Nuclear Generation II&III Alliance

NUGENIA VISION

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With the contribution of all NUGENIA members and especially the sub-technical area leaders.

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Introduction

The deployment of advanced Light Water Reactors (LWR) for electricity production could valuably make the bridge throughout the 21st century between the ageing nuclear installations currently in operation and/or the Generation III ones, now under construction, and the Generation IV reactors, proposed by the Generation IV International Forum (GIF) and promoted by the European Sustainable Nuclear Industrial Initiative (ESNII) and Nuclear Cogeneration Industrial Initiative (NC2I). To assess and reinforce their attractiveness, there is a need to continuously improve their performance and safety and to propose new technology and/or new concepts with new attributes.

The current global fleet was developed with plant design lives that were typically either 30 or 40 years. The newly installed ones are for at least 60 years. The economics of nuclear are characterized by low and stable operating costs, resulting from the low proportion of fuel cost in the total cost structure, which have enabled nuclear power plants (NPPs) to supply reliable, competitive and safe low-carbon baseload power. Once built and commissioned, and assuming a good operational performance, NPPs should be able to carry out this indispensable role for the long term. With high fixed costs and low running costs, average electricity costs for NPPs fall substantially with increased output. It is therefore vital for nuclear operators to achieve high plant capacity factors for long-term operation.

A safe, efficient and economically competitive operation of the NPPs is the result of a number of interlinked human, organisational and technical factors. Owners of NPPs, currently mostly operating in deregulated competitive markets, are under pressure to reduce operation cost to be more competitive with other energy production options. To recover the initial investment costs and to maintain necessary level of profitability it is reasonable to prolong operation of plants (LTO – long-term operation) where it is feasible, naturally without compromising safety and security. Along with traditional safety and reliability parameters, economic and financial factors are needed to be taken into account in new perspectives. Another aspect is that NPPs will be operated in markets with increasing number of decentralized and variable renewable sources (weather conditions derived energy production) and therefore flexibility (higher manoeuvrability) of NPPs will be quite important.

It should be noted that operators of NPPs continually improve their assets by various measures, notably i) power uprate (design reserves utilization, efficiency,…), ii) optimization of maintenance and outages, iii) upgrade and more efficient utilization of nuclear fuel (increased cycle length, enrichment, burn-up, reload patterns, multi-recycling…..), iv) flexibility of operation (load-following mode,..), and last but least v) supply chain optimization.

Improvements in operation are also realized based on inputs from missions and peer reviews that are focused mainly on safety, but also taking into account operational aspects of NPPs. The most important reviews are organized under auspices of IAEA and the World Association of Nuclear Operators (WANO). The WANO mission is to maximally increase reliability and safety worldwide through common efforts in assessment, benchmarking, mutual support, exchange of information and use of best practice. Areas contributing for improvement of reactor and NPP operation could be divided into management, organisational and human performance measures on the one hand and technical measures on the other hand.

Europe produces about 25% of its electricity through the operation of 131 reactors. Maintaining a high level of safety and competitiveness is a major challenge and requires the establishment of a coordinated R&D programme at European level. NPP operators have joined forces to build R&D programmes since 2011 with research centres, nuclear industry and technical support organisations. The support of the European Commission enabled the launch of transnational programmes with major R&D advances in fields as varied as severe accidents or the estimation of the lifespan of critical components. Nevertheless, these advances must now be part of a logic of industrial deployment that will allow Europe to have a globally competitive nuclear sector, particularly with China and Russia. The establishment of an ambitious R&D programme will also consolidate a very high-level nuclear science and technology sector whose spin-offs impact the energy, health, production of clean heat and hydrogen, construction and industrial manufacturing industries.

Specific challenge represents higher level of **flexibility** (non-baseload operation) as a response to market conditions with increasing portion of variable renewables. NPPs should be prepared to participate in the trading of electricity in quite complex conditions and provide various ancillary services such as frequency control, load following or reactive power control.

An analysis of recent technological innovations in the field of manufacturing, digital technology and safety approaches leads us to propose three R&D and innovation priorities for the next FP9 Horizon Europe Framework Programme (2021-2028).

Innovations and Competitiveness of Nuclear:

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

Digital Transition:

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

Safety and Environment.

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

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

Scope and purpose

NUGENIA is a pillar of the Sustainable Nuclear Energy Technological Platform (SNETP) dedicated to innovation, research and development of nuclear fission technologies, with a focus on Generation II and III nuclear technologies. It gathers international stakeholders from industry, research, safety organisations, SMEs and academia committed to cooperate and develop joint collaborative projects in the field.

The activities of NUGENIA are carried out in eight technical areas, within a general scope defined by the SNETP Strategic Research and Innovation Agenda (SRIA) and technical scope outlined in the NUGENIA vision (2015). Harmonisation and cross-cutting issues are tackled within the different technical areas and streamlined by the pillar governance: the coordination board composed by the leaders of each technical area.

The NUGENIA governance, the coordination board, operational teams and technical experts focus on monitoring of R&D&I activities and defining high level challenges and priorities within the context of the European Union policies and its Member States interests. For increased visibility and credibility at international level, a number of cross-cutting initiatives were launched in the past years and formalised interactions put in motion at different levels. This covers relations with other SNETP pillars, EU bodies, international organisations and national public and private actors. NUGENIA, in its short but intense historical activities that started by building upon the existing bricks within the European landscape (unification of NULIFE, SARNET, SNETP Gen II/III TWG, ENIQ networks), followed by the creation of a non-profit association that has gathered more than 100 members from all around the world. Thanks to the EURATOM support (FP7-NUGENIA+ project), it has been able to create services to the community, foster the creation of innovative project ideas and to play an effective role at the international level by co-organising international level and collaborating with international stakeholders such as IAEA, WNA, COG, OECD-NEA …. Up to 2019, NUGENIA has labelled more than 60 projects and launched more than 2/3 of them, published books, guidelines and positions papers increasing therefore the dissemination level of the R&D&I output.

The Roadmap is a major technical document of NUGENIA. It is based on the high-level challenges expressed in the NUGENIA Global Vision document consolidated back in 2014. The first technical roadmap was issued in 2013 and served for the past 7 years to identify major R&D&I topics of importance and/or interest for the international community. The NUGENIA roadmap has been serving as an important reference that contributes to the building of the European agenda, Euratom R&T programme as well as the SET-PLAN among others.

Beside safety, additional topics of importance, driven by the need of innovation to tackle new societal, environmental and economic challenges, have been raised. Among others the cyber security, digitalisation, SMRs, new fabrication routes for materials, new fuels that would allow an enhanced tolerance to accidents and last but not least new technologies for dismantling, decommissioning and waste management nuclear plants.

The goal of this document is to highlight the need of a strong international collaboration accompanied with a substantial financial support both from the private and public sector in order to ensure a safe and efficient production of low carbon energy.

Indeed, nuclear needs to play its role in minimising the carbon emissions that are becoming more and more deleterious to the climate.

The scope of the work performed by the coordination board of NUGENIA aims at:

- Fostering collaboration between industry, SMEs, research centres, academia and technical safety organisations
- Building knowledge and expertise
- Facilitating the emergence of innovation
- Achieving projects with high added value to the community,
- Maintaining and developing the needed skills, competences and infrastructures to tackle the up-coming challenges (LTO, new build, dismantling, ….)

To facilitate the interaction between experts in different areas, this work is structured in 8 different technical areas, namely,

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

The main challenges to be addressed within and between the areas are the following:

- Improve safety in operation and by design
- High reliability and optimized functionality of systems
- High reliability of components
- Improve modelling of phenomena in NPPs
- Increase public awareness
- Efficient integration of NPPs in the energy mix
- Prepare the future to avoid technology obsolescence

- Performance and ageing of NPPs for long term operation

Therefore, the missions of the NUGENIA Coordination Board, defined in its charter, include, but are not limited to:

- Elaborate, consolidate and update the NUGENIA strategic and technical documents
- Contribute to the elaboration, consolidation and update of the SNETP strategic documents
- Initiate and facilitate the creation of project ideas
- Propose mature project ideas for labelling by the SNETP GB
- Monitor NUGENIA's project portfolio

Each technical area is chaired by a TA leader, and divided into various subareas. Each subarea is chaired by a subarea leader. Meetings of the individual TAs are organised at least once a year.

TA leaders are elected by the members of the TA. The election mode and the duration of his/her mandate remains at the discretion of each TA, but in the absence of any specific process, the following generic rule should apply: Each TA leader is elected by the identified organisations of the TA for a three-year mandate, renewable.

The missions of the TAs include, but are not limited to:

- Follow-up the progress of projects labelled by SNETP pillars, which fall under their TA;
- Initiate and facilitate the creation of new project ideas.

Each TA has been summarized using, as input, the fully developed NUGENIA R&D roadmap that is available to all NUGENIA members. The R&D topics have been selected in a consensual manner by the experts and the challenges are those which need to be addressed with the widest possible collaboration both at the European and international level.

1. Technical Area 1 (TA1) - Plant Safety and Risk Assessment

Safety of nuclear installations is among the absolute priorities from the very beginning of nuclear reactors construction in 1940s. During the nearly 80 years of designing, construction and operation of research reactors and commercial NPPs, the concept of nuclear safety has developed into a complex and sophisticated system, with the defense-in-depth approach at its core. Nuclear safety is a critical condition for sustainable NPPs operation and therefore SNETP puts significant emphasis on R&D activities focused on increasing safety of NPPs and improving understanding of accident phenomenology and abilities for NPP safety and risk assessment. An accident in any country in any part of the world effects the nuclear sector globally. That is why support of nuclear safety related R&D programmes and harmonization of approaches to nuclear safety is an important aspect of nuclear safety effort.

1.1. Scope

TA1 is devoted mainly to improving the physical understanding and the numerical modelling of the relevant phenomena involved in NPP incidents and accidents, to increase the capacity and comprehensiveness of the plant behavior and to enhance the accuracy of safety margin assessment accordingly.

1.2. Objectives

The main challenges identified are:

- The comprehensive adoption and use of the Probabilistic Safety Assessment (PSA) for understanding and pointing out safety risks, including quantitative aspects for risk and margin evaluation, methodologies to assess shut-down states, and external events, quantification of the risk inherent to spent fuel pool, best practice for probabilistic safety assessment (PSA) application and appreciation of residual risk.

- The deterministic assessment of plant transients, mainly focusing on the improvement and validation of models and tools for plant transient analysis, including reactor physics and thermal hydraulics, design and evaluation of passive safety systems, coupled multi-physics simulations, containment behaviour, and fluid-structure interactions.
- The impact of external loads (including electrical disturbances) and other hazards on the safety functions.
- The advanced safety assessment methodologies: safety margins and best estimate methods, integrating the deterministic and probabilistic safety assessments.
- The design of new reactor safety systems to comply with new safety requirements.

The main objectives that have been identified are: advancements in NPP probabilistic assessment and human reliability analysis, further development of computational tools for deterministic plant assessment including coupled codes to progress towards multi-level and multi-physics computational capabilities, advanced safety assessment methodologies (identification and reduction of all uncertainties), development of methods and tools to better insure complementarity of probabilistic and deterministic assessment, including integration of such methods, extended validation of deterministic computational codes and benchmarking of probabilistic assessment methods (including determination of missing experimental data), improved understanding and modelling of internal and external hazards, development and application of tools and methods for upgrading of reactor safety systems to handle new safety demands, effective replacement of obsolete components and support to LTO (Figure 1-1).

Figure 1-1: NARSIS Toy Bayesian Network for integrated multi-risk analysis and PSA on PWR.

2. Technical Area 2 (TA2) - Severe Accidents

2.1. Scope

The fundamental purpose of nuclear safety is to protect people and the environment from harmful effect of ionizing radiation, particularly under those conditions that pose higher radiation risk, like severe accidents (SAs)in NPPs. With appropriate site risk evaluations, plant designs and management, current Generation II and III NPPs show high levels of robustness and low probabilities for SAs. However, despite the highly efficient accident prevention measures adopted for the current Generation II and the still more demanding ones for the Generation III plants, some accident scenarios may, with a low probability, result in SA, as emphasized with the Fukushima-Daiichi accidents in Japan. This brings to core melting, plant damage and dispersal of radioactive materials outside the containment, thus threatening public health and the environment.

This risk can be substantially decreased when state-of-the-art devices currently available for prevention and mitigation of severe accidents are installed. Lessons from the Fukushima-Daiichi accidents and consequences related to accident management provisions from the ENSREG (European Nuclear Safety Regulators Group) stress tests and other national activities will lead to further safety enhancement of NPPs.

Considerable knowledge has been gained about SA phenomenology through research carried out during the last 30 years, also in the framework of the SARNET network [TA2-1] and afterwards in NUGENIA/TA2 [TA2-2]. It is based on experimentation, mostly out-of-pile but with a few in-pile programmes like Phébus-FP, and on theoretical developments that have resulted in computation tools capable of simulating accident key-phenomena like the ones occurred at Three Miles Island (TMI2) in 1979, Chernobyl in 1986, and at Fukushima-Daiichi in 2011 (figure 2-1).

Figure 2-1: Fukushima Daiichi site right after the accident.

Since the latest NUGENIA roadmap in 2013, many European and international R&D projects have started in diverse frames such as Euratom (FP7 and H2020), OECD/NEA and IAEA. Some EU road maps have been proposed in the frame of EU projects, such as SAFEST [TA2-3] (for phenomena involving corium needing complementary R&D studies), and a number of projects are ongoing under the H2020 frame (i.e., MUSA, R2CA, AMHYCO). No less important, in-kind projects within TA2, like SAMHYCO, ASCOM and IPRESCA have also been launched and some of them are still running. Among the entire SA projects portfolio of these years, those related to the Fukushima Daiichi forensic analysis, under the auspices of OECD/NEA, have had particular relevance [TA2-4] (i.e., OECD/BSAF, /BSAF2, ARC-F, etc.).

2.2. Objectives

The extreme complexity of SA scenarios makes them hard to be thoroughly and accurately characterized, and uncertainties still remain. The generic objective of TA2 is to reduce such uncertainties as much as feasible, so that an effective enhancement of Severe Accident Management Guidelines (SAMGs) can be achieved.

Specific objectives might be formulated as follows:

- To identify and investigate key-phenomena in NPP SA unfolding and/or their consequences through experimental and numerical platforms.
- To develop analytical methodologies capable of providing a better assessment of safety margins and of giving better insights into the timeliness and effect of SAM actions.
- To enhance efficiency of prevention and mitigation devices supporting accident management and to propose innovative

ones with high potential in accident management.

- To capitalize the gained knowledge in SA phenomenology in powerful SA numerical simulation tools.
- To provide the most reliable information necessary to implement robust and effective emergency plans.
- To spread the gained knowledge on SA to the different stakeholders and, in particular, to new generations of nuclear scientists and engineers.

In order to achieve the TA2 objectives, the six sub- areas below were identified, all of them being more and more directly linked to SA management and in particular to mitigation processes:

- In-vessel corium/debris coolability
- Ex-vessel corium/debris interactions and coolability
- Mitigation of gas explosion risk in containment
- Source term assessment and mitigation
- Severe accidents linkage to environmental impact and emergency situations
- Management of severe accident scenarios

3. Technical Area 3 (TA3) - Improved NPP Operation

3.1. Scope

NPP operators are facing economic pressure in the current competitive market conditions with significant implications for plant operation. The optimization of operation and maintenance costs is therefore a key component of a broader integrated business planning process. Asset management and decision making is integral part of the overall operation strategy. Specific challenge represents higher level of flexibility (non-baseload operation) as a reaction to market conditions with increasing portion of variable renewables. NPPs should be prepared to participate in the trading of electricity in quite complex conditions and provide various ancillary services such as frequency control, load following or reactive power control.

TA3 is devoted to improving the technical and economical characteristics of NPP operation by various measures including maintenance strategies and also to minimise the radiological impacts on plant workers, the environment and general public during normal plant operation (covering also periods of shut-down, reshuffling, abnormal operational situations and emergency states, but excluding severe accidents).

3.2. Objectives

The key challenges identified are:

- Measures for achieving higher level of flexible operation of NPPs while minimizing negative impacts on lifetime of components.
- Application of risk-informed decision making in human factor area and methods, means and tools for improvement of safety culture and operating practices.
- Digital transformation - advanced sensoring (including IoT), high level of automation and robotization, virtual and augmented reality, implementation of digital twins and advanced data analytics and decision making (including machine learning, deep neural network learning and other forms of artificial intelligence).
- Maximize cycle energy production with minimum fuel cost while maintaining sufficient margins to improvement of precision of core calculations and better estimation of their uncertainties.

- Advanced and more accurate chemistry control.
- Improvement of radiation protection and reduction of occupational exposures by application of new tools (real time monitoring of received dose, augmented reality tools, ..) and minimization of radiological impacts on the environment and general public.

The above-mentioned topics are addressed within TA3 in six sub-areas:

3.1 Improvement of operational economics and nuclear power plants flexibility
3.2 Human and organisational factors
3.3 Implementation of advanced digital technologies and solutions for cybersecurity
3.4 Improvement of core management modelling tools and core monitoring and instrumentation
3.5 Water chemistry and low-level waste management
3.6 Radiation protection

4. Technical Area 4 (TA4) - Integrity Assessment of Systems, Structure and Components

4.1. Scope

Safety-classified SSCs of a NPP have to function when called upon with a high level of reliability, based on conservative assumptions and methods, not only for normal operation, but also for anticipated events, transients and accidents as well as postulated events, in other words Design Basis Events (DBE) and Design Basis Accidents (DBA). Furthermore, SSCs also need to function under postulated conditions beyond DBE and DBA. Such postulated conditions are denoted Design Extension Conditions (DEC) and under such conditions the reliability may be shown with realistic assumptions and methods. Equipment in a NPP therefore needs to be environmentally and seismically qualified. Long-term operation (LTO) of NPPs entails reliable equipment function in all safety-classified SSCs. This is ensured via appropriate maintenance, replacement and repair strategies through an appropriate plant life management (PLiM), so that the equipment is able to perform its intended function in a reliable and safe manner throughout its lifetime or intended time of use.

There is a need, particularly for assessing nuclear plant components in terms of LTO, to properly quantify, demonstrate and understand levels of conservatism in current integrity assessment methods with a view to revising the guidance and procedures in the member countries. Uncertainty factors should be considered and quantified. Furthermore, unified European guidance would be a significant advantage. The modelling of integrity assessment is important in order to be able to translate the mechanistic understanding to simulation tools and assessment procedures to predict theoretical margins for the safe operation of NPPs taking into account structural features, real or postulated flaws, loading conditions and relevant material characteristics including ageing effects.

4.2. Objectives

The objective of TA4 is to improve knowledge and methods in order to ensure high integrity and high performance in the case of internal and external loads, to demonstrate the safety and to increase availability and control the lifetime of SSCs. While the integrity assessment principles and approaches relating to SSCs are generally similar (and even pretty much the same) in Europe, some differences in technical details (could be the result of requirements of underlying nuclear design code) persist (see [TA4-1] in case of the reactor pressure vessel).

With the longer term objective of European harmonization in mind, it is necessary that the differences are fully understood and for the lessons learned from Gen II NPPs to be taken into account when developing and/or revising best practice guidance for the safe operation of SSCs with satisfactory, but not over-conservative safety margins (see [TA4-1] and [TA4-2] as examples).

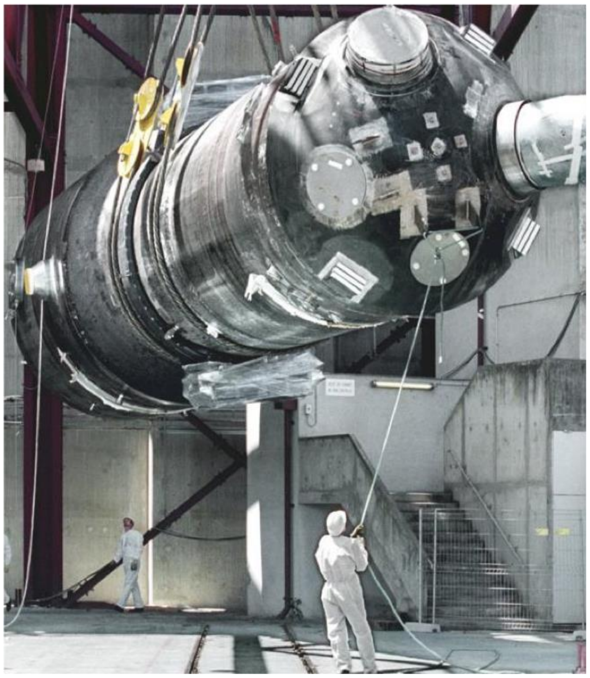

Figure 4-1: Replacement of a steam generator (Courtesy of EDF).

The identification of the SSCs that are subject to ageing is a key issue for PLiM. It is essential to perform analyses for understanding and modelling of the main ageing mechanisms concerning each SSC (potential or encountered). Finally measures have to be set up to justify the integrity of each SSC based on nuclear codes & standards (see [TA4-3], [TA4-4], [TA4-5]), regulations (e.g. [TA4-6] see Finnish nuclear regulation as an example:), specifications & guidelines and scientific knowledge of the ageing mechanisms.

For ageing monitoring new monitoring methods, diagnostics and monitoring simulation tools that can greatly increase the ageing management efficiency have to be developed. Prevention and mitigation measures are the development of efficient and applicable preventive measures (see [TA4-7]) and repair technologies.

5. Technical Area 5 (TA5) - Waste Management and Decommissioning

5.1. Scope

TA5 focuses on waste management and decommissioning. Broadly this covers the management, treatment and disposal of waste arising from operations across the nuclear fuel cycle (including fuel fabrication, power generation and fuel recycling/reprocessing). Beyond waste management the area incorporates the dismantling and decommissioning (D&D) of nuclear facilities as the last step in their lifecycle. The emphasis is on the identification of best practice from the international community, development and maturation of innovative technology and methods that drive towards improved safety, enhanced environmental performance, sustainable solutions and project efficiencies, through a holistic lifecycle approach. We maintain strong interactions with relevant Horizon 2020 projects; including SHARE [TA5-1] and PREDIS [TA5-2].

5.2. Objectives

As decommissioning and dismantling activities proceed across the globe, significant experience is being gained. For D&D, the focus is on development of pre-planning for decommissioning, decommissioning strategies, and the transition phases between operation and decommissioning. Key technical areas that underpin the D&D activities are plant characterisation, decontamination techniques, dismantling equipment, remote operations (including robotics) and land remediation.

Furthermore, it is also essential to focus on the implementation of the waste hierarchy in the context of radioactive waste management. This involves characterisation of waste, innovative approaches for treating waste (decontamination and revalorisation of radioactive materials), waste storage, waste form development, long term condition monitoring and disposability. Innovative approaches can reduce the burden of waste management activities and lead to a more sustainable long-term approach. As with all areas, active demonstration of new technology is vital to increase the technology readiness and demonstrate the maturity of new approaches.

Some of the major TA5 objectives are summarised below and as research themes in figure 5-1:

- Application of the waste hierarchy to avoid/minimise waste generation: through smart design, appropriate material selection, operational measures, and designing for decommissioning.
- Establishment of improved (Predisposal) treatment technologies (thermal or other) to reuse/recycle materials, minimise waste volumes and to develop robust and passive waste forms. Specific waste focus areas include, organic wastes, metallics, contaminated concrete, irradiated graphite, etc
- Development of characterisation techniques for waste inventory assessment, and plant/facility assessment to aid planning for decommissioning and waste management
- Development of waste segregation/sorting, advanced decontamination techniques and optimized measurement/assay methods to enable a circular economy where appropriate.
- Application of transformative technologies to optimize decommissioning scenarios: for example, digitalization, supercomputing, artificial intelligence, in-situ characterization and robotics.
- Identification of synergy effects for multi-unit sites or fleet-wide D&D projects, standardization of approach, use of mobile treatment facilities and optimization of post-operational phase

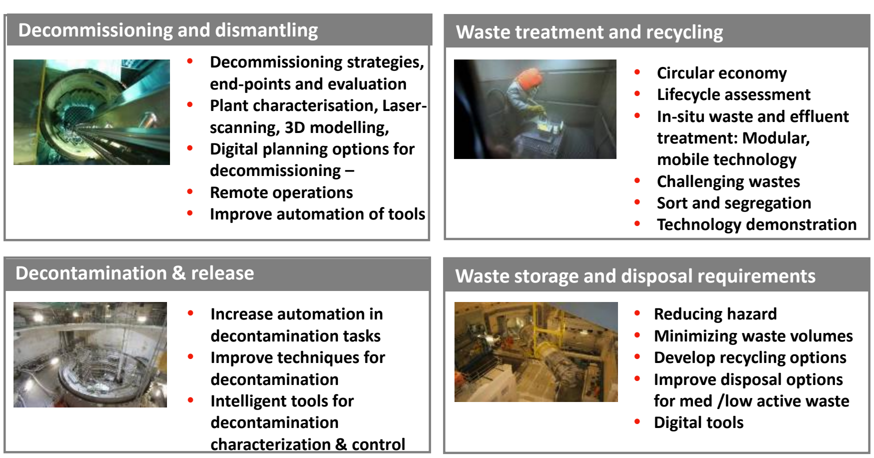

Figure 5-1: Focus areas for Waste Management and Decommissioning (TA5).

6. Technical Area 6 (TA6) - Innovative LWR Design and Technology

6.1. Scope

Innovative technology will be developed along with a transverse view for fulfilling the needs and requirements of the currently operating LWRs and new designs. On the one hand, this will provide new solutions and/or use of new methods and techniques for addressing key issues pointed out in the other TAs which will be used as input. On the other hand, this will support the development of advanced LWR concepts with improved sustainability making better use of uranium resources and multi recycling capabilities of fissile materials. This will also allow the development of small modular reactors (SMRs), which offer simpler design, inherent safety advantages and modular construction. Progress should also be achieved developing cogeneration, nuclear flexibility in a ch chn both in the field of economics particularly when changing energy mix and in the field of public understanding and awareness, especially following the Fukushima accident and considering a diverse use of nuclear energy for district heating, industry and hydrogen production.

Figure 6-1: NUWARDTM small modular reactor (©TechnicAtome).

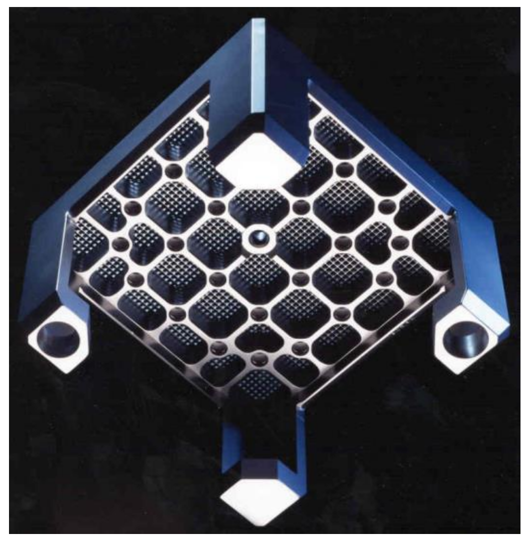

Figure 6-2: Debris trapper considered within additive manufacturing NUCOBAM project (Framatome courtesy).

6.2. Objectives

Innovation is the key driver for addressing technology, methods, testing and computation capacities, with the objective of supporting the competitiveness of LWRs (figures 6-1 and 6-2).

The main challenges are the following:

- The development of new materials, manufacturing and assembly technologies will result in the fabrication of highly reliable components for LTO. In this domain, the challenges are to promote technologies like hot isostatic pressing, additive manufacturing and to develop new or improved materials for LWRs.
- Alternative LWR concepts benefiting from the experience gained in the field of LWR technology are for instance high conversion ratio LWRs which better use fissile material and LWRs which favour multi-recycling of plutonium.
- SMRs [see SMR booklet TA6-1] have smaller core size, smaller footprint and

lower capital cost compared to large LWRs. Their simpler design and the integration of passive safety systems combined with smaller residual heat allow improvements in safety. Developing numerous smaller reactors facilitates standardization and series effect but requires harmonization in the licensing process [see ongoing ELSMOR project TA6-2]. Besides SMRs are clear candidates for modular construction with modules manufactured and tested in factories.

- Even though less mature than LWRs, supercritical water-cooled reactors (SCWRs) operate at significantly higher pressures and temperatures compared to current LWRs and therefore have higher plant efficiencies.
- Deployment of innovative LWRs / SMRs in a changing energy market with carbon neutrality consideration: Techno-economic studies are necessary to analyse and optimize hybrid nuclear/renewables power systems and systems where nuclear energy can serve new applications like district heating, desalination and clean hydrogen production.
- Building public awareness, understanding and social acceptance: Studies in these areas are particularly helpful for the construction of new nuclear facilities, like NPPs, storage or disposal facilities or new applications with nuclear plants closer to local demands.

7. Technical Area 7 (TA7): Fuel Development and Spent Fuel Management

7.1. Scope

TA7 covers the research on nuclear fuel elements for existing, advanced and innovative core designs including assembly and control rod considerations. As defined in [TA-1], it includes the development of new fuel elements, manufacturing, fuel elements use in reactors, assembly instrumentation and pre-disposal management of spent fuel.

In spite of the large knowledge base on existing nuclear fuel types, mainly UO_2 and $(U,Pu)O_2$ pellets with a zirconium alloy cladding, there are still data gaps, which necessitate dedicated material property measurement and modelling. In addition, there are many challenges for a number of innovative nuclear fuel element types under development, in particular with enhanced accident tolerance.

The focus is first on the safety criteria for the fuel behaviour in the core under normal, transient and accident conditions, as well as for the fuel cycle. Of particular importance is that the roadmap takes account of lessons from the Fukushima accident to propose research, development and innovation to improve the safety and resilience of the existing and new build LWR reactor fleet. A second focus is to improve the economics and sustainability of nuclear power, through optimization of the use of available fissile and fertile nuclear material resources, reduced fuel costs, increased burn-ups and development of SMRs. Finally, in relationship with a more varied energy mix, fuel flexibility also has to be improved.

7.2. Objectives

Numerous R&D programmes were carried out to qualify fuels and fuel performance codes for current designs and operating conditions. A transposition of this knowledge to new conditions requires a thorough understanding and detailed description of the fuel behaviour. Physics-based validated fuel performance codes capitalizing the results of a combination of irradiation experiments, post-irradiation examinations, separate effect experiments and multiscale modelling are the way forward to answer these new questions. This knowledge must then be transferred in industrial simulation tools and undergo verification, validation and uncertainty analysis.

The priority topics are as follows.

- **extend the validity of the fuel performance codes for new designs, materials and operating conditions**
  - ✓ Consolidated multiscale modelling approaches and associated physical property databases,
  - ✓ Description of a large range of phenomena such as clad ballooning, pellet fragmentation, fuel relocation, fuel creep, pellet-cladding interaction, fission gas behaviour
- **develop accident tolerant fuel elements for the increase of safety margins under operation and accident conditions**
  - ✓ Innovative microstructures to improve power evacuation and reduce the fuel temperature
  - ✓ Innovative design and fuel material to reduce the mechanical and chemical pellet-to-cladding interaction
- **guarantee the fuel development for SMRs**
  - ✓ Evolution of fuel microstructure and properties, as well as fission gas behaviour, at lower temperatures with a reduced irradiation defects annealing rate
  - ✓ Development of fuels with higher concentrations of burnable poisons for boron free reactors
- **improve spent fuel management**
  - ✓ Long term fuel behaviour assessment and physically based modelling to complete the Spent Fuel Characterization WP of the European Joint Program EURAD.
- **enable multi recycling of fuels**
  - ✓ Extend the knowledge obtained on single recycling of MOX fuels with new data regarding the impact of a higher content in Pu or minor actinides and of degraded isotopic composition on fuel thermal and mechanical properties, as well on fission gas behaviour

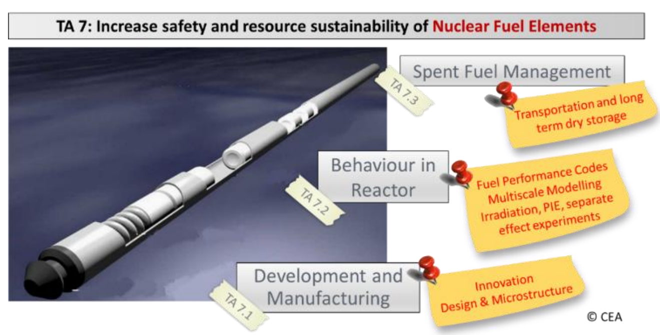

Figure 7-1: TA7 methodology.

It is also critical to maintain key experimental facilities, in particular experimental irradiation devices in research reactors, hot cells and hot laboratories, and to expand their capabilities to meet future requirements regarding advanced characterization techniques or online data acquisition in irradiation experiments.

8. Technical Area 8 (TA8): In-service Inspection and Inspection Qualification

8.1. Scope

The European Network for Inspection and Qualification (ENIQ) was created in 1992 and is a utility-driven network deals with the reliability and effectiveness of non-destructive testing (NDT) for NPPs. ENIQ is working mainly in the areas of qualification of NDT systems and risk-informed in-service inspection (RI-ISI). ENIQ is recognised as one of the main contributors to today's global qualification guidelines for ISI.

The ENIQ methodology has been developed with regard to the inspection of pressurised metallic components and is used in European LWRs and CANDU Reactors and accepted by IAEA and WENRA as recommended practice to follow for inspection qualification.

ENIQ has two sub-areas in which the technical work is performed, the Sub Area for Qualification (SAQ), and the Sub Area Inspection Effectiveness (SAE). ENIQ members come from utilities, ISI vendors, Qualification Bodies (QBs) and research organisations in Europe with additional members from Canada, Japan and the USA. The ENIQ steering committee (SC) is the decision-making body of ENIQ and its members come from utilities of EU member states plus observers from Canada, Japan, USA and the leaders of the two sub-areas. In 2012 ENIQ was integrated into NUGENIA, becoming Technical Area 8 of NUGENIA.

8.2. Objectives

By coordinating expertise and resources, ENIQ aims at supporting licensees (utilities) and stakeholders in:

- Addressing issues where the practice and implementation of NDT will ensure the safe and reliable operation of NPPs through inspection qualification, the application of risk-informed approaches, and other processes;
- Providing recommendations and guidance to optimise and harmonise processes;
- Continually improving the processes for inspection qualification and RI-ISI for increased effectiveness and efficiency;
- Responding to the new challenges resulting from plant life extension (PLEX) and new Build;
- Promoting ENIQ approaches outside Europe and in non-nuclear industries;
- Maintaining links with other Technical Areas, especially TA4 and TA6.

Accordingly, the corresponding R&D challenges are:

- Qualifying NDT Systems that make Use of machine learning and Artificial Intelligence; an ENIQ recommended practice on the topic will be published in 2021 that will also identify the gaps.
- Use of virtual flaws on qualification: Practical trials or technical justification
- Understand the technical barriers that preclude the transport of qualifications between countries and find methods or procedures on how to overcome these. A related benchmark project on re-qualification of inspections was completed in 2020.
- An independent assessment to verify the accuracy of NDT inspection simulation software
- Use of structural health monitoring systems in NPP to complement ISI

- Review of risk-informed pre-service inspection (PSI) for new build and modifications of existing plants.
- Extension of RI-ISI to all mechanical components, i.e. beyond piping. ENIQ SAE completed a technical report on topic which will be published in 2021.
- Benchmarking of RI-ISI approaches worldwide to harmonize them and improve credibility

Way forward

Nuclear energy is an important contributor to all three main pillars of EU energy policy set out in the SET-plan: i) environmental sustainability, ii) security of supply and iii) economic competitiveness.

Nuclear energy is a key asset for achieving the EU's 2050 carbon-neutral target in an affordable, reliable and safe way as

- It is low carbon over its entire life cycle;
- It is a proven industrial technology and is a major employer, supporting skilled high value-added jobs and local economic activity;
- It has the smallest land and resource footprints of any energy source;
- It does not contribute to air pollution such as NOx, SOx, heavy metals and particulate matter;
- It provides 24/7 reliable power for future new infrastructure and Industry growth, but can also load follow if needed;
- It is resilient, and decreases vulnerability to extreme weather phenomena and external threats;
- It provides rotational inertia that helps to stabilise the grid and regulate frequency;
- It enables stockpiling of fuel, which boosts security of energy supplies;
- It can provide isotopes and support for research, medicine, industrial and agricultural purposes;
- It is improving, with new technologies offering greater efficiencies and opening up new applications to enable decarbonisation of heat, industry and transport sectors.

Several major events occurred during the last decade, with the tsunami in Japan effecting the Fukushima-Daiichi NPP in 2011 and the financial crisis in 2008-2009 which triggered the evolution of energy policy in European member states. As a result, public acceptability has been weakened and the financing community together with local authorities have lost part of their trust in the competitiveness of new projects and in the life extension of existing reactors.

The nuclear sector needs to innovate to overcome these challenges. It shall:

- Continue increasing its safety and security standards despite its already excellent records;
- Minimise and manage efficiently its waste by providing long term solutions;
- Enhance public awareness and acceptability by engaging multilateral dialogue;
- Improve the economic performance of new builds;
- Continue safe, efficient and competitive long-term operation of existing NPPs;
- Develop, attract and retain skills and competences.

NUGENIA as a pillar of SNETP needs to pursue its evolution by:

- Strengthening the positioning of nuclear energy in today’s and tomorrow’s European energy mix and consolidate European research, development, demonstration and innovation on fission technologies;

- Defining proprieties on innovative topics of high added value to the fission technologies in compliance with our long-term strategy namely the nuclear will continue to play a major role in the energy mix in Europe;
- Promoting and strengthening the collaboration between all stakeholders including industry, SMEs, research centres, academia around its priorities;
- Developing links and crosscutting topics with the actors towards the objective of neutrality promoted by the European commission for 2050: renewable energy platform (such as EERA, …) and also with those acting in the so-called “Digital transformation”;
- Establishing close and “win-win” collaboration with international agencies and other legal entities;
- Maintain and develop the needed skills and competences to tackle the up-coming challenges (LTO, decommissioning, dismantling, new build, ….);
- Building open knowledge and expertise in the highly demanding technological/scientific fields;
- Managing in a project driven way all the activities in order to get results rapidly and in an efficient way, through openness on the new topics;
- Liaise with all the European Research community and Organise an active participation in European/international events;
- Communicate in a proactive and open way on the perspectives opened by the R&D and innovation activities.

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Glossary

ATF	Accident Tolerant Fuel or Advanced Technology Fuel
D&D	Dismantling and Decommissioning
DBA	Design Basis Accident
DBE	Design Basis Events
DEC	Design Extension Conditions
DHR	Decay Heat Removal
EC	European Commission
EERA-JPNM	European Energy Research Alliance – Joint Program on Nuclear Materials
ENIQ	European Network for Inspection and Qualification
ENSREG	European Nuclear Safety REgulators Group
ESNII	European Sustainable Nuclear Industrial Initiative
EU	European Union
EUR	European Utility Requirements
I&C	Instrumentation and Control
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IGDTP	Implementing Geological Disposal Technology Platform
IPCC	International Panel on Climate Change
ISI	In-Service Inspection
JHR	Jules Horowitz Reactor
LCOE	Levelized Costs Of Electricity
LLW	Low Level radioactive Waste
LTO	Long-term Operation
LW-SMR	Light Water – Small Modular Reactor
LWR	Light Water Reactor
MOX	Mixed Oxide
NC2I	Nuclear Cogeneration Industrial Initiative
NDE	Non-Destructive Examination
NDT	Non-Destructive Testing
NEA	Nuclear Energy Agency
NPP	Nuclear Power Plant
ODS	Oxide Dispersion Strengthened
OECD	Organisation for Economic Cooperation and Development
PIE	Post Irradiation Examination
PINC	Nuclear Illustrative Programme
PLiM	Plant Life Management
PWR	Pressurized Water Reactor
R&D	Research and Development
RI-ISI	Risk Informed In-Service Inspection
RPV	Reactor Pressure Vessel
SAMG	Severe Accident Management Guidelines
SAR	Safety Analysis Report
SET	Strategic Energy Technology
SNETP	Sustainable Nuclear Energy - Technology Platform
SSC	Structures, Systems, and Components
TA	Technical Area (of NUGENIA)

ABOUT NUGENIA

The **Nuclear Generation II & III Alliance (NUGENIA)** is dedicated to the research and development of nuclear fission technologies, with a focus on Gen II & III nuclear plants. It provides scientific and technical basis to the community by initiating and supporting international R&D projects and programmes.

NUGENIA is one of the three pillars of the Sustainable Nuclear Energy Technology Platform (SNETP) that 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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