to operational safety for SNF handling at packaging facilities.

To contribute to education, training and building of competence in the subject.

The experimental tasks included:

- Fuel properties characterisation and related uncertainty
  - Analysis to produce experimentally verified procedures to estimate reliable source terms of spent nuclear fuel (SNF), including realistic uncertainties. The main source terms of interest are gamma-ray and neutron emission rate spectra, decay heat and inventory of specific nuclides

- Behaviour of nuclear fuel and cladding after discharge
  - In order to understand and describe numerically the behaviour of spent nuclear fuel (SNF), irradiated cladding, fuel/cladding chemical interaction (FCCI) and ageing effect under conditions of extended interim storage, transportation and emplacement in a final disposal system.

- Accident scenario and consequence analysis

Study SNF behaviour under accident conditions which may lead to a potential loss of confinement during storage, transport and predisposal activities. Perform criticality safety analysis for credible transport accident scenarios after long-term storage (including fuel rod failure and in-cask fuel distribution). Determine the accumulated dose in materials relevant for moderation and/or shielding.

Finally, Peter identified a 20 strong users group and invited any other interested organizations to join.

2.3.3. Emerging project ideas

The following FRAMATOME proposals have been discussed in a NUGENIA TA7 online meeting held the 4th February afternoon.

- Fuel multi-physics platform to provide improved safety margin assessment
- Advanced simulation and experimental techniques for safety margin assessment of Accident Tolerant Fuels
- Holistic approach for Accident Tolerant Control Rod Absorbers

3. Technical session #4 – Innovative and perspective materials solutions

This session was moderated by Lorenzo Malerba (CIEMAT) and Karl-Fredrik Nilsson (JRC).

3.1.1. Scope

Innovative nuclear materials solutions ranging from composites to strengthened materials, coatings or self-healing protections, traditional and newly identified alloys, coupled with advanced manufacturing, offer the possibility to prolong component lifetime, decrease costs, improve efficiency and simplify design, especially in the case of new types of reactors. This session intends to provide examples and stimulate discussion on the most interesting and promising innovative and perspective materials solutions, their development, their characterisation and qualification, and open issues.

3.1.2. Summary of the technical session

- **Additive manufacturing for nuclear applications (P. Aubry, CEA)**

Additive manufacturing (AM) means to fabricate a physical object by adding matter layer by layer following a digital file. The market size of AM increased dramatically in the last 15 years, especially concerning 3D polymer printers. AM is especially suitable in nuclear to produce in-house (e.g. for replacement or repair) relatively small parts with any geometry, even without stopping operation. It is however necessary to integrate AM materials in the nuclear codes, which is a very significant work. All steps require attention, from the material in powder to the component digital design, the technique used and its control, finishing and characterization/quality control. Applications made or ongoing at CEA on different nuclear components for current and future (ASTRID) reactors have been shown, based on two techniques: directed energy deposition and powder bed fusion. The materials are mainly "traditional ones", such as 316L, Ni-base alloys and, to a lesser extent, F/M steels, although HEA are also produced in this way.

Q. Is the material, the process or the component that has to be qualified?

A. Not fully clear, it depends on the industry and the application, but it is mainly the material.

- **Ceramic coatings for nuclear applications (F. Di Fonzo, IIT)**

This talk summarized about 10 years of work on pulsed laser deposition of amorphous/nanocrystalline ceramic coatings, with a view to increasing operating temperature and dpa of nuclear systems with increased safety. In this framework, suitable coatings can provide protection against corrosion and act as permeation barriers to H isotopes, while not affecting the mechanical properties of the substrate. Amorphous Al_2O_3 oxides offer mechanical and physical properties that match those of substrate steels such as 316L, showing no corrosion attack over large surfaces, based on testing in several heavy liquid metals. No cracking observed even under nano-scratch tests or up to large applied strains. Irradiation induces (re)crystallization, thereby losing the benefit of the amorphous or nanocrystaline structure in terms of absence or removal of defects. There are by now several data obtained under irradiation although full characterization requires more thorough tests.

Q. What happens if the coating fails for licensing purposes?

A. (given later) So far, no failure ever observed under all conditions to which coatings have been subjected but it should be possible to monitor with NDE benefiting from the insulating nature of the alumina coating.

- **High Entropy Alloys for nuclear applications (A. Weisenburger, KIT)**

High entropy alloys (HEA) or compositionally complex alloys (CCA) or multiphase alloys are composed by five or more elements, originally in equiatomic concentrations: the high mixing entropy with low mixing enthalpy provides stable solid solutions (2004). Now they are not any more strictly equiatomic. The high distorsion of the crystal produces slow diffusion and further stabilises the solid solution. The overall properties, sometimes surprisingly good, come out of the "cocktail" of elements. For example, some HEA exhibit exceptional mechanical properties, even at high T in some cases (drops above 600ºC). For nuclear application they need to resist not only exposure to high temperature, corrosive fluids, stress and heat fluxes, but also irradiation. For nuclear applications Co, often found in HEA, has to be removed. HEA have potential use in all generation reactors, especially for cladding. Recently low swelling HEA compared to conventional alloys have been obtained.

The talk described the HEAFNA pilot project of the EERA JPNM: large project, so far in-kind, covering a broad spectrum of activities, from alloy design and production to qualification in terms of compatibility, high T, irradiation tolerance and understanding of radiation effects. A short overview of some results concerning design of alloys and compatibility was given. Alumina formation on surface was observed with no (or very low) hydrogen production over time at high T for ATF applications. Open issues: improved modelling for alloy pre-selection, long term stability especially under irradiation. A project involving NUGENIA and EERA JPNM is under discussion. The NEA Expert Group on Innovative Structural Materials is preparing a workshop on HEA.

Q. For HEA development, how well can you predict the behaviour and how much do you rely on screening tests?

A. Modelling is advancing but still based on minimizing Gibbs function; other approaches are developed for better prediction, e.g. minimizing stacking fault energy, but this must go together with new screening methods. One idea is to use thin film sputtering in with variety HEA compositions in one sample in combination with advanced examination methods. Clearly HEA is still low TRL.

- **Alumina forming steels for ATF and GenIV cladding (P. Szakálos, KTH)**

Alumina forming steels can be ferritic (FeCrAl), austenitic (AFA) or martensitic (AFM). Concerning FeCrAl it is by now known which regions of Cr-Al composition + reactive elements provide optimal microstructure and alumina layer stability. Excellent properties obtained with a 10%Cr-4%Al+RE steel, which forms very thin (10-20 nm), but stable and self-healing, alumina superficial layers. As a ductile laser-welded overlay with 10Cr-4Al on 316L cladding tube offered excellent corrosion protection up to 800ºC on the liquid lead side. However, the inside corrosion (Fuel-Clad Interactions) might be a problem since 316L is sensitive to tellurium, caesium and iodine. A potentially very interesting solution would be to change 316L (or 15/15Ti) to a corrosion resistant AFA in the future which would give protection against internal corrosion due to fission products as well. Recently, alumina forming martensitic (AFM) steels were developed at KTH as well: they offer very good corrosion resistance and excellent erosion resistance together with the good properties of martensite, but above 650ºC the martensite becomes unstable.

In conclusion all alumina forming alloys with self-healing properties are good for LFR: Fe10Cr4Al good as self-healing overlay weld up to high T, AFM and AFA offer good blend of mechanical properties and corrosion resistance up to reasonably high temperature (600-700ºC).

Q. Can AFM be also a good candidate material for fusion technology in contact with PbLi?

A. There are no data in PbLi but if the temperature does not exceed its inherent limitations it should work.

- **SiC/SiC joining for cladding applications (M. Ferraris, POLITO)**

There are different concepts of nuclear grade SiC/SiC tubes for cladding: Japanese NITE (Nano-Infiltration Transient Eutectic), CEA sandwich tube with internal metallic layer for hermeticity and tubes with different layers of monolithic and composite SiC from ORNL. For all, joining is crucial: both to develop joining methods and to test them under shear, checking their behaviour under irradiation. Glass ceramics have the advantage of being rapid and to work at 0 joining pressure: these materials act like a glue that seems to be resistant to irradiation: at 530ºC to 20 dpa the microstructure remains unchanged, with the same torsional strength.

The IL TROVATORE project includes SiC/SiC as cladding material for ATF, thus in a LWR environment. Both Japanese NITE (for which joining is considered as solved) and CEA sandwich are included in the qualification programme. For LWR ORNL and General Atomics developed hybrid polymer pyrolisis CVI joint as precursors to SiC, in this way SiC is eventually the only material in the joint, however it then needs to be CVD coated: it is a long process. For LWR Polito developed a SilicaAluminalYttria (SAY) glass ceramics method, which is being tested by CEA and in Japan, as well as at TUD. It has to be demonstrated that these joints are LWR resistant.

Q Your presentation referred mainly to LWR, but wouldn't SiC/SiC be more suitable for high temperature reactors?

A. Joining is a key issue for any reactor system. IL TROVATORE focuses on LWR, and in particular corrosion that can be addressed by coatings. For gas cooled reactors we don't have the corrosion problem, so it should be easier.

- **Advanced online monitoring and NDE for nuclear systems (M. Rabung, FhG IZfP)**

NDT methods enable easy characterization of materials and components. Ageing models fed with continuously monitored data enable predictive maintenance as opposed to scheduled maintenance. Digital replica and/or twins aggregate these data. The goal is to develop intelligent NDE technologies, by collecting data along all component lifetime with intelligent sensors, to understand, mitigate and control ageing. The example of the DBTT prediction by NDE in RPV steels with multisensors has been presented. The outlook is compressed sensing, i.e. filter and collect only data that indicate a change of material property: less data, with simpler sensors and less power consumption, to have less data to handle.

Q. Are there plans to apply sensoring to decommissioned RPV?

A. It would be an interesting option, but as far as I know it has not been done yet.

- **Innovation on concrete structures (M. Ferreira & E. Bohner, VTT)**

Concrete is the most used manmade material worldwide because of its good properties and versatility. It is easy to produce and apply, and available at low cost. However, it comes with a large sustainability burden. On one hand cement is responsible for 8% of CO2 emissions, and on the other hand it consumes many natural resources. The main factors driving innovation in the concrete field are policies addressing sustainable development (carbon neutral concrete and circular economy), the need for greater safety and better quality, concrete, improved sustainability, addressing the raw material scarcity.

Novel concrete covers aspects such as new cement chemistry, alternative aggregates types and sources, special concretes, digitalization and new methods of construction. Examples of innovation are:

- New binder chemistry to reduce CO2 emissions: three different examples were presented highlighting the challenges yet to come until commercialization;
- Alternative aggregates: recycling from concrete demolition (upgrading recycled aggregates, more difficult for binders); use aggregates other industry wastes or side streams, or then produce artificial aggregates;
- Reuse by appropriate disassembly design and service life monitoring of structural elements,
- Self-healing, self-sensing, CO2 capturing concrete;
- Digitalization for circularity of concrete technology, checking quality along the whole production chain;

- Prefabrication technology (used eg in AP1000);
- AM can reduce waste, labour cost and production time significantly;
- Understand concrete ageing under irradiation (neutrons and gamma): swelling, creep, shrinkage: use AI for monitoring and decision-making.

Furthermore, the EURATOM funded research Project ACES was briefly presented.

Conclusions: currently there is no clear alternative to structural concrete for NPP, but there is a need for alternative chemistries (also to reduce carbon emissions) and to enable better recycling/reuse of concrete. Digital technologies are needed across the entire process chain.

Q: How is blockchain technology used?

A: It is used because it is incorruptible.

A: It guarantees integrity and liability of the data, and enables use of smart contracts

Q: Is there any specific nuclear issue or are problems common to all technologies?

A: There are specific issues: The common structural typology of NPP is rather unique, with very large cross-section, heavily reinforced, with prestressing ducts, and possibly embedded liners. The environmental loading conditions can be extreme and included radiation which normal concrete structures do not encounter. LTO of these structural elements challenges our current knowledge on concrete performance, and our capacity to effectively assess it (e.g. with conventional NDE).

- **A way to innovative polymers for nuclear applications: the MEGAPOL initiative (M. Kuntz, EDF)**

Polymers enabled the boom of renewables (wind, concentrated solar, …). They provide protection against several phenomena: corrosion, fire, seism … There is margin for more application in nuclear: some repairs are only possible with polymers, cost implications, life extension.

The MEGAPOL initiative involves 6 members in a nuclear consortium, covering most NPP types, each bringing case studies: it is collaborative, co-funded and co-directed. The goal is to extend the use of polymers to contribute to extending operating life and reduce costs in nuclear.

D1- Nuclear elastomers: widely used in nuclear, look at ageing processes to extend lifetime: chase lifetime with no ageing or model ageing in empirical or multiscale way;

D2- Repairs: fix severe leaks at the bottom of the spent fuel pool in a few minutes without emptying the water or sending divers.

Consortium open to solve new polymer issues.

Q: Is the use of polymers foreseen for load bearing components?

A: Not now but maybe in the future

- **How to introduce new materials in design codes (C. Pétesch, CEA)**

The core of the presentation is that there is interest to connect R&D and standardization. The advantage of design codes is that all the info is collected once for all, for use of all instead of spreading it through different clients. However, the regulator needs to be confident in the validity of the code. For innovative reactors standardization this is a way to increase TRL. Users want to be more and more involved in the code development.

The example of RCC-MRx was given:

- Code = set of rules dedicated to specific types of components, e.g. mechanical, for all steps, from manufacturing to component design, welding, examination;
- For reactors working at high T, research reactors or fusion reactors, rules have been extended for application to conditions of significant creep and significant irradiation;
- Code structure: probatory phase rules, code opening, guideline for innovative concepts, components, coolants and materials;
- The material needs to be completely defined before introduction: full mechanical characterization, composition, fabrication, mechanical properties … this is necessary to define the specification of that material to ensure procurement with quality
- Both base metal and welded joints need to be fully defined
- Design data will be those of the material selected: tensile properties, fatigue behaviour, …
- Then the variation of properties when creep and radiation are significant may also be added;
- When the material file is not complete, a dedicated part of the code, called probationary phase rules, has been created to collect results of R&D or pre-normative developments not always sufficient to be included in the code, but to be completed.

Example of EUROFER: it was gradually introduced, proposal received in 2011, basic data included in 2012, irradiation data introduced by 2018. It took 7 years to introduce a material in the code! This is a long time!

Conclusion: Nuclear needs innovative materials and processes but to ensure quality assurance and qualification in nuclear is challenging → strong collaboration is needed between R&D and design coders / industries.

Q. New materials for new coolants, how does it work?

A. Currently only a limited set of coolants is considered with an opening to use the code in innovative coolant. The community is now working to define better in the codes the criteria and steps for the introduction of new materials for new coolants, all parameters and effects of the coolant on the material are needed.

- **Panel discussion (all)**

Speakers were invited to address the main realistic priorities in their field:

- A. Weisenburger: HEA are still at TRL 2-3, there is still a long way to go. Probably the closest application is to think of using HEA as coating materials.
- P. Szakalos: AF are relatively close to use for corrosion protection: China is moving fast to them, in Sweden the Sunrise project with 6 M€ is studying the possibility of building different components of LFR with AF steels, finally producing a mock-up.

- F. Di Fonzo: What are the problems of coatings? They are not self-healing. But they are also not easy to break. The high energy of the procedure of coating seems to prevent delamination under all conditions. The main issue is the industrial fabrication upscale because the process is completely new. Currently 30 to 100 cm long tubes are feasible in lab, but there is no industrial process ready. For the qualification the strategy is that, when the demonstrator exists, data on coated components will be gathered in the proper environment. It should be possible to monitor coating breaking with NDE techniques, taking advantage that they are insulators.
- C. Petesch: Do standardization bodies collaborate between themselves? Yes, e.g. the Cordel consortium compares standards to give elements for authorities to show equivalence of codes on specific points.
- M. Ferreiro: Concrete changed over time and this complicates things in connection with life extension. Good studies have been done in the recent past to identify knowledge gaps more clearly, to define a roadmap for R&I.
- M. Rabung: Materials qualification takes a long time. How realistic is it to add the sensor variable for continuous monitoring? Sensors themselves must resist corrosion and irradiation. No activities are underway on this topic.
- U. Ehrnsten: It is important to see what other industries do on monitoring. E.g. what does the aerospace industry do? VTT already implants sensors in components fabricated by AM.
- K. Nilsson: It is useful in general to look at what other industries do.

3.1.3. Emerging project ideas

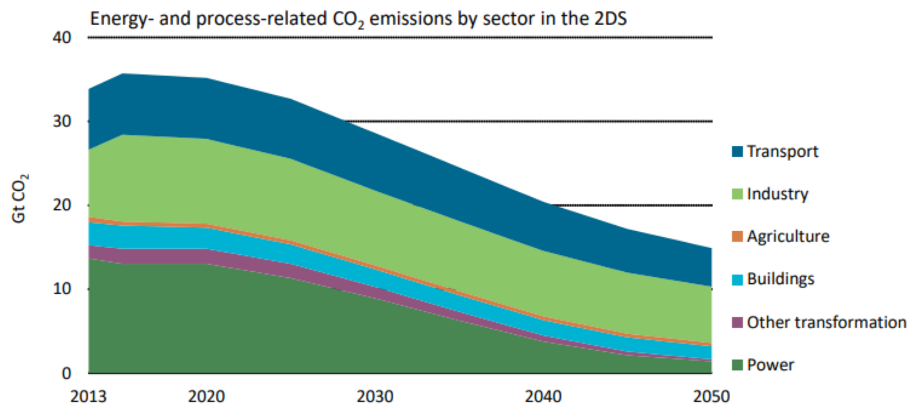
At the moment the only project that is being discussed concerns HEA from several points of view, including fabrication, coating, coding and other aspects. This project should be able to include several, though not all, of the issues discussed in the TS4.

3.2. Technical session #5 – Energy systems, new applications, economy and licensing

This session was moderated by Marc Deffrennes (weCARE) and Franck Carré (CEA).

3.2.1. Scope

The objective of this technical session was to highlight and discuss the potential for nuclear energy to contribute to decarbonisation beyond the power sector. According to the International Energy Agency 2DS Scenario (limiting temperature increase to 2 °C by 2100), the industry and transport sectors account today for around 45% of annual CO_2 emissions, on par with the power sector. While electricity production is expected to be nearly fully decarbonised in 2050, this might be more difficult to reach for industry and transport. It is thus critical to investigate how low-carbon nuclear energy may contribute to this endeavour.



3.2.2. Summary of the technical session

- **Role of nuclear in future energy mixes – Kirsty Gogan (TerraPraxis)**

The speaker first recalled the high dependence of our economies on fossil fuels and the paradigm shift necessary to save the planet. Similar to replacing meat in hamburgers by plant-based “Impossible Burgers”, she suggested replacing fossil high-carbon fuel by synthetic low-carbon fuel. Advanced heat sources need to be at the core of the innovation process. Just as an example one may name flexible cogeneration of heat and power, producing hydrogen for electricity (fuel cells) and fuels (synfuels) etc. Economics is for sure a key factor for industrial deployment beyond the development and demonstration phases. Economics will be a function of fossil fuel prices, but also of the price of CO2. It will also be function of the scale/series effect and the readiness of an advanced supply chain based on modularity and advanced manufacturing techniques. The study performed by TerraPraxis shows that the investment needed for fuel substitution in 2050 would require of the order of 17 billion USD in case of synfuels and hydrogen facilities, 25 billion for further exploration and exploitation of oil and gas, and 70 billion in case of renewable power to fuel. And beyond the economic cost, the production of hydrogen by renewable sources would require a lot of geographical surface, on land or sea. In conclusion, given the scale and urgency of the required clean transition combined with growth of the global energy system, all zero-carbon hydrogen production options should be pursued. The potential of advanced heat sources to power the production of large-scale, very low-cost hydrogen and hydrogen-based fuels could transform global prospects for near-term decarbonization and prosperity. The TerraPraxis report “Missing Link to a Livable Climate” sets out a pathway to decarbonize a substantial portion of the global energy system, for which there is currently no viable alternative.

- **Beyond Electrification: ways to tackle difficult to decarbonize sectors – Aiden Peakman (NIRO)**

Electrification using low-carbon energy sources will play an important role in decarbonising the global energy system; but the speaker confirmed the importance to consider low-carbon forms of energy for non-electric applications. The way individual countries meet their energy needs and the technologies they employ, will differ. For instance, with respect to heating, some countries already operate well established district heating networks and others have significant gas networks, which will impact their individual pathways for decarbonising the heating sector.

The industrial sector is responsible for around 20% of global greenhouse gas emissions, and again whilst increased electrification using low-carbon energy sources will play a role, there will likely be a need to employ more novel routes to help decarbonisation. Nuclear energy offers a number of solutions that could support industrial decarbonisation via the direct application of nuclear heat and the production of low-carbon hydrogen for heat and/or as a low-carbon chemical feedstock.

Finally, with respect to transport, battery electric vehicles are becoming a well-established technology for reducing emissions in the transport sector. For heavy duty vehicles, maritime and air transport, the adoption of hydrogen, ammonia and/or synthetic fuels offer solutions for decarbonising these sectors. These energy carriers could create significant additional demand for low-carbon hydrogen required in their synthesis, which nuclear energy could deliver.

- **Industrial applications of HTRs and the Horizon 2020 GEMINI+ project – Dominique Hittner / Michael Fütterer (NC2I)**

GEMINI+ is the most recent project of a series co-financed by successive Euratom Framework Programmes since the 1990s for technology development of High Temperature Gas-cooled Reactors. Owing to its specific safety and performance characteristics, this type of nuclear reactor is particularly well suited for industrial process heat applications including large-scale bulk hydrogen production. GEMINI+ laid the groundwork for technology demonstration by proposing the main design options, the basis for a licensing framework, and by corroborating the feasibility of demonstration in the near term.

Industrial requirements can be met such as operational flexibility, cost competitiveness with natural gas, and the absence of mutual perturbations between the nuclear plant and the industrial user of the process heat. A design was developed with a potential application in Poland for the delivery of high temperature heat for industrial processes, replacing ageing standard coal and gas boilers. A programme for the development of an experimental pilot on the site of NCBJ in Świerk has been launched by the Polish government. It shall demonstrate HTGR technology and licensing in combination with various heat user applications. GEMINI+ delivered significant progress in the areas of technical feasibility, safety & licensing, and economic analysis of an HTGR for industrial process heat applications.

HTGR are unique in their capability to deliver massive amounts of low-carbon energy in the form of process heat to industry as an alternative to fossil fuels. The GEMINI+ system proposes a solution to implement this opportunity, while complying with the flexibility expected by industry, and being competitive with natural gas. This solution is sufficiently mature to be deployed early enough to provide a contribution to the Green Deal targets.

First, a "plug-in" deployment is considered, delivering process steam to existing industrial infrastructures, but the technology has potential for further extending into a large and growing market. In addition to low-carbon process heat, HTGR enable in particular large-scale production of low-carbon hydrogen, thus providing a major contribution to decarbonisation of industry and transport. Further cooperation with industry will allow optimising the integration of a nuclear heat source with industrial applications.

- **Enabling industrial carbon capture using green hydrogen – Ted Moryto (CNL)**

Climate change is rapidly advancing. It is imperative to deploy carbon emissions reduction technologies as soon as possible to slow the accelerating effects of global warming.

Carbon capture and sequestration in synthetic fuels is a technology that is currently available and capable of partial reductions in GHG emissions. This technology can play an important role in carbon emissions reduction bridging the gap until new technologies that promise near zero emissions have been developed for hard to abate sectors such as aviation and marine.

Replacing fossil fuels with low carbon clean energy is the simple solution to reducing carbon emissions. Unfortunately, in industries such as cement, steel and fertilizer production, even after replacing fossil fuels with cleaner energy, carbon emissions still exist in substantial quantities as a result of the chemical processes involved.

New process technologies are in development for these industries to eliminate carbon emissions, but these technologies are a decade or more away and more importantly require brand new facilities to replace existing ones which have decades of life remaining. These existing technologies have been developed over decades and currently operate at very high efficiencies of energy consumption. Off-site and on-site infrastructure to support these new processes would also require expensive modifications to support these new technologies.

A less capital-intensive solution is to capture the remaining CO2 emissions and combine them with clean hydrogen in an electrolysis cell to produce syn-gas, a feedstock for synthetic fuel.

Clean hydrogen can be produced from renewable electricity or from nuclear heat using thermo-chemical processes such as the copper-chlorine cycle used in HCuTEC™ being developed by Canadian Nuclear Laboratories. Thermo-chemical hydrogen production has the benefit of being able to recuperate heat from the industrial processes to produce hydrogen providing a net higher efficiency than pure electrolysis. These technologies coupled together can produce a fuel that is more uniform, burns cleaner and utilizes all of the existing infrastructure required to transport, store and power existing systems with a substantial net reduction in CO2 emissions.

The system would provide immediate carbon emissions reductions until such time that zero emissions alternatives are available for these industries. When that time does come the infrastructure will already be in place to produce clean hydrogen to power these zero emissions technologies.

- **Green Ammonia – Tobias Birwe (ThyssenKrupp)**

With ongoing climate change, the desire for sustainable solutions is increasing. With further developing renewable energy infrastructure at lower cost and increasing political pressure by implementing carbon taxes, the industry recognizes the necessity of reducing carbon footprints. Carbon-free power will become the key energy provider of the 21st century. While renewable power requires space and good renewable energy conditions, nuclear power requires none of it. Therefore, nuclear power could be considered as a great enabler for green technologies as it is constantly available and can balance the fluctuations that are characteristic for renewable energy sources.

Green hydrogen, ammonia or chemicals in general could benefit from nuclear power, as those plants will be most feasible with constant power import at low rates and with minimized fluctuations. With the combination of nuclear power being base load provider and renewable power being peak load provider, the feasibility of green chemicals plants will be enhanced and will also enable the transition from “grey” to “green”. In order to make that power storable and transportable, it is best to convert it to hydrogen, ammonia or methanol. These base chemicals are perfectly suited to be used also for downstream processes or as e-fuels. Ammonia has the advantage of having highest energy density, which makes it quite favorable for long distance energy transport and for long-term storage. The economy could benefit as it can start with a smooth conversion from grey to green production - and ThyssenKrupp has the Power-to-X solutions based on Uhde technology.

- **Integrated Nuclear-Renewable Energy Systems to Maximize Clean Energy Utilization – Shannon Bragg-Sitton (INL)**

The speaker started the presentation by highlighting the current situation in electricity, industry and transport, with all sectors largely dominated by fossil fuels. She then addressed the strong new trend towards political commitments against climate change and noted the move (in the US) from a renewables-only approach towards developing "technology-inclusive" solutions combining renewables, nuclear and fossil+CCS. The difficulty to accommodate the variability of renewable electricity in the grid was explained, and the fact that higher renewable market penetration tends to lead to increased system complexity with an exacerbated burden on thermal plants for load following, and creating the need for large energy storage capacities. A future multi-input/multi-output energy system was presented together with an outline regarding technology innovation needs in areas such as energy storage, thermo-electric chemical conversion, instrumentation and control for operation or cyber security aspects.

The pivotal role of hydrogen in such a system was pinpointed with several examples.

The presentation concluded with a summary of US DOE efforts in the area. Examples for this are energy system integration and collaboration between nuclear/fossil/renewable laboratories on subjects such as market analysis and techno-economics, plant and region-specific analysis, or the DETAIL lab at INL. At the same time, a public private partnership was created for demonstrating hydrogen production with LWR. Also mentioned were the support to advanced reactors and their integration in energy systems as well as the collaboration with the IAEA on hybrid energy systems.

- **Potential of SMR technologies for cogeneration and hybrid energy systems – Jean-Michel Ruggieri (CEA)**

The purpose of this presentation was to present the R&D underway at CEA on Pressurized Water type SMRs (PW SMR). The SMR program within the CEA Energies Division has two components:

- Participation in the NUWARD™ industrial project for the export market to decarbonize global electricity production;
- A prospective R&D program on PW SMR systems that not only generates electricity but that decarbonizes the production of energy vectors other than electricity;

On the NUWARD ™ component, the state of play of the project was presented, the general objectives, the partnerships as well as the success criteria of the French project. CEA's contribution to this project aims to enable the technological success of the product but also its international promotion.

On the R&D component on hybrid SMRs, CEA focuses on the use of nuclear energy production, expanding its role beyond electricity generation. Following an opportunity study carried out in 2019 on the coupling of SMR with High Temperature Electrolysis, an R&D program was defined on SMR concepts for other uses (heat, H2...). This program is divided into 4 complementary axes: market studies and definition of the needs (hydrogen and heat), SMR studies for hydrogen production, SMR studies for heat production, and R&D on Innovative Energy Conversion Systems in cogeneration. This latter line of work consists in studying multi-vector energy conversion systems (electricity, H2 heat, drinking water, etc.), their optimization by integrating storage technologies (battery, thermal, gas...) and other sources of energy production: PV and Fuel cells.

The objective of this R&D is ultimately to provide elements of the technical and economic feasibility of SMR systems for multi-vector uses.

- **HTTR licensing experience and commercial modular HTGR safety design requirements including coupling of process heat applications – Hirofumi Ohashi (JAEA)**

JAEA has been conducting R&D on safety standards for commercial Modular HTGR for power generation and process heat application to contribute for the establishment of commercial modular HTGR safety standards by regulatory authority. The R&D includes the safety demonstration test using Japans' test reactor (HTTR: High Temperature engineering Test Reactor) to demonstrate and obtain data on inherent safety features of HTGR, and development of modular HTGR safety design requirements which takes into account inherent safety features demonstrated by HTTR and the safety approach for coupling with process heat applications. Following the nuclear accident at the Fukushima Daiichi nuclear power station, revised regulatory requirements were issued by the Nuclear Regulation Authority (NRA) in 2013. The safety of HTTR was reviewed by NRA, and permission was obtained on June 3rd, 2020. The inherent safety features demonstrated by HTTR were taken into account for the safety review, and NRA confirmed that there are no major reinforcements needed due to its inherent safety features. JAEA is planning to conduct the HTTR heat application test to contribute to the development of safety standards for the coupling of process heat applications.

- **Economics of SMRs in cogeneration systems – Błażej Chmielarz/Alexandre Bredimas (USNC)**

This economic analysis was performed as part of the GEMINI+ project outlined earlier in this technical session. Poland has a strongly coal-based economy with big industrial consumers of process heat and hydrogen with a rather pro-nuclear public opinion. The speaker first presented his projections of energy costs in Poland and introduced his study as an analysis based on levelized cost of energy coupled with a sensitivity analysis for a variety of parameters. The speaker then presented as an example a Hybrid Energy System comprising a fossil (coal/gas) boiler and an HTR producing process heat, hydrogen, electricity, and district heating with a variety of technologies.

The results confirm the finding that the fossil part of the plant is very sensitive to external costs (fuel, CO2 tax), whereas the nuclear part depends most strongly on CAPEX and construction time, but also on discount rate and load factor, which obliges the nuclear part to run in 100% power mode. Different scenarios for hydrogen production were assessed, and levelized cost of hydrogen compared to today's dominating practice of auto-thermal steam methane reforming. While steam methane reforming of natural gas yields a hydrogen cost below 2 €/kg, the cheapest nuclear production method would be the combination of an HTGR with the thermo-chemical iodine-sulphur process, leading to approx. 3 €/kg. Avenues for cost reduction are in particular efficiency increase or reduction of CAPEX and O/M costs of the IS process, which is expected as the technology matures.

- **Tractebel's vision on SMRs – technical due diligence and market studies – Anicet Touré (Tractebel)**

This presentation summarized the work performed for a recent Tractebel vision report regarding SMR. For the electricity market in three very different countries, UK, Switzerland and Poland, the energy mix situation was extrapolated to 2050 based on local strengths and weaknesses with minimum grid-level LCOE as the target and with four strategies allowing increasing fractions of nuclear electricity in the system. The results point at a clear cost benefit assuming a strong nuclear component in mixes with high RES components, thanks to reduced needs for capacity building in storage and transmission.

Pushing decarbonisation beyond electricity generation, the speaker also presented the results of a market study investigating opportunities for SMR in the areas of electricity generation, hydrogen production, process heat, district heat and seawater desalination. The study confirms that very significant numbers of SMR could be built on different existing industrial sites across Europe.

3.2.3. Conclusions and recommendations

Together with the push for energy efficiency and carbon capture and storage or utilization, nuclear energy is being increasingly recognised for its large potential contribution to decarbonise the economy. Nuclear power has proved itself capable of displacing fossil-based electricity in countries such as France or Sweden and supports the decarbonisation of uses with low-carbon electricity where it can be economically viable. Lessons from the session were that small modular reactor (SMR) projects were offering new opportunities for local load-balancing, saving extensions of transmission lines, repowering decommissioned coal-fired plants, as well as providing solutions for hard to decarbonise sectors. As such, SMRs are especially suitable for hybrid energy systems and appear as a cornerstone of complex energy ecosystems.

The presentations in Technical Session 5 have been quite consistent in illustrating the role that nuclear energy can play in providing heat and power to decarbonise the industry and transport sectors. Examples were given for the production of process heat (Bruce, Calder Hall, Halden, BN 350, Stade, Gösgen…) or low-carbon hydrogen for industrial applications and heavy transport, as well as for the production of synfuels for transport (biodiesel, methane, methanol, ammonia…).

SMR-based hybrid energy systems were presented that would maximise energy utilisation and generator profitability (nuclear and solar photovoltaics for hydrogen, nuclear instead of natural gas boilers for steam generation…). Beyond near-term applications of LWR-SMRs, examples were given of high temperature reactor (HTR) plug-in applications including the production of synthetic hydrocarbon fuels before addressing further heat market opportunities (> 500°C) in Europe and overseas, e.g. through the collaboration of SNETP/NC2I with international partners. Guidelines for the licensing of non-LWR reactors and coupled nuclear-chemical plants were given through the presentation of the stepwise approach that was implemented in Japan for licensing the combined installation composed of the HTTR and the sulphur-iodine water splitting plant intended to demonstrate massive nuclear production of clean hydrogen around 2028, and plans to use this experience as a stepping stone towards the licensing of commercial HTRs and coupled industrial applications.

The unique suitability of hydrogen to address cross-energy sector issues as a clean storable multipurpose energy carrier for industry and transportation was emphasised, thus raising two issues: (i) producing hydrogen at large scale and low cost with all zero-carbon hydrogen options, and (ii) developing sustainable P2X solutions while being mindful about their overall efficiencies.

Presentations evidenced the significance of modelling energy systems for optimising their design and operation, and the significance of digitalisation for new nuclear and future energy systems for optimising the real-time dispatch according to the availability of stored energy and the efficiency of demand-side management (“peak shaving”).

Presentations furthermore highlighted the significance of techno-economic analyses for optimising the economics of processes, for determining cost to produce opportunities, for determining levelised costs of energy products, and evaluating costs relative to incumbent products.

It is vital, in order to reach the 55% CO2 emission reduction by 2030 and carbon neutrality by 2050, that European and national authorities perceive this potential role and provide the conducive environment where promising developments can take place. Clearly, progress cannot happen without such positive signals. Therefore, it is important that the EU put meat on the bones, going beyond declarations, by supporting the inclusion of nuclear cogeneration and heat production related projects under the adequate financing schemes.

Presentations globally evidenced great potential of transformative innovations for nuclear energy, such as SMRs as flexible generators to offset the variability of solar and wind power, or to supply low-carbon heat, hydrogen and synfuel in giga factories. They also emphasised challenges that lie in licensing issues and developing public-private partnerships for demonstration projects.

All directions discussed in this session offered quite promising prospects for new and innovative nuclear to play a significant role in future sustainable low-carbon economies.

In conclusion, it is important that the discussion on sustainability grasps the full dimension of this concept, integrating environmental protection considerations with economics and security of energy supply. Flexible energy systems need to develop where the different forms of very low carbon energy can be integrated and optimally used. In particular, pilot and demonstration projects should be strongly supported, where all stakeholders, from research organisations to industry and licensing authorities are involved. This would in parallel accelerate the process of both technology and licensing readiness, thereby gaining time in a period where there is none to lose in the battle for decarbonisation.

3.3. Technical session #6 – Decommissioning and waste treatment

This session was moderated by Erika Holt (VTT) and Anthony Banford (NNL).

3.3.1. Scope

The scope of TS6 was Decommissioning & Waste Treatment. The emphasis was on dismantling and decommissioning of nuclear power plants, along with the factors related to the generation and management (predisposal) of radioactive waste. The presentations were arranged to give longer (15 minute) industry perspectives of current practices along with challenges and needs. The industry perspectives were intermixed with shorter (5 minute) snapshot presentations about on-going projects in the decommissioning and waste management domains, many of which have been endorsed or created from the SNETP (NUGENIA) community. There were two items in the agenda for which roundtable discussions were held, moderated by the session chairpersons to ask questions for participants to elaborate on the future technology development and opportunities for implementation. A few live polls were administered during the session to gain insights from participants and these also aided the roundtable discussions.

3.3.2. Summary of the technical session

- **Fuel cycle closure, D&RDWM, Massimo Sepielli (ENEA, Italy)**

An overview presentation was given on the current status of waste management practices and challenges in Italy.

Italy is required to dispose of 90,000m3 of waste. All the waste will be disposed of in the national repository. Within the national repository there will be 2 dedicated areas. One area for the disposal of VLLW and LLW, and another area for the long-term storage off ILW and HLW (for 100s years).

The national repository will be realised within a ‘Technology Park’, which will act as a centre of excellence for advanced research and (R&D) on nuclear matters and sustainable development with structures dedicated to information and training. The location of the site is undefined; however, a map of potential suitable areas was published recently.

Italian companies are interested stakeholders in EURAD and PREDIS, and earlier participated in JOPRAD.

Italy's challenges and technology research needs include:

- National repository siting and construction
- Return to Italy of HLW residues from fuel reprocessing in UK and France
- Pre-disposal issues (R&D needs)
  - Carbowaste management (Graphite of the Latina NPP)
  - Resins / sludge / liquid / organic streams treatment and conditioning
  - Legacy waste characterization and re-treatment
- Geological disposal of ILW and HLW

- **Decom waste characterization and tools: MICADO project, Massimo Morichi (CAEN, Italy)**

The Measurement and Instrumentation for Cleaning and Decommissioning Operations (MICADO) project, aims to develop a platform capable of integrating hardware (HW) and software (SW) technologies, to enhance the ALARA concept, and hence reducing operational exposure during dismantling and decommissioning (D&D) operations.

The project aims to be able to measure legacy waste/ bitumized and concrete Radiological Waste Packages (RWP) and to be able to declassify RWP. This will be completed by combining measurements via the use of technologies such as:

- Assessment and management software
- Hotspot locations
- Low resolution gamma spectroscopy
- High resolution gamma spectrometry
- Active and passive neutron measurements
- Photofission measurement and imaging
- Monitoring Grid (SciFi and SiLiF)
- AI (choice of scenario and processing)
- Uncertainties assessment

- **Decom waste characterization and tools: CHANCE project, Denise Richard (Andra, France)**

The Characterisation of conditioned nuclear waste for its safe disposal in Europe (CHANCE) project, aims to further develop, test and validate the following three non-destructive techniques that will be able to improve the characterisation of conditioned radioactive waste (CRW):

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

- **Decommissioning and pre-disposal waste handling needs, a French perspective, Clément Bocquier (EDF, France)**

DP2D is EDF's Business unit in charge of Decommissioning Projects and Waste Management Services. It is responsible for the successful decommissioning of 4 types of shut-down nuclear reactors (9 NPPs - in progress; 2 NPPs – under preparation) and to prepare for the future dismantling of EDF's operating nuclear fleet (56 operating NNPs).

In decommissioning the Natural Uranium Graphite Gas reactors (UNGG), there are technical issues due to conception and very limited experience on graphite reactor decommissioning (2 small reactors in the UK and US). These include:

- Cutting pre-stressed concrete (up to 9 m thickness)
- Cutting metallic components (up to 20 cm thickness)
- Graphite dust management
- Deployment of remote handling tools on large dimension (up to 30 m)

DP2D's solution was the creation of the Graphitech subsidiary, building of an industrial demonstrator and launching of a collaborative project, Inno4graph.

Currently, French regulation does not authorise the free release of recycled material (for example of VLL metallic material). VLL metallic waste is currently managed by melting and surface disposal. This has led to the direct disposal of a lot of metallic materials and components, which is not consistent with the strategy to minimise the environmental impact and preservation of disposals. A change in the regulations, making possible recycling of VLLW, is currently open for public consultation.

From EDF's point of view, new topics could be subject to work at a European level in order to coordinate efforts:

- For graphite reactors decommissioning: Specificities of the technology other than graphite (already dealt with in Inno4graph) E.g.: Cutting of very thick and pre-stressed concrete, means of investigation for inaccessible areas
- For the decommissioning of other reactor technologies: To enhance the efficiency of complex remote operations

- **Industry SRA within SHARE project, Christine Georges (CEA, France)**

The Stakeholders-based Analysis towards More Collaborative Projects of Research for Decommissioning (SHARE) project aims to develop a roadmap for decommissioning research aiming at safety improvement, environmental impact minimisation and cost reduction. The roadmap will be ready by the project conclusion in autumn 2021 and has been influenced by stakeholders in the global decommissioning community. The aim has been to align the roadmap with the community's issues, challenges, needs and opportunities for the improvement of decommissioning activities.

The roadmap will be able to facilitate the establishment of collaborative projects among organisations with common needs and may lead to better harmonisation of technical and non-technical approaches in decommissioning in the future.

- **Decom dismantling PLEIADES project, Christine Georges (CEA, France)**

The Platform based on Emerging and Interoperable Applications for enhanced Decommissioning PRocessES (PLEIADES) newly starting project aims to demonstrate a modular decommissioning support ecosystem based on interconnection of tools provided by the partners through a decommissioning specific viewpoint building upon open BIM. The project is about looking at the ontology of fostering innovation in decommissioning by deploying technology.

- **Decommissioning of Ignalina NPP, Dmitrij Ekaterinicev & Jurij Sapoval (INPP, Lithuania)**

The Ignalina Nuclear Power Plant (INPP), continues to go through preparatory activities for decommissioning, post-closure operation, defueling of the units and dismantling and decontamination (D&D). The intention is to construct interim-storage or disposal facilities on or adjacent to the NPP site. This reduces the need for transportation and simplifies obtaining permissions and hopefully improves stakeholder confidence.

The current dismantling methods used at INPP for D&D include:

- Hot cutting – plasma cutting, acetylene oxygen cutting.
- Cold cutting – band saws, electric hand saws, electric and hydraulic shears, etc.

The current decontamination methods at INPP for D&D include:

- Physical (mechanical) techniques such as blasting, jetting, wiping, brushing, etc.
- Ultrasonic techniques.
- Chemical techniques.

The challenges INPP faces include:

- Dismantling the RBMK Reactor (particularly in the reactor shaft)
- The radioactive waste management for the waste generated as a result of the units being graphite stacks - 3,400 tonnes of irradiated graphite

- **Roundtable discussion - Priorities for Decom R&D cooperative projects (Anthony Banford (NNL, UK) moderator and co-chairperson)**

- Characterisation is important for the planning of decommissioning activities. The benefit of characterisation is to reduce the ‘unknown unknowns’ within the waste/material. There is a need for innovation in the planning of characterisation work and for the technologies themselves.
- The R&D topics of interest for EDF include technology for graphite decommissioning and remote operation. Representatives from Lithuania also echoed the need to research the removal, and treatment (considering interim storage) of irradiated graphite
- In Italy, there is a crucial issue for the treatment and conditioning for graphite and carbowaste management. Additionally, if cement is to be used for the conditioning matrix for final disposal there should be further research studying cemented waste. Italy does not have a final repository site; this leaves a gap in the process.
- Further improvement for the liquid stream management, would be to reduce the volumes of the secondary waste streams.

- The ability to treat waste via remote control provides an opportunity to increase the volume of contaminated waste treated. However, the use of the technology usually limits the area that it is able to reach.
- A mobile treatment facility would really support small inventory programmes.
- There is a balance between what technology is currently available, and the benefits and disadvantages for each application.
- There would be a benefit in taking representative sampling during PWR and BWR operation and outages to obtain the radioactive inventory (including exotic radionuclides e.g.93-Mo, 14-C). This would help the planning stages, by understanding the challenges prior to dismantling.
- Designing for decommissioning in new build.

- **Sweden's decommissioning and radwaste perspectives, Andreas Knutsson (Vattenfall, Sweden)**

Vattenfall are responsible for the decommissioning of Ringhals 1 & 2 (PWR), Ågesta (PHWR), and SVAFO R2 (Research). Ågesta's (PHWR) shut down was in 1974, meaning that there is a challenge of knowledge management and information retention. The site also has small entry and exit points (reactor built into the rock face). Some of the waste management and clearance challenges include:

- The planned Swedish back-end system for decommissioning wastes is not yet in operation. This in turn has required a request for the expansion of an existing operational waste repository concept for short-lived waste, details regarding the modification of the existing transportation system and the timing for final conditioning of wastes remain unfinalized.
- The up-scaling/modification of the current waste management practice. For example, the introduction of new waste packages and optimisation of existing WM processes and IT-systems.
- The development of nuclide vectors is needed as early as possible. This is because resulting nuclide vectors may influence the preferred order for system dismantling (e.g. grouping of systems). Additionally, knowledge regarding the size of waste management routes (i.e. the number of waste packages, size of (buffer) storage areas etc.) would be useful in the planning stages.
- Confirmation on the expected end-state for rooms, buildings, areas and site so that clearance can be planned accordingly.

- **Decom waste minimization: INSIDER project, Danielle Roudil (CEA, France)**

The Improved Nuclear SIte characterisation for waste minimisation in D&D operations under constrained EnviRonment (INSIDER) project aims to develop and validate a new and improved integrated characterisation methodology and strategy during nuclear decommissioning and dismantling operations (D&D) in a waste-led approach via coupling sampling and measurements. The approach has been tested via 3 case studies. This project meets the research needs discussed by many industrial parties, such as comments raised in the session by Vattenfall, Sweden.

There is the potential for further research in Euratom on:

1. Extension/application of the methodology and approaches: historic wastes, graphite reactors, NORM…
2. Nuclear reference material production (CRM).
3. Support to D&D Standards (sampling, measurements and validated methods).
4. Management of other waste (legacy waste, NORM, future waste…).
5. Decommissioning standardised practices, remediation issues.

6. Characterisation process contribution to circular economy.

- **THERAMIN project on thermal treatments, Matti Nieminen (VTT, Finland)**

The Thermal treatment for radioactive waste minimization and hazard reduction (THERAMIN) project was completed in 2020 and aimed at promoting the thermal treatment of low and intermediate radioactive waste prior disposal (L/ILW), by reviewing the:

- Strategic impact of thermal treatment (e.g. estimation of waste volumes, value assessment).
- Demonstration of thermal treatment technologies (i.e. direct Joule heating, plasma melting, thermal gasification, Hot Isostatic Pressing (HIP)).
- Disposability of thermal products (generic disposability criteria were developed based on participant's WAC).

Some of the recommended outcomes of the THERAMIN project have led to progressing technology withing the new PREDIS project (WP6 for immobilisation of solid organic wastes).

- **Sellafield Challenges: Steering the Supertanker, David Connelly (Sellafield, UK)**

Sellafield are currently at a unique position during the Post-Operational Clean-Out (POCO) to reduce risk and consider future phase opportunities in order to provide lower hazards and risks during D&D operations. Decisions should reflect a cost benefit analysis to provide the best value to the UK taxpayer, as to how much decontamination is enough.

Sellafield's Thermal treatment Challenge statement is "The Sellafield & UK ambition for the thermal treatment of Higher Activity Wastes (HAW) is to process PCM, Pumpable (Sludge), MBGW and Bulk metals due to benefits such as significant volume reduction and waste passivation. This long-term ambition will be demonstrated via a near term pilot production scale modular thermal capability located at the Sellafield site." This has led to the creation of a Thermal Programme to develop three initial capabilities:

- Pumpable wastes (sludges and ion exchange material)
- PCM
- Solid Mixed Beta Gamma Wastes (MBGW)

This has resulted in pumpable and MBGW pilots focusing on addressing engineering and operational challenges, and a PCM pilot focus on addressing the key technical challenges (scalability of criticality and radiological safety case).

- **Radwaste joint programs: EURAD ROUTES waste streams and WAC, Elisa Leoni (IRSN)**

The Waste Management routes in Europe (ROUTES) work package within the EURAD project aims to share experience and knowledge on waste management routes within Europe, identify safety-relevant issues and R&D needs associated with the routes, and compare the different approaches/interdependencies between the different routes to highlight the possible opportunities for collaboration. One specific task within ROUTES addresses waste acceptance criteria (WAC) and has close synergy with needs from waste producers through waste disposal facility operators. ROUTES and PREDIS are working in close cooperation on WAC issues.

- **Radwaste joint programs: PREDIS project predisposal waste treatment needs, Erika Holt (VTT, Finland)**

The Pre-disposal Management of Radioactive Waste (PREDIS) project which started in autumn 2020 aims to develop or improve existing solutions (methods, processes, technologies and demonstrators) for future treatment and conditioning of waste (metallic, liquid organics, solid organics and cemented waste) for which no industrially mature/inadequate solutions are currently available or provide optimisation to current solutions to make them safer, cheaper or more effective. The project was directly planned within NUGENIA forum March 2019.

- **Small inventory program needs in decom and waste management, Andrea Rapić (Krško NPP, Croatia)**

Croatia and Slovenia are both responsible for the decommissioning of the Krško NPP (located in Slovenia). Krško NPP shutdown is expected in 2043. The management of LILW will be shared between the 2 countries, each of which is responsible for treating, conditioning, packaging and storing the waste in their own repository under their own national programs. Their program represents challenges faced by many other countries who also have a smaller inventory and interests in cross-border cooperation.

Croatia’s technology challenges include:

1. On-site RW and RW package characterisation
2. Mobile predisposal options (characterisation, treatment, conditioning, packaging)
3. Treatment and conditioning of relatively small amounts of specific RW streams
4. Evaporator concentrates and tank sludges (IDDS products) - corrosive (gas generation)
5. Compacted RW containing organics / corrosive (possible gas generation)
6. Spent primary and secondary iron resins (IDDS products/Vermiculite matrix) – hygroscopic (swelling)
7. Spent filters – in cement matrix but containing organics and gaps
8. Storage/disposal container aging calculations

- **Roundtable discussion - Priorities for Radwaste R&D cooperative projects (Erika Holt (VTT, Finland), moderator and co-chairperson)**

There is a challenge regarding the classification and characterisation of waste. The development of new techniques for characterisation would be of benefit.

A discussion regarding what is classed as the appropriate level of cleaning in decommissioning took place. This is because a deep clean may not always be the correct strategy. This is particularly true for concrete, VLLW and LLW. The material’s end point requires consideration. There is also a potential trade-off with respect to volume reduction if it leads to the waste having higher density of radioactivity, which could then require moving it to a higher waste classification. Another consideration would be that the volume of secondary waste, which is additive to the quantity of primary waste, produced can be controlled. A recycling strategy is of interest for nuclear waste management. There is a divergence between societal and industrial expectations on waste management, as each define value differently. Where open release may be difficult, the supply chain could be utilised in using the recycled materials. The waste hierarchy and the circular economy are important themes for future research, development and decommissioning.

Research on the best approaches for segregation for awkward shapes could be of benefit (i.e. advise on the best way to dismantle a glovebox).

Supercomputing may have a massive potential in decommissioning by providing the ability to hold information and track and analyse all the characterisation data.

- **Results of Live-Polling**

Live-polling results are summarized as follows (see below for all live-polling results and on appendix 3):

1. The majority of respondents thought that 'characterisation during decommissioning' is the most important research need in decommissioning.
2. The majority of respondents judged that 'management of material and radioactive waste from decommissioning' is the most urgent research need in decommissioning.
3. The majority of respondents considered 'management routes for materials including radioactive waste streams to be the biggest challenge in the management of material and radioactive waste from decommissioning.
4. The majority of respondents decided that 'segregation and sorting' and 'classification and characterisation' are the biggest challenges in predisposal management of radioactive waste.
5. The majority of respondents determined that near-term R&D on 'solid organic' waste would result in the greatest impact on predisposal management activities.
6. The majority of respondents indicated that the 'development of mobile or modular treatment options' should be the primary focus of near-term R&D related to waste treatment and conditioning.

3.3.3. Emerging project ideas

- Innovative decommission planning approaches to include characterisation activities very early in the process (even during operations).
- Deployment of remote handling tools over large areas and volumes.
- Handling higher complexity remote operations, with high efficiency.
- Advanced concrete and metal cutting methods.
- Segregation optimisation.
- Graphite decommissioning procedures and waste management of decommissioned graphite.
- Management of organic waste streams.
- Circular economy through application of the waste hierarchy.
- Minimization of secondary wastes.
- Mobile or modular characterisation and treatment options, allowing cross-border cooperation.
- Digitalisation of decommissioning and waste management plans and procedures.
- Addressing the question of "How much decontamination is enough?"
- Improvements to characterisation and classification methods.

3.4. Technical session #7 – Advanced reactor systems

This session was moderated by Paul Schuurmans (SCK-CEN) and Nathan Paterson (Foratom).

3.4.1. Scope

Technical session 7 deals with advanced reactor systems. The systems covered in the session were selected based on the scope of the GENIV initiative, the priorities in SNETP as defined in the ESNII roadmap and global interest. After a general introduction on GenIV systems, the session discussed systems cooled with heavy liquid metal (MYRRHA & ALFRED), sodium (ESFR), helium (Allegro), supercritical water and molten salts. In each presentation, near-future system development plans and/or key research issues were addressed. The session also featured a lively Q&A with the audience and the speakers including topics such as deployment planning, addressing design requirements, materials verification, international collaboration and skills development.

3.4.2. Summary of the technical session

- **Overview of GenIV developments and Generation IV international forum**

On an international level, development of advanced reactor systems is promoted by the GIF forum. Kamic Tucek reviewed its working, including the operation of the different working groups in the forum, and the highlights in the development of the various advanced systems. In the EU, the main active projects on GenIV systems are the lead-bismuth cooled MYRRHA R&D infrastructure (ADS demonstrator) under construction in Belgium, the LFR demonstrator ALFRED in Romania and preparatory phase of the Allegro GFR carried out by the V4G4 Centre of Excellence. Other advanced systems are investigated as well with significant support from EU collaborative projects. Further details are given in the subsequent topical presentations. Regarding work outside the EU, the completion of the licensing of the BREST LFR demonstrator and ongoing site preparations in Tomsk, Russian Federation and the construction of two pilot SFR units (CFR600) and the prototype MSR TMSR-LF1 in China were highlighted.

- **Development of advanced reactor systems: the MYRRHA project**

The objectives, applications and status of the MYRRHA project were reviewed. Following the decision of the Belgian government in 2018, the MYRRHA Accelerator driven system will be developed under a non-profit organization MYRRHA AISBL/IVZW in three phases: the 100 MeV linac demo (MINERVA) for which construction has started, the 600 MeV linac and the reactor. In the first phase, the pre-licensing of the reactor should be realized as well. The planned completion for each phase is in 2026, 2032 and 2036 respectively. Furthermore, a design update (revision 1.8) to address technical issues identified in revision 1.6 was completed. The change in design improved safety and reduced the power and size of the system by 30% while at the same time satisfying the MYRRHA application catalogue and the top-level requirements. This update will form the basis for further licensing and engineering activities.

- **ALFRED project: status and next activities**

ALFRED was presented as the advanced lead-cooled fast reactor European demonstrator that is also prototypic of a lead bases SMR bridging the gap between research and industrial application. The system is developed by the FALCON consortium of Ansaldo Nucleare, ENEA and Raten ICN and is planned to be hosted in Romania. The challenging roadmap foresees operation by 2030. In addition, new research infrastructures are developed. These include a loop facility for full scale TH testing of core components (HELENA2), a pool facility for long term experiments to characterise components and systems (ELF), a broad scope HLM chemistry and materials science laboratory (chemlab) and a pool facility for large scale components testing in representative conditions (Athena). The construction contract for the latter two was signed mid 2020.

- **HLM research**

An overview is given of the research approach supporting the design and safety assessment of HLM systems. The large potential synergies between Pb and Pb-Bi coolants and the role of MYRRHA as a development tool for LFR systems was emphasised. As the HLM systems developed in the EU are approaching the (pre-)licensing phase, sufficient attention must be paid the completeness of the R&D programme and the build-up of a comprehensive knowlegde database using proper documentation, standardisation of procedures and QA. This must also be applied to model validation of numerical simulations. The priority topics for materials are the assement of the environmental effects and corrosion mitigation. Design validation of components via proof of principle test and their thermal hydraulic characterisation is a key issue and finally development of coolant impurity management systems and procedures also including radiological release are needed.

- **H2020 ESFR-SMART project**

The European Sodium Fast Reactor is a large power reactor development taking into account SFR experiments and operational experience. Its goal is to improve safety, economics and management of nuclear materials. ESFR-SMART is an EU funded H2020 project supporting this development that aims to select and evaluate new safety measures for the ESFR and develop new research tools in the form of numerical codes, data and facilities. The innovative safety measures involve a new core region design with a.o. a low-void effect core, passively activated control rods, a revised core catcher and an update of all three decay heat removal systems. Numerical benchmarks performed include coupled neutronic and thermal hydraulic calculations, CFD model validation, thermal hydraulics of sodium boiling and vapour condensation, airosols in sodium vapour atmosphere and severe accidents with (simulant) corium. In addition, new data will be generated on thermal-physical properties of MOX fuel.

- **ALLEGRO project overview**

The gas (He) cooled fast reactor aims to combine the advantages of fast and high-temperature reactors. However the required power density makes decay heat removal very challenging. For materials and technologies there is a synergy with HTRs albeit that there are some GFR specific issues. Allegro, developed by the V4G4 centre of excellence, is set up as a proof of concept and faesibility of the GFR and as testbed for new materials and technologies. It will have experimental positions for fuel qualification with a target outlet temperarture of 850°C and a focus on fully passive safety. The safety concept is built upon the presence of a guard vessel serve as a radionuclide barrier and to keep elevated residual gas pressure in LOCA's, a DHR system and emergency coolant injection system. In addition a core catcher and a DHR loop with battery-powered blower for low-pressure scenarios is foreseen. The R&D programme on Allegro is supported by national programmes of V4G4 members and by the H2020 programme SafeG.

- **New challenges for SCWR development**

Supercritical water reactors operate with coolant pressues around 25 MPa allowing higher core outlet temperatures and better efficiency. Important technical challenges are the development of high temperature/high pressure cladding materials, establishment of chemistry-control and the optimization of the fuel assembly geometry and configuration. Collaboration between partners from EU, Canada and China eventually resulted in the project ECC-SMART that works on the development of a SCW-SMR. Its goals are to foster transcontinental collaboration and collect experience from design studies in the EU, Canada and China to jointly define design requirements for future SCW-SMR technology and to harmonise laboratory procedures and tools for effective R&D. Technical goals include materials qualification support by corrosion behaviour studies at different conditions, a reactor physics analyses of the preliminary core layout, V&V and development of numerical codes used to assess the proposed SCW-SMR concept and finally development of a pre-licensing study and guidelines for the safety demonstration of the SCWR-SMR concept in further development stages.

- **Support to MSR technology**

Recently molten salt reactors have gained significant interest with many developers emerging worldwide. However, few of them invest significantly in the experimental effort needed for design, safety evaluation, code and system validation, and licensing. As MSRs are complex, there are several technological challenges threat need to be solved. The experimental needs include irradiation knowledge on fuel bearing molten salts and MS exposed materials, processing chemistry regarding salt conditions, salt purification, redox control and waste chemical processing. Furthermore, modelling and numerical simulation support is needed. In the EU, MSR development is supported by national programmes and by the H2020 project SAMOSAFER. Here the focus is put on irradiation technology and generic (not design or concept specific) topics. Examples are salt irradiation tests to study radiolytic gas production, fission product release and noble metal deposition and materials test to look into He embrittlement of Ni based alloys and molten salt corrions and FP behaviour.

- **Actinides Conversion in Molten Salt Reactor**

In France, closing the fuel cycle is the reference strategy for waste management. Complementary to the main R&D ongoing on GenIV SFR, an R&D programme is started to assess the feasibility of fast MSRs and to confirm their potential assets. The required hard neutron spectrum brings the focus to chloride salts rather than fluorides salts that are often used for thermal spectrum reactors or Th breeders. The work programme includes work on neutronics, reactor design and technological developments, material studies and corrosion, simulation tools actinide chemistry and fuel cycle development. Furthermore, the CNRS expertise on MSFR design, simulation tools and thermochermistry is added. The involvement or ORANO allows the possibility of coupling the SMR to the La Hague fuel reprocessing plant where the molten salt can be produced and recycled.

3.4.3. Emerging project ideas

- R&D for advanced reactor systems approaching licensing
  - Establishment of a database on environmental effects on materials
  - Design validation of components and procedure tests
  - Development and qualification of coolant impurities management (coolant purification and radiological release) systems and procedures
- Realisation of passive safety in advanced reactors
- Research towards on-line fission product and minor actinide management from MSR

3.5. Technical session #8 – Digitalisation – modelling and simulation

This session was moderated by Ferry Roelofs (NRG) and Didier Banner (EDF).

3.5.1. Scope

The field of digitalization, modelling and simulation is relatively new for the European collaborative R&D programme and comprises a wide variety of physical processes and numerical or digital techniques to enhance analysis and assessment of design, operational and safety features. The SNETP FORUM intends to provide an overview of this field discussing numerical code development, the role of machine learning, the importance of code qualification and uncertainty quantification. Another important development in the field of digitalization, modelling and simulation is the combination of numerical codes at various levels of accuracy (multi-scale code coupling) and with different kinds of physics (multi-physics code coupling). Finally, the role of digitalization is highlighted by discussing the upcoming and promising role of digital twins and virtual reactor technology for application to existing and new reactors.

3.5.2. Summary of the technical session

- **Code development, machine learning, qualification, uncertainty quantification**

Although many simulation codes have been developed in the nuclear field, code development remains today important to cover new challenges or to increase the accuracy of simulation results. Code development firstly requires understanding the physics. Next to that, both physical, empirical and numerical models need to be developed, implemented, and validated. Recently, making advantage of the increasing computer power, the role of high-fidelity numerical analyses is gaining importance. Such analyses serve, complementary to experimental data, as reference and help to understand the physics. They also allow to reduce uncertainties in engineering models and support the validation process. In combination with machine learning techniques, the use of such high-fidelity data is expected to play an increasingly important role.

A toolkit for design and safety support of nuclear reactors will probably exist of a combination of existing commercial codes and open source codes. Commercial codes typically undergo a thorough verification and validation process before a new version is released. Code developments for commercial codes often profit from code developments initiated and financed from other industries and applications. Open source codes on the other hand profit from having access to the source code preventing the code to be a black box for the nuclear engineer. On top of that, open source codes do not encompass license issues. Examples of such open source code developments are the GeN-Foam and OFFBEAT multi-physics initiatives based on the open source OpenFOAM software platform, and software like Salome-Meca which allows a nuclear utility like EDF to ensure quality of the results, to develop and implement state-of-the-art models and numerical schemes, and to create dedicated customized tools. Recently, the IAEA together with EPFL have launched an initiative to establish a repository for open source code called 'Open Source Nuclear Codes for Reactor Analysis (ONCORE)'. ONCORE promotes collaboration and sharing of resources, materials and tools and research and education. Its members actively contribute to the development of new software, receive community support and participate in the organization of training events and outreach activities.

For existing as well as new reactors, safety analysis codes need to be properly qualified. Relevant good practices for code verification and validation are given e.g. in IAEA SSG-2 and several regulatory guides. New challenges are identified for passive safety systems with small driving forces, innovative components or new materials require to enhance internal procedures and processes, including use of continuous integration techniques. Apart from code qualification, also uncertainty quantification and associated numerical practices like best estimate plus uncertainty quantification are expected to play an increasing role in the acceptance of numerical simulation results by regulators. Development and validation of cost-effective uncertainty quantification methodologies for engineering simulations with long simulation times are a necessity.

For all these topics, international collaboration is essential. Initiatives from the IAEA, OECD/NEA and especially in Europe from the European Commission under the Euratom program are crucial to further development of codes and code capabilities for application to nuclear reactor design and safety analyses.

- **Multi-scale and Multi-physics**

Increasing computer power and possibilities enable to combine simulations at various scales, from sub-component level, ultimately to plant level in one simulation platform either by integrating models in one numerical code or by coupling dedicated codes. Noteworthy are the challenges lying ahead for the multi-scale treatment of multi-phase flows. Similarly, numerical codes covering different fields of physics can now be coupled to provide integrated answers to the mostly multi-disciplinary challenges posed by nuclear reactor design and safety analysis. The GeN-Foam initiative is a good example of developments in this direction, coupling various physical models in an integrated platform.

Since regulators are expected to treat a coupled code as a new code, qualification and validation of a coupled code needs to be performed thoroughly. To that respect, creation of a generic qualified and validated multi-scale, multi-physics toolkit should be preferred above qualification and validation of coupling exercises on a case-to-case basis.

Also, in the development of such multi-scale, multi-physics code platforms, artificial intelligence techniques like big data and machine learning are expected to play an important role. Exploratory work is being performed in one of the current H2020 projects with respect to core monitoring techniques.

- **Digital twins and virtual reactors**

Integration of new digital techniques allows to create digital twins or virtual and augmented images of existing as well as new reactors. An advanced digital twin will contain and strongly couple several building blocks: real-time simulators, state of the art multi-physics and multi-scale simulations, innovative and interactive visualization techniques all the while ensuring a thorough verification and validation process. Moreover, strong coupling between the plant life-cycle management system and the digital twin will facilitate keeping an up-to-date digital mock-up available for each plant. In addition, the aforementioned coupling will guarantee that all stakeholders such as design teams, engineering departments, field operators or industrial partners are always in possession of the most recent data as well as automatically triggering a novel set of numerical experiments following an update. Initiatives in this field are the Nuclear Virtual Engineering Capability program in the UK and the Digital Nuclear Reactor Initiative or 'Réacteur Numérique' in France.

Digital techniques like virtual reality, augmented reality and interactive 360° videos are being developed to achieve operational excellence as well as to increase safe performance allowing to integrate and test novelties without having to actually implement a change in the physical reactor. Such techniques allow to monitor the interaction of plant personnel with new systems and situations and help the plant owner to decide on the way forward.

3.5.3. Emerging project ideas

During Technical Session 8 ongoing initiatives like the exploratory multi-physics H2020 CORTEX project, the IAEA ONCORE initiative, and the French Digital Nuclear Reactor Initiative or 'Réacteur Numérique' (France) or British Nuclear Virtual Engineering Capability project were discussed.

Next to that some recommendations for future development were identified and one concrete project idea. The recommendations identified were:

- Continuous improvement of codes to increase accuracy and reducing conservatisms.
- Continuous validation efforts to cover new challenges like passive safety systems, innovative components and new coolants and materials.
- Development of VVUQ for long running 3-D simulations.
- Multi-scale coupling of two-phase flows.
- Development of generic code coupling platform allowing tool qualification by nuclear regulators.
- Use of artificial intelligence techniques like big data and machine learning for code and model development.

One project idea was launched. This idea, presented by Dr. Komen of NRG is to combine experiments and high-fidelity simulation for development of engineering models. The project should cover single as well as multi-phase flow and uncertainty quantification, and is expected to make use of machine learning techniques.

Appendix 1: Forum Programme

SNETP Forum 2021 – Full Programme

2 February	3 February	4 February
14:00 – 17:30 GMT+1 (CET) **Plenary Session**	**9:00 – 10:30, 11:00 – 13:00 GMT+1 (CET)** **Technical Sessions – 1st Part**	**9:00 – 10:30, 11:00 – 13:00 GMT+1 (CET)** **Technical Sessions – 2nd Part**
Keynote & panel discussions	**TS1 –** Long-term operation & construction **TS2 –** SMRs **TS3** – Fuel Development and fuel cycle efficiency **TS4** – Innovative and perspective materials solutions	**TS 5 –** Energy systems, new applications, economy and licensing **TS 6** – Decommissioning & waste treatment **TS 7** – Advanced reactor systems **TS 8** – Digitalisation – modelling and simulation

14:00 – 17:30 | DAY 1 AFTERNOON – 2 FEBRUARY | SNETP FORUM PLENARY SESSION		
Timing	**Topic**	**Speakers**
14:00 – 14:05	**Welcome & Introduction**	**B. Salha – EDF, SNETP President**
14:05 – 14:20	**Presentation of SNETP Strategy**	**B. Salha – EDF, SNETP President**
14:20 – 15:20	**Presentation of the vision of SNETP pillars: ESNII, NC2I, NUGENIA**	**S. Napier – NNL** **M. Schyns – SCK-CEN** **J. Sobolewski – NCBJ**
15:20 – 15:35	**Coffee Break**	
15:35 – 17:15	**Panel discussion**	**Michael Chudakov – IAEA** **William Magwood – OECD/NEA** **Sama Bilbao – WNA** **Yves Desbazeille, Foratom** **Rosalinde VAN DER VLIES – DG RTD** **Nicolas Février – EDF**
17:15 – 17:30	**Q&A**	**B. Salha – EDF, SNETP President**
17:30	**End of Day 1**	

3 FEBRUARY 2021 | SNETP FORUM TECHNICAL SESSIONS				
#	TS 1 - Long Term operation & Construction	TS 2 - SMRs	TS 3 - Fuel Development and fuel cycle efficiency	TS 4 - Innovative and perspective materials solutions
	Moderators: Pavel Kral (UJV) + Luis Herranz (CIEMAT)	Moderators: Eric Hanus (CEA) & Rob Arnold (BEIS)	Moderators: Steve Napier (NIRO) & Bruno Michel (CEA)	Moderators: Lorenzo Malerba (CIEMAT) + Karl-Fredrik Nilsson (JRC)
09:00	Implementation of new safety requirements in post-Fukushima period (including LTO considerations) **J. Misak (UJV)**	Micro-reactors - an overview **Mark Davies (USNC)**	Developments in Advanced Recycle and Sustainability for Future Fuel Cycle Options **Robin Taylor (UK NNL)**	Additive manufacturing for nuclear applications **P. Aubry (CEA)**
09:20	Hydrogen Management **Chaumeix, CNRS / Bentaib, IRSN**	NUWARD TM **Eric Hanus (CEA)**	Thorium cycle **Franck Carré (CEA)**	Ceramic coatings for nuclear applications **F. Di Fonzo (IIT)**
09:40	Progress towards simulation of passive safety systems **Michael Montout (EdF)**	EnergyWell - SMR under development in the Czech Republic **Marek Ruščák (CVR)**	Update on the nuclear data for Advanced Fuel Cycle Programme **Allan Simpson (UK NNL)**	High Entropy Alloys for nuclear applications **A. Weisenburger (KIT)**
10:00	Presentation of results from the PANAS project **Frances Viereckl (TU Dresden)**	Execution of first privately funded EU SMR deployment **Kalev Kallemets (Fermi Energia)**	Benchmark and improvement of fuel performance codes" **Lelio Luzzi (Politecnico MILANO)**	Alumina forming steels for ATF and GenIV cladding **P. Szakalos (KTH)**
10:20	Material research for LTO **Concetta Fazio (JRC)**	ELSMOR **Ville Tulkki (VTT)**	Fully Ceramic Microencapsulated Fuel fuel **Mark Davies (USNC)**	SiC/SiC joining for cladding applications **M. Ferraris (Polito)**
10:40	Coffee Break			
11:10	Fluid Structure Interaction: A Multi-Physics Application for Design and LTO Support **F. Roelofs (NRG)**	Passive safety in SMR **Christophe Herer (IRSN)**	Future prospects in Framatome Fuel development and related R&D needs **Guy Gentet (FRAMATOME)**	Advanced online monitoring and NDE for nuclear systems **M. Rabung (FhG IZFP)**
11:30	Perspectives and opportunities for LTO in Europe **Andrei Goicea (Foratom)**	Experimental support for SMR passive safety systems **Roberta Ferri (SIET)**	Using a basic research approach to improve fuel performance codes **Marjorie Bertolus (CEA)**	Innovation on concrete structures **Miguel Ferreira (VTT) & Edgar Bohner (VTT)**
11:50	Leveraging Research and Operational Experience for Plant Upgrades and LTO at Loviisa NPP **Harri Tuomisto (Fortum)**	Lessons-learned from approval of NuScale SMR **Dom Claudio (NuScale)**	IRSN FUEL+ software plateform to simulate fuel behviour in accidental conditions **Gaétan GUILLARD (IRSN)**	A way to innovative polymers for nuclear applications: the MAGAPOL initiative **Marc Kuntz (EDF)**
12:10	On-going" and/or planned research in the present Spanish context **L.E. Herranz (CIEMAT)**	Nuclear: the need for radical innovation **Jacopo Buongiorno (MIT)**	"Spent fuel characterization and evolution until disposal (SFC)" ***Peter Jansson (UPPSALA)***	How to introduce new materials in design codes **C. Petesch (CEA)**
12:30		Advanced Modular Reactors for UK **Zara Hodgson (NIRO)**		Round-table discussion - Realistic priorities concerning innovative and perspective nuclear materials solutions

4 FEBRUARY 2021 | SNETP FORUM TECHNICAL SESSIONS				
#	TS 5 - Energy Systems, new applications, economy, licensing	TS 6 - Decommissioning & Waste Treatment*	TS 7 - Advanced reactor systems	TS 8 - Digitalisation - Modelling and Simulation
	Moderators: Marc Deffrennes (weCARE) & Franck Carré (CEA)	Moderators: Erika Holt (VTT), Anthony Banford (NNL)	Moderators : Paul Schuurmans (SCK-CEN) & Nathan Paterson (Foratom)	Moderators: Ferry Roelofs (NRG), Didier Banner (EDF)
09:00	Role of nuclear in future energy mixes **Kirsty GOGAN (TerraPraxis)**	Fuel cycle closure, D&RDWM **Massimo Sepielli (ENEA, Italy) with Sogin and ISIN Regulator views**	Overview of Gen-IV developments and GIF **Kamil Tucek (JRC)**	IAEA-EPFL activities on open-source software development **Carlo Fiorina (EPFL, Switzerland)**
09:20	Beyond electrification: ways to tackle difficult to decarbonise sectors **Aiden PEAKMAN (NIRO)**	Decom waste characterization and tools: MICADO project **Massimo Morichi (CAEN, Italy) and CHANCE project, Denise Richard (Andra, France)**	Development of Advanced reactor systems : The MYRRHA Project **Didier De Bruyn SCK•CEN**	SALOME-MECA: A structural mechanics open-source simulation platform **Dominique Geoffroy (EDF, France)**
09:40	Industrial applications of high temperature reactors and the Horizon 2020 GEMINI+ project **Dominique HITTNER /** **Michael FÜTTERER (NC2I)**	Decommissioning and pre-disposal waste handling needs, a French perspective **Clement Bosquier (EDF, France)**	Status and next activities related to the ALFRED project. **Michele Frignani (Ansaldo)**	The role of high fidelity numerical simulations, complementary to experiments, for nuclear reactor safety analyses **Ed Komen (NRG, the Netherlands)**
10:00	Enabling industrial carbon capture using green hydrogen **Ted MORYTO (CNL)**	Decom dismantling PLEIADES project and industry SRA within SHARE project **Christine Georges (CEA, France)**	HLM reactor research **Paul Schuurmans (SCK•CEN)**	Qualification of System Codes for New Builts - Code requirements and model improvement **Thorsten Hollands (GRS, Germany)**
10:20	Green Ammonia **Tobias BIRWE (ThyssenKrupp)**	Decommissioning of Ignalina NPP **Dmitrij Ekaterinicev & Jurij Sapoval (INPP, Lithuania)**	H2020 ESFR-SMART project **Konstantin Mikityuk (PSI)**	Uncertainty Quantification **Celine Lascar (Framatome, Germany)**
10:40	Coffee Break			
11:10	Hybrid Energy Systems **Shannon BRAGG-SITTON (INL)**	Roundtable discussion - Priorities for Decom R&D cooperative projects (Banford moderator)	Allegro Project and update on Gas cooled fast reactor (GFR) technology **Branislav Hatala,** **(VUJE, a.s.) and Petr Vácha (ÚJV Řež, a. S)**	Multi-scale Analysis **Antoine Gerschenfeld (CEA, France)**
11:30	Potential of SMR technologies for cogeneration and hybrid energy systems **Jean-Michel RUGGIERI (CEA)**	Sweden's decommissioning and radwaste perspectives **Andreas Knutsson (Vattenfall, Sweden)**	New challenges for the SCWR development **Marketa Krykova (CVR)**	Modelling the effect of stationary perturbations onto the neutron flux in nuclear reactors **Christophe Demaziere (Chalmers, Sweden)**
11:50	HTTR licensing experience and commercial modular HTGR safety design requirements including coupling of process heat applications **Hirofumi OHASHI (JAEA)**	Decom waste minimization: INSIDER project, Daniele Roudil (CEA, France) and THERAMIN project on thermal treatments **Matti Nieminen (VTT, Finland)**	Support to MSR technology **Ralph Hania (NRG)**	The digital nuclear reactor initiative **Chai Koren (EDF, France)**
12:10	Economics of SMRs in cogeneration systems Alexandre BREDIMAS / **Blazej CHMIELARZ (USNC)**	Sellafield Challenges: Steering the Supertanker, **David Connelly (Sellafield, UK)**	Converter of actinides in a molten salt reactor **Paul Gauthé (CEA) & Bertrand Morel (Orano)**	UK VRD initiative **Albrecht Kyrieleis (Jacobs, UK)**
12:30	Tractebel's vision on Small Modular Reactors - Technical due diligence and market studies **Anicet TOURÉ (Tractebel)**	Radwaste joint programs: EURAD ROUTES waste streams and WAC, Elisa Leoni (IRSN, France), PREDIS project predisposal waste treatment needs **Erika Holt (VTT, Finland)**		
		Small inventory program needs in decom and waste management **Andrea Rapić (Krško NPP, Slovakia)**		
		Roundtable discussion - Priorities for Radwaste R&D cooperative projects (Holt moderator)		

Appendix 2: Virtual platform visuals

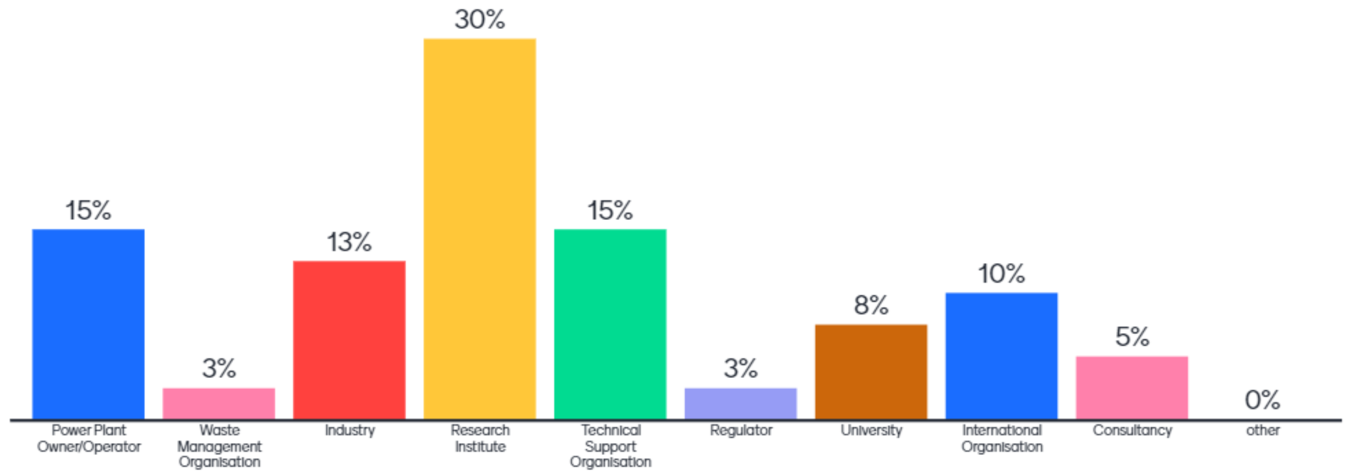
Main Hall

Auditorium – Plenary session

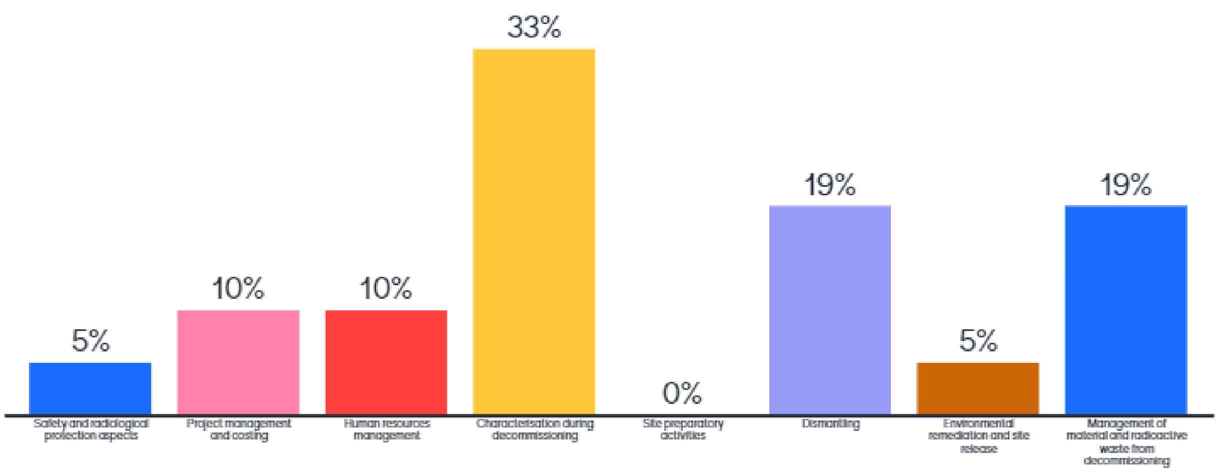
Breakout rooms – Technical sessions

Appendix 3: Technical session #6 Poll figures

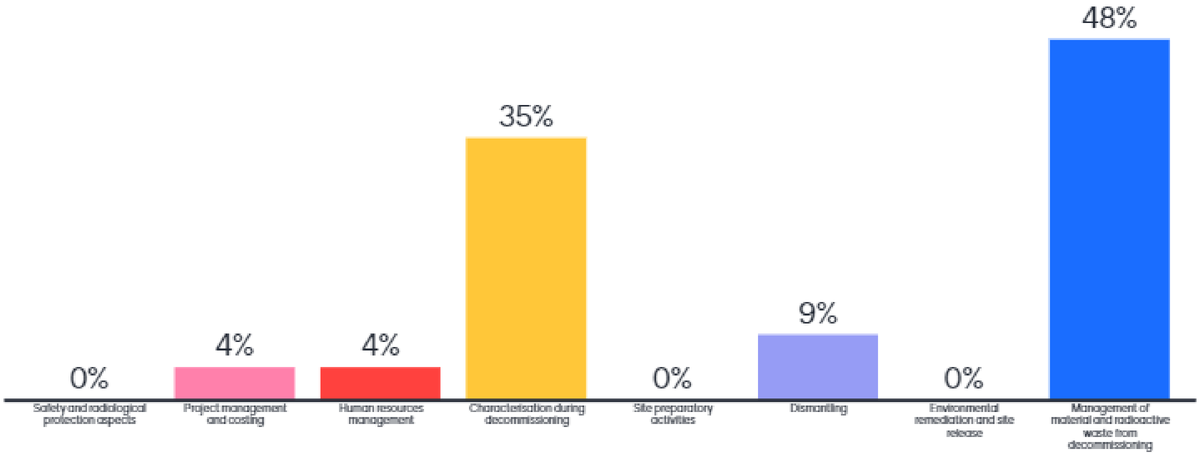
Who are you representing today?



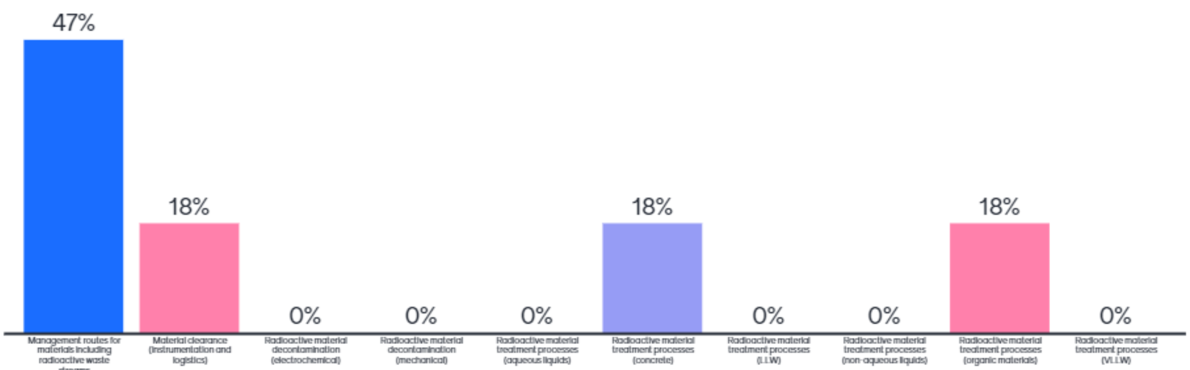
What do you consider as the most IMPORTANT research need in decommissioning?



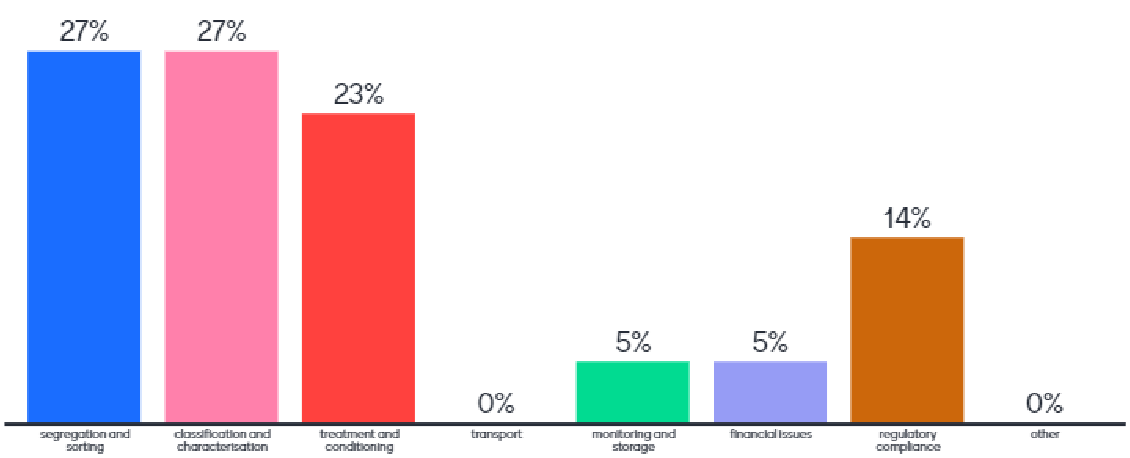
What do you consider as the most URGENT research need in decommissioning?



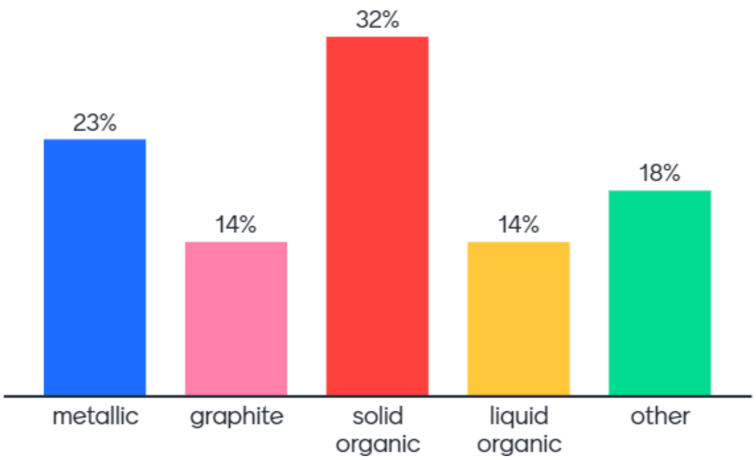
What is the biggest challenge in Management of material and radioactive waste from decommissioning?



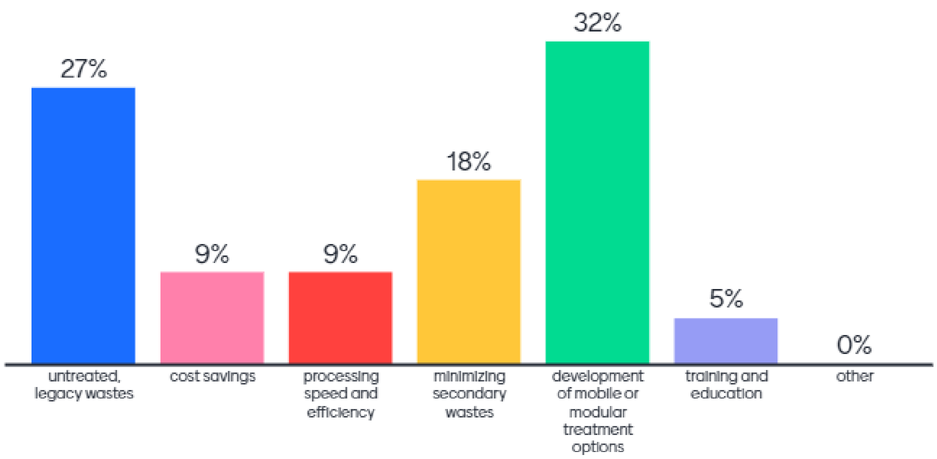
What is the biggest challenge in predisposal management of radioactive waste?



For which waste type would near-term R&D result in the greatest impact on predisposal management activities?



What should be the primary focus of near-term R&D related to waste treatment and conditioning?



SNETP
Sustainable Nuclear Energy
Technology Platform

ABOUT SNETP

The Sustainable Nuclear Energy Technology Platform (SNETP) was established in September 2007 as a R&D&I platform **to support technological development for enhancing safe and competitive nuclear fission in a climate-neutral and sustainable energy mix.** Since May 2019, SNETP has been operating as an international non-profit association (INPA) under the Belgian law pursuing a networking and scientific goals. It is recognised as a European Technology and Innovation Platform (ETIP) by the European Commission.

The international membership base of the platform includes industrial actors, research and development organisations, academia, technical and safety organisations, SMEs as well as non-governmental bodies.

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