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Foreword

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Executive Summary

Future of Nuclear Energy in Europe

The world today faces a tremendous challenge in providing mankind with the energy required. The world population will not stop rising and the worldwide standard of living will also keep rising. Such factors are important indicators for energy consumption, noting that more people with increased welfare will consume considerably more energy. Meanwhile, the International Panel on Climate Change (IPCC) warns us that we are facing a global warming because of human presence, partly driven by our energy consumption. Even though some people may be sceptical about these studies, a ‘no regret policy’ requires the potential environmental impact of energy consumption to be avoided and energy for the coming generations to be secured.

On the other hand, many current power plants are facing shut down because they are reaching the end of their technical or economical life times, or they are forced to shut down because of regulatory requirements. The combination of the predicted growth and the phase out of the current power plants means an even more significant challenge. In summary:

Mankind faces the issue of possible climate changes due to the increasing CO_2 concentrations in our earth atmosphere while at the same time our energy consumption world-wide will rise significantly.

Nuclear energy is an important contributor to all three main pillars of EU energy policy set out in the SET-plan and mentioned in the long term strategy document ‘A clean planet for all’ (EC, 2018): environmental sustainability, security of supply and economic competitiveness. Nuclear electricity provides 26% of the EU’s electricity and about half of the EU’s low-carbon electricity. Nuclear has one of the lowest life-cycle climate impacts of any energy source. Greenhouse gas emissions from the nuclear cycle on average are similar to those of wind power and only one quarter of the emissions of solar photovoltaics.

On top of that, when compared with other sectors, the nuclear industry generates a very limited amount of waste. The average EU citizen generates about 1.4 tonnes of waste per year, of which 54kg is toxic waste and only 54g is classed as radioactive. Unlike other sectors, the nuclear industry takes great care to segregate and manage its waste safely, with dedicated funding set aside for its ultimate disposal. Because nuclear is energy-intensive, the area of land occupied by a nuclear power plant is, for example, less than one-hundredth of the area required for a wind farm of equivalent electrical output. Therefore it is the considered view of the SNE-TP members that nuclear energy will play an important role in a clean, affordable and reliable future European energy mix alongside other low-carbon technologies. This view is confirmed in the EC long term strategy document ‘A clean planet for all’ (EC, 2018) which shows that nuclear will form the backbone of a carbon-free European power system, together with renewables. Therefore, nuclear energy will have to address the new challenges raised by the integration of renewables in the future energy mix in Europe, with a perspective of nearly 30% of the energy provided by renewables in 2030 (EC, 2020).

The **SNE-TP vision**, presented in the original vision document (SNE-TP, 2007), is:

to aim at achieving a sustainable production of nuclear energy, a significant progress in economic performance, and a continuous improvement of safety levels as well as resistance to proliferation through the development and deployment of potentially sustainable nuclear technologies, as well as actions to harmonise Europe’s training and education, whilst renewing its research infrastructures.

This document presents the latest update of the strategic research and innovation agenda (SRIA 2020). While maintaining the objective to address challenges for nuclear fission technologies and priorities set by the SNE-TP members, this third edition has adopted a new format. This new format aims to reflect the common challenges and interaction between the three pillars of SNE-TP (NUGENIA, ESNII, and NC2I), while maintaining the unique features and separation between the pillars. The document intends to provide a holistic SNE-TP view on the current agenda for strategic research and innovation identifying and presenting together:

- common challenges and R&D orientations,
- specific challenges and R&D orientations, and
- cross cutting challenges and R&D orientations.

This is possible because each pillar has a well established program and related reference documents. Common and specific challenges with respect to reactor technology are discussed with respect to operation and construction, in-service inspection, qualification and non-destructive examination, advanced reactor development and the next generation of fission reactors, and development of small modular reactors. Subsequently, enabling conditions like safety of nuclear power plants, development of fuel, the fuel cycle, and spent-fuel management, dismantling and decommissioning, and social, environmental and economic aspects are discussed. After that, cross-cutting technologies, like digitalisation, modelling and simulation, and materials are presented. Finally, non-technological cross-cutting aspects like research infrastructure, harmonisation and education, training and knowledge management are shown. In this way, the SNE-TP Strategic Research and Innovation Agenda 2020 is expected to shape the program of SNE-TP as one association to maximise the benefit to society from the exploitation of nuclear fission as a power source.

Reactor Technology

Low-cost baseload electricity supply is a critical enabler of economic and social development. Nuclear power has played a key role in delivering such supply for decades in many countries and will continue to do so in the upcoming years, but new challenges are coming. Therefore, maximum and efficient utilization of the existing portfolio of nuclear reactors is currently a priority for Europe, despite the development of new technologies like renewables. The current nuclear fleet was developed with plant design lives that were typically either 30 or 40 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 plants to supply reliable, competitive and low-carbon baseload power. Continued optimization of operations and innovation have enabled nuclear operators to achieve high plant capacity factors for long-term operation.

One of the most important challenges for the actual fleet of nuclear plants, being nearly 30 years old, is to be able to connect to the ENTSOE network in Europe (ENTSOE, 2020), which includes all transmission system operators. The capability of the existing and future nuclear power plants to connect to the ENTSOE grid, through their so-called Gridcodes, is one of the most important issue. Those Gridcodes give the rules for a utility to have the right to connect to the European network. Because of the building of the future energy mix including renewables, those Gridcodes are most of the time more severe than the actual operating procedures in the actual states, leading to wider voltage and frequency ranges at the delivery point. The Gridcodes may lead to more stresses on the equipment of the power plants, the reactor itself but also on the main large electric equipment.

As aging is an important issue, having an impact on the operation and maintenance costs, in order to reduce operation and maintenance costs, the nuclear industry has taken advantage of digital technologies to automate some of its testing and maintenance activities. On top of that, license renewal of nuclear power plants has accelerated, allowing some plants to operate up to 60 years or more. Many utilities are maximizing their power output through uprating projects and retrofits. This puts additional demand and more stress on the plant equipment such as the instrumentation and control systems and the reactor internal components making them more vulnerable to the effects of aging, degradation, and failure.

The components, systems, and structures in NPPs are in general categorized in two classes: active or passive. Active components are managed under a maintenance rule, and this covers items such as pumps, motors, valves, and compressors. Passive components, which include the reactor pressure vessel, piping, core internal components, the containment structure, and cables, are managed using in-service inspections performed in the context of an aging management plan. For passive component assessment, researchers have investigated non-destructive examination technologies that are sensitive to degradation precursors due to mechanical fatigue, thermal aging, and radiation effects.

In-service inspection is a preventive maintenance measure to guarantee the integrity of safety relevant components in a nuclear power plant, and as such is critical to the safe long-term operation of plants. Throughout the last 25 years, nuclear power operating countries have established inspection qualification frameworks, which govern the qualification of non-destructive testing methods prior to their application on site.

The current and projected fleet of plants consists largely of water-cooled, water-moderated reactors. These reactors have over time achieved a high degree of maturity in terms of economic performance and safety. These reactors produce electricity in a reliable way without CO_2 emissions. Above that, there are several solutions to deal with spent fuel. However, to achieve major steps in terms of sustainability (reduced high-level waste production, better use of resources and higher thermal efficiencies) and to open the way for high-temperature non-electricity applications, new types of reactors based on other coolant technologies are being developed alongside more effective and advanced fuel cycles. Thorium fuel cycles (especially in liquid-fueled molten salt reactors) theoretically offer some potential advantages in terms of sustainability, but the short term, economic drivers are lacking to justify the industrial deployment of a thorium-based fuel cycle, whereas significant progress with regard to sustainability can be made through advanced uranium-plutonium fuel cycles.

The use of fast reactors in a closed fuel cycle will allow a large decrease in natural resource (uranium) consumption, by a factor of at least 50, leading to a more sustainable implementation of nuclear energy. One of the major concerns of society regarding the implementation of nuclear energy is also the high-level nuclear waste. Fast spectrum reactors with closed fuel cycles will allow a significant reduction in radiotoxicity and volume of high-level nuclear waste. Advanced reprocessing and fuel manufacturing techniques are needed to recycle the minor actinides in order to meet this goal.

For those countries phasing out nuclear energy in Europe that desire to reduce the legacy high-level waste from LWR NPPs, dedicated advanced reactors can be considered for transmutation of the high-level waste. For the transmutation of high-level waste in a double strata fuel cycle approach four building blocks need to be addressed: the reprocessing of current spent fuel, the fabrication of dedicated minor actinide containing fuel, the dedicated burning of MA-containing fuel and the reprocessing of these irradiated MA-containing fuel. This is considered a significant short term barrier to achieve the longer term goal.

Some advanced reactors are designed for non-electricity production as a potential application. Examples are hydrogen production, desalination of salt water and high-temperature heat applications. Fast reactors with a higher outlet temperature than current LWR NPPs can address most needs of industrial steam supply, whilst higher temperature applications are presently well suited for the future High Temperature Reactor (HTR). This has been outlined further and acknowledged by international organisation in reports such as IEA (2018) and IAEA (2018).

There is an increasing interest in small modular reactors (SMRs) and their applications. SMRs are defined as power reactors up to 300 MWe, whose components and systems can be shop-fabricated and transported as modules to their designated sites for installation as demand arises. The most promising SMR designs adopt inherent safety features and are deployable either as a single or multi-module plant. The key driving forces of SMR development are fulfilling the need for flexible power generation for a wider range of users and applications, replacing ageing fossil power plants, providing the opportunity of cogeneration, supplying energy to remote areas or developing countries with small electricity grids, and enabling hybrid nuclear/renewables energy systems.

In the future, mini-nuclear reactors may also be a part of the new segmentation in terms of technical challenges and business opportunities. With rated powers between 0 and 30 MW, mini-reactors may reshape the nuclear industry, in order to compete with new technologies such as renewables as outlined by the European SmartGrids Technology Platform (2006).

The small size offers potential advantages when compared to large power plants, in terms of design simplification and potential to use passive systems, increased resilience against external hazards and terroristic acts, as well as potential to reduce emergency preparedness zones. Through modularization, SMRs aim for economics of serial production and shorter construction time; this, along with the reduced capital investment per unit and the generation of revenues from initial units while constructing the follow-up ones, is also a key enabler for a significant decrease of the investment risk.

With respect to reactor technology, the following main R&D topics have been identified in the areas of operation and construction, in-service inspection, qualification and non-destructive examination, advanced reactors and the next generation, and small modular reactors:

Operation and Construction

- Identification, analysis, and countermeasures for ageing mechanisms together with development of monitoring systems and predictive tools for degradation in metallic components.
- Improvement of the understanding of long-term concrete performance under irradiation conditions and development of monitoring methods.
- Development of methods for cable condition monitoring and modelling.
- Development of digital twins of the major components based on physical modelling of the relevant phenomena and on-line monitoring of the main phenomena;
- Use of advanced technologies (artificial intelligence, virtual reality, 3D imaging, …) to help reducing the costs (construction, maintenance, outage, …) and increase the safety level.

In-Service Inspection, Qualification and Non-destructive Examination

- Development of risk-informed in-service inspection to all mechanical components.
- Understanding the technical (or other) barriers that preclude the transport of qualifications between countries, and finding methods or procedures on how to overcome these.
- Design for inspectability
- Verification of the accuracy of non-destructive testing inspection simulation software.

- Explore new non-destructive methods for plant-condition monitoring.
- Ensure high quality, simplified and reliable interfaces between components; controls and operators.

Advanced Reactors and the Next Generation

- Fuel and materials development and qualification.
- Improved understanding of coolant behaviour, thermal hydraulics and chemistry control.
- Component design and testing.
- Development of appropriate instrumentation and reactor control.
- Safety assessment and code validation.
- Fuel handling technology and fuel-coolant interaction.
- Robust decay heat removal systems.
- Development of out-of-pile and in-pile mock-ups and demonstrators.

SMR

- Development of compact heat exchangers and associated fabrication processes.
- Understanding the heat transfer in natural circulation, and justification of the function of safety features relying on natural circulation.
- Human factors when employing multi-module SMR plants monitored in a single control room.
- Design simplification, compactness, and modularity.
- Advanced manufacturing, assembly and digitalisation of processes.
- On-line monitoring of components, systems and processes using advanced digital technologies.

Enabling Conditions

The safety of nuclear installations has been a priority since the beginning of nuclear reactor design and deployment. During the nearly 80 years of designing, construction and operation of research reactors and commercial nuclear power plants, the concept of nuclear safety has developed to provide protection against a wide range of potential hazards with defense-in-depth providing resilient safeguards. Nuclear safety remains a priority for sustainable nuclear power plant operation, and therefore SNE-TP puts emphasis on R&D activities to continuously improve safety of plants, and to improve understanding of accident phenomenology and methods for safety and risk assessment. An accident in any country in any part of the world affects the nuclear sector globally. Therefore, support of nuclear safety programs and harmonization of approaches to nuclear safety is another important aspect of nuclear safety effort.

Nuclear fuel production and use in commercial reactors have reached a relatively mature state. Nevertheless there is work to improve existing fuel types and to develop innovative fuel, which can improve safety margins and reduce overall operating costs. Research on fuel behavior mechanisms and computational codes research is focused on behavior in both normal operation and accidental conditions, performed experimentally and with simulation models. An understanding of fuel behavior is underpinned by fuel R&D, which provides the evidence to support innovation and safety analysis.

Fuel treatment, transportation and interim storage (spent-fuel management) research satisfies the need to fully understand the challenges faced by managing the extended storage periods of the spent-fuel and their storage systems following reactor utilization, provide confirmation of the condition of stored fuel and storage systems and optimize the fuel management options. Management activities include handling of the spent-fuel, associated diagnostics, storage in spent-fuel pools at power plants, transport, drying of fuel, interim storage in either wet or dry conditions before either reprocessing and recycling or transfer for final disposal, all need to be qualified and validated.

For light water reactors, the most commonly adopted fuel cycles are the open fuel cycle, with final direct disposal in geological repositories, or mono-recycling of plutonium, via the production and storage of MOX fuel pending future recycling. Fuel cycle sustainability, in terms of resource utilization and high level waste minimization, can be substantially improved using closed fuel cycles with fast reactors. In addition to the development of fast nuclear reactors, R&D is required to develop more radiation tolerant separation processes, separation process that support the separation of long-lived minor actinides and associated fuel fabrication processes. Qualification of modified fuels based on fuel PIE and fuel modelling will also be required and their impact on spent fuel management and disposal systems will have to be demonstrated. Such R&D is valuable in order to significantly reduce the long-term uranium consumption, making the present reserves last for several thousand years, and reduce the long-term radiotoxic inventory by more than a factor of 100 and reduce the repository heat load by more than a factor of 10, depending on geology.

Waste management and dismantling & decommissioning covers the management, treatment and disposal of waste arising from operations across the nuclear fuel cycle. Beyond waste management, the area incorporates the dismantling and decommissioning of nuclear power plants and fuel cycle processing facilities as a last step in their lifetime. Finally, it also considers waste minimization and recycling of non-fuel materials. The focus is on the identification of best practices from the international community and the development of innovative technologies and methods that will reduce decommissioning costs and timescale, thereby also improving safety and enhancing environmental performance.

Nuclear energy currently provides a large fraction of low carbon power generation in the EU. It therefore plays an important role in efforts to decarbonize society and meet climate change targets. To continue this contribution and to reduce the burden on society associated with rapid development and deployment of new technologies in order to decarbonize society in the coming decades, R&D will continue to be needed to reduce the costs of nuclear generation by optimizing current operations and implementation technological innovations to reduce the capital costs of new capacity, improve the sustainability of nuclear generation and improve social and political acceptability, whilst adapting to changing conditions.

With respect to enabling conditions, the following main R&D topics have been identified in the areas of safety of nuclear power plants: development of fuel, the fuel cycle and spent-fuel management; dismantling and decommissioning; and social, environmental and economic aspects:

Safety Assessment of Nuclear Facilities

- Development of methodologies extending the scope of existing probabilistic safety assessment
- Focus on long-term and multi-units loss of safety functions.
- Development and validation of advanced tools and methods for deterministic and probabilistic safety analysis.
- Focus on the impact of the new Gridcodes on the equipment of the power plants, with the determination of the stresses on them.
- Integration of new equipment in power plants (converters, vacuum circuit-breakers, etc…) and evaluation of their impact and reduction of the stresses they may generate.
- Support operation of remaining European experimental facilities.
- Safety and reliability assessment of the capability of passive safety systems to perform the assigned function.
- Methodology for the reliability evaluation of digital instrumentation and control systems and its integration into probabilistic safety assessment.
- In- and ex-vessel corium/debris coolability
- Mitigation of gas explosion risk in containment
- Source term assessment and mitigation
- Accidents mitigation tools in spent-fuel pools

Development of Fuel, the Fuel Cycle and Spent-fuel Management

- Development of new fuel forms with focus on safety and economics (ATF(C), high burn-up, increased enrichment, high density fuel forms)
- Improvements in assembly design and manufacturing.
- Improvement and validation of predictive fuel performance and safety tools.
- Improvement of post-irradiation examination (PIE) methods.
- Ensuring availability of key experimental facilities (research reactors, hot cells and laboratories)
- Improved understanding and optimization of temporary spent-fuel storage system behaviour.
- Integration of spent fuel management and disposal for open cycles.

Decommissioning, Dismantling & Waste Management

- Minimization of waste production by design, material selection, operational measures, efficient dismantling technologies, and development of advanced waste treatment and conditioning technologies.
- Development of separation and characterization techniques for waste inventory assessment and plant and facility assessment.

Social, Environmental and Economic Aspects

- Deterministic and probabilistic safety assessments for increasing availability factors and enabling optimization of safety margins and power uprates.
- Retrofitting of state-of-the-art (passive) safety features targeting better operational economy.

- Creation of a pan-European communication campaign allowing citizens to educate themselves.
- Analyses of the impact of intermittent external loads including grid disturbances on safety functions of existing and new nuclear power plants.
- Analyses of the impact of new hazards (e.g. drone attacks, stuxnet viruses) on safety functions of nuclear power plants.
- Effect of climate change on the NPP's operation

Cross-cutting technologies

Cross-cutting technological topics like materials, digitalisation, modeling and simulation are essential for progress in the nuclear field. Digital technology is an essential tool for increasing the competitiveness of the nuclear industry as it is for other industrial sectors such as aerospace or automotive. All the three SNE-TP pillars are involved in this digital transformation. The main objective of digitalization, modelling and simulation is to continuously increase safety and competitiveness for the operation and maintenance of existing nuclear power plants and for new build. It will also enable improved cooperation between partners of the nuclear research sector.

Developments in the field of modelling and simulation have three goals. The first is to adapt and accelerate the coupling between existing calculation codes by improving interoperability in order to provide a more complete understanding of complex, inter-related phenomena. The second goal is to unify numerical applications and make them consistent by linking the world of advanced expertise studies and industrial modelling. The third goal is to benefit from breakthroughs in advanced visualization technologies (including virtual reality and augmented reality).

Research and development on structural materials is important for both operational reactors and future reactors. A deeper knowledge of the materials used in the reactor plants currently in use allows us to estimate and predict the residual life with greater precision and to assess the degree of safety of long-term operation. Regarding the new reactor concepts, the availability of new materials more resistant to neutron damage, to high temperatures and to the aggressiveness of non-moderating coolants, is necessary to deploy advanced reactors. Moreover, in the event of a nuclear accident, the availability of structural materials with better resistance to high temperatures may delay or even cancel the most detrimental consequences. Finally, the second principle of thermodynamics assures us that the achievement of higher temperatures makes the production of mechanical energy more efficient, and therefore economically more advantageous.

With respect to cross-cutting technologies, the following main R&D topics have been identified in the areas of digitalisation, modeling and simulation, and materials:

Digitalisation, Modeling and Simulation

- Development and validation of multi-scale, multi-physics, and multi-phase analysis tools including uncertainty quantification methodologies.
- Development of methodologies to ensure digital continuity over the complete life-cycle.
- Integration of cybersecurity in the digitalization process.
- Digital Twins.

Materials

- Advanced manufacturing in a broad spectrum methods;
- Understanding physical mechanisms and development of relevant models;
- Materials with better resistance to high temperature and corrosion after irradiation;
- Methodologies related with materials qualification, especially of welds and joints, internal stresses evaluations and online monitoring;
- The use and maintenance of nuclear material testing infrastructures.

Non-technological Cross-cutting Aspects

Apart from the technological cross-cutting topics, also non-technological aspects play a role in the progress of nuclear energy. An important example is to ensure the availability of state-of-the-art research infrastructures (in particular for materials research, innovation and nuclear safety). Key infrastructure elements are irradiation facilities, hot cells and transport routes. Current initiatives in France with the Jules Horowitz Reactor, in Belgium with the MYRRHA initiative, and in the Netherlands with the PALLAS reactor are complementary and essential to renewing European irradiation facility infrastructures for the coming decades and to provide important non-power related nuclear services for medical and industrial applications. Political support will be important in providing sufficient financial support to realize these capital intensive projects. Current-day models do not sufficiently account for the increasing costs imposed by security and waste handling, endangering access and availability of these infrastructures, amongst others. Therefore, further work is planned to establish a financially sound basis for the operation of such infrastructures.

Another non-technological cross-cutting challenge is ensuring consistency of components, tools, and safety standards which will be a prerequisite for a cost-effective deployment of new nuclear reactors in Europe. This program encourages vendors and suppliers to engage in an initiative to standardize their components and codes to a higher degree in order to ensure a faster procurement process, higher compatibility and more transparent and higher safety standards, and knowledge management. Among them, the most challenging task is harmonization of safety standards. Because nuclear safety is a national responsibility, national regulators are independent and we face many different sets of safety rules in EU. It is not widely appreciated yet, that the independence of judgement does not exclude cooperation in preparation of harmonized safety standards.

A final non-technological cross-cutting aspect is education, training and knowledge management. High quality education and training is vital to provide a sufficient, long-term workforce to deliver a nuclear energy program and provide reliable advice to policy making bodies. Excellence in this endeavor arises from universities and training to work together with industry and regulators, as well as governments in some countries, to ensure the required quality and quantity of the workforce is available from inception of a nuclear program until final completion of remediation and disposal activities.

With respect to non-technological cross-cutting aspects, the following main R&D topics have been identified in the areas of research infrastructures, harmonisation, and education, training and knowledge management:

Research Infrastructures

- Collecting, updating and maintaining research infrastructure databases internationally at one place in collaboration with organisations with existing databases, e.g. IAEA.
- Creation of a financially sound basis for the operation and maintenance of these infrastructures.

Harmonisation

- Enlarge the scope to take into account in service inspection and life management.
- Benchmarking of the EUR documents against all applicable WENRA reference levels IAEA standards and the amended directive on nuclear safety as detailed by the EC.
- A detailed description of the technical content that an EU common pre-licensing process should include.

Education, Training and Knowledge Management

- Development of multi-disciplinary knowledge and skills.
- Ensuring a steady demand and supply for nuclear positions.

Conclusions and Way Forward

Multiple agencies indicate that the world, and Europe in particular, will need nuclear fission energy in its energy mix to facilitate a rapid transition to a low-carbon society and minimise the effects of climate change. SNE-TP’s vision aligns with this understanding and its recent transformation into a legal association enables it to formulate and deliver technological innovations required to maximise the contribution of nuclear power production to achieving this goal.

This updated Strategic Research and Innovation Agenda sets out R&D priorities that support optimisation of the current nuclear fleet and the development of innovative technologies to substantially reduce the financial costs and environmental impact of its use in the medium and long term. This agenda therefore validates the long term vision of SNE-TP while at the same time adapting to the changing landscape and taking account of progress in research and innovation methods, tools, and knowledge.

The Strategic Research and Innovation Agenda will also provide valuable underpinning of commercial nuclear service delivery by EU organisations in other countries, bringing financial benefits to European society, and continues SNE-TP’s commitment to inform the public at large about the benefits and challenges of nuclear energy. To this end SNETP continues to develop relationships with organizations like Foratom, the OECD/NEA, and the IAEA.

While safety will always remain a first principle in nuclear research, this update of the Strategic Research and Innovation Agenda emphasizes that research towards affordability, reliability and financial risk mitigation is a requirement for long-term operation and future deployment of nuclear systems. After all, without long-term operation and new nuclear deployment in Europe, we will not be able to meet the environmental goals set in international agreements. SNE-TP will continue to inform the public at large about the benefits and challenges of nuclear energy. To this end SNETP maintains relationships with organizations like Foratom, WNA, EPRI, COG, GIF, EERA, OECD/NEA, and IAEA among many others.

The current Strategic Research and Innovation Agenda has been aligned with the Strategic Energy Technology (SET) Key Action 10 Implementation Plan, including the visions of the three SNE-TP pillars, NUGENIA, ESNII, and NC2I

The future for development and deployment of nuclear technology in Europe is bright if we manage to:

- Operate our assets in a reliable, affordable and safe way,
- Reduce capital and operational costs through innovation,
- Develop break-through technologies to improve sustainability,
- Communicate in an effective way the benefits of nuclear energy to European citizens and policy makers to create the conditions for nuclear energy to support society’s climate change and competitive aspirations,
- Continue to invest in the facilities and workforce needed to deliver these objectives,
- Work effectively with international organisations to leverage European knowledge and skills,
- Connect scientists and reactor designers, operators, and vendors (to ensure we are working on the right challenges),
- Link experimental teams with numerical modellers (to ensure mutual knowledge exchange improving both sides of the scientific spectrum).
- Connect electrical engineers involved in NPPs and those involved in network codes.

Clearly, the speed of innovation and responsiveness of this sector will depend on the funding available to drive innovation. Funding mechanisms put forward by the European Commission, e.g. through Horizon Europe, but also national initiatives will play an important role in which SNE-TP may act as a catalyser to encourage collaboration and maximise integration of research, development, and innovation efforts. This Strategic Research and Innovation Agenda, provides the means by which these objectives can be achieved.

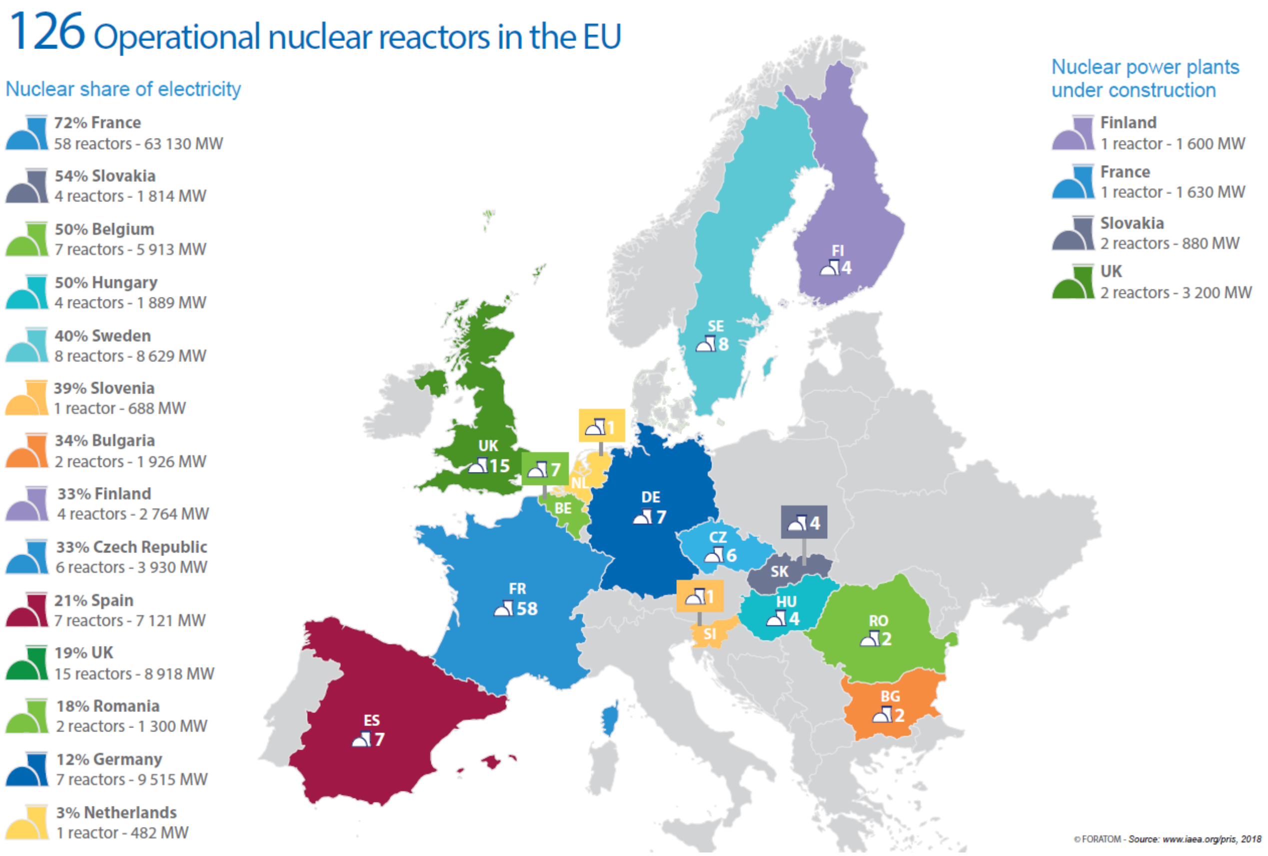
In this light, SNE-TP will continue to collaborate with the EC, e.g. by contributing to the SET plan and by writing an updated deployment strategy.

1 Introduction

1.1 A Mature SNE-TP

Since SNE-TP was founded in 2007, the organization has largely matured. Over the years, SNE-TP has succeeded to promote collaboration between European partners coming from industry, research, regulators, technical support organizations, and academia. With this, the role of nuclear fission in providing safe, reliable and affordable electricity, with low greenhouse gas emission, has been reinforced. Such collaboration between experts is essential for assessing the maturity of nuclear technology. First of all, to continuously seek for improving safety and performance of the industrial installed base. Secondly, to prepare the next nuclear generation and to develop nuclear process heat applications. Major events occurred during the last decade, with the tsunami in Japan effecting the Fukushima nuclear plants in 2011 and the financial crisis in 2008-2009 which triggered the evolution of energy policy in European member states and strongly affected investments in nuclear capacities.

Nuclear reactors provide about 26% of the EU's electricity generation, with 14 Member states operating a total of 126 nuclear power plants. There are 6 plants under construction and more are planned. Notably, nuclear energy is a reliable source of energy, producing electricity at full power for nearly 90% of the time thus enhancing the security of supply at prices which are among the lowest compared to other sources of energy. The nuclear energy industry supports around 800000 jobs in Europe (all figures and the map below derived from Foratom, 2019) and substantial exports to non-EU countries.



1.2 A Mature Sectoral Organization

Since SNE-TP was founded in 2007, the organization has promoted collaboration between European partners from industry, research entities, safety organizations and academia with the vision to

'aim at achieving a sustainable production of nuclear energy, a significant progress in economic performance, and a continuous improvement of safety levels as well as resistance to proliferation through the development and deployment of potentially sustainable nuclear technologies, as well as actions to harmonise Europe's training and education, whilst renewing its research infrastructures' (SNE-TP, 2007)

SNETP’s work has reinforced nuclear fission’s ability to provide safe, reliable, affordable low carbon electricity, by fostering research and development to improve the performance of the current installed generation plants while preparing the next generation of nuclear reactor systems and developing nuclear heat process application as well.

SNE-TP has a mature structure reflecting these three strategic themes in its three pillars: NUGENIA, ESNII and NC2I which have well-established programs and governance (thanks to dedicated EC funded projects) for succeeding in their missions:

- NUGENIA
  Conduct a research and development programme of nuclear fission technologies, with a focus on Generation II & III nuclear plants, through providing a scientific and technical basis to the community by initiating and supporting international R&D projects and programmes.
- ESNII
  Demonstrate Generation IV Fast Neutron Reactor technologies, together with supporting research infrastructures, fuel facilities and R&D work.
- NC2I
  Demonstrate an innovative and competitive energy solution for the low-carbon cogeneration of heat and electricity based on nuclear energy.

The members of SNE-TP and its pillars decided in 2017 to pursue an evolution of the platform towards a legal association to provide:

- the capacity for signing agreements with international agencies and other legal entities for extending SNE-TP network
- Increasing SNE-TP visibility as the European association leading fission R&D program in its relationship with stakeholders and the European Commission
- Ensuring the financial means to provide services to its members while ensuring a technical secretariat, this way increasing the attractiveness of the platform

Final approval of all members on 22 May 2019 and a royal decree by the King of Belgium on 2 September 2019 completed this transition. The aim of the legal association will be to strengthen 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

1.3 Added Value

The SNE-TP program is based on the core program of its three pillars: NUGENIA, ESNII, and NC2I. The added value of the platform lays in the global vision it aims to develop in support to the nuclear systems, the identification of major milestones for ensuring R&D fission alignment with the nuclear energy challenges, and also, the evaluation of cross cutting issues which could open new routes for collaboration among the pillars while optimizing the resources and infra structure. The reference documents of SNE-TP, are published on a regular basis and circulated through the European and international community for highlighting these high level objectives and challenges, and monitoring the progress.

- Strategic Research and Innovation Agenda
- Deployment Strategy

In its last version, the Deployment Strategy 2015 displayed an integrated vision of the SNE-TP activities spanning Generations III and IV and Co-generation development till 2050, in connection with the operations and foreseen evolution of the European nuclear fleet. Cross cutting issues were identified in basic technology, and strong interaction in development and application of methods, tools, and transfer of knowledge is promoted. A new forum, in line and joined with the existing NUGENIA Forum, is being initiated to enhance the joint programming among the three pillars, in a view to facilitate the achievement of their own core program.

Regarding the collaboration outside SNE-TP, working groups have been activated:

- for sharing information on spent-fuel and nuclear waste with the 'Implementing Geological Disposal of radioactive waste Technology Platform' (IGDTP), as the reference technology platform on geological disposal,
- on nuclear material research with the European Energy Research Alliance Joint Programme on Nuclear Materials (EERA/JPNM).
- On exchange of expertise and knowledge (IAEA, OECD/NEA, GIF, WNA, ….)

New services may be developed by SNE-TP members, and this will be facilitated by its evolution towards a legal association.

1.4 Structure of the Strategic Research and Innovation Agenda

This SRIA is organised into three parts, drawing together, as far as possible, common areas of work and cross cutting themes and retaining unique aspects associated with each pillar in the specific challenges section. The document intends to provide a holistic SNE-TP view on the current agenda for strategic research and innovation identifying:

- common challenges
- specific challenges
- cross cutting challenges,

and presenting them together. This is possible as each pillar has a well established program and related reference documents.

The next chapter will highlight the future of nuclear energy in Europe by considering international energy outlooks and their impact on nuclear energy in Europe, by summarizing the benefits and potential of nuclear energy, and by summarizing the SNE-TP Deployment Strategy established a couple of years ago. After that, the third chapter will present the common and specific challenges with respect to reactor technology discussing challenges in operation and construction, in-service inspection, qualification and non-destructive examination, advanced reactor development and the next generation of fission reactors, and development of small modular and mini reactors. Chapter four will deal with enabling conditions like safety of nuclear power plants, development of fuel, the fuel cycle, and spent-fuel management, dismantling and decommissioning, and finally social, environmental and economic aspects. The fifth chapter will discuss cross-cutting technologies, like digitalisation, modelling and simulation, and materials. And finally, chapter six will present non-technological cross-cutting aspects like research infrastructure, harmonisation and education, training and knowledge management.

This way, the SNE-TP Strategic Research and Innovation Agenda 2020 provides an integrated program for the entire SNE-TP association, which will provide the technical innovations required to meet the strategic vision for nuclear's contribution to a vibrant, low carbon European society.

2 The Future of Nuclear Energy in Europe

2.1 Latest Outlooks

The world today faces a tremendous challenge in providing mankind with the energy it requires. Both the world population and welfare standards continue to rise driving an increasing need for energy, which is outstripping the gains made by increased energy efficiency. Meanwhile, authoritative international studies, e.g. IPCC (2018), warn mankind that we are facing a global warming that threatens our current way of life, due in large part by the means of satisfying this need for energy. Even though some people may be sceptical about individual studies, there is a sufficient breadth of evidence of the impact of current energy consumption that it is prudent to make substantial efforts to minimise the greater potential impacts predicted for the future. In summary:

Mankind faces the issue of possible climate changes due to the increasing CO_2 concentrations in our earth atmosphere while at the same time our energy consumption world-wide will rise significantly.

Recent international studies from EC (2016), IEA (2018), IPCC (2018), MIT (2018), IAEA (2018), EC (2017), BP (2019), and OECD/NEA (2019) demonstrate that nuclear energy provides a significant proportion of current low carbon energy and that it has a crucial role in future low-carbon economy and society. In many studies the share of nuclear in the energy mix decreases. However, this is more than compensated by the anticipated increase in overall energy demand, leading to increased need for nuclear energy generation.

There were 450 nuclear reactors operating in 2018 (IAEA, 2019), with a net capacity of 396413 MWe supplying 2563 TWh low-carbon electricity. In addition, 55 more nuclear power reactors are under construction. Nuclear energy, therefore, provides about 11% of world's electricity production, compared to about 24% by hydro and other renewable sources, and 65% by fossil sources like oil, gas and coal. In Europe, the situation is slightly different with nuclear making up for about 14% of electricity production, compared to 7% renewables and 79% fossil sources. Given the overriding need to reduce atmospheric CO_2 urgently, it is clear that nuclear's contribution to low-carbon energy generation will remain vital in the foreseeable future and that both renewable and nuclear generation are likely to be important. In fact, EC (2016) expects that nuclear energy production will remain stable through increased investments in long term operation and introduction of new nuclear capacity. The fact that the contribution of renewables will rise to 30% within 2030, which is a rather rapid change in the energy landscape in Europe, implies important challenges to the nuclear sector. The long term strategy (EC, 2018) states that the share of nuclear in 2050 is still 15%, demonstrating the need for LTO and new build.

The OECD/NEA (2019) analysis of the overall system costs of various energy generation technologies including balancing and grid costs identified that the lowest investments costs to achieve a low-carbon energy mix were associated with scenarios with substantial shares of nuclear. When carbon emissions have to be reduced with renewables only, the price of electricity rises drastically. When a combination of nuclear and renewables is used, the price increase is manageable. Nevertheless, there are significant obstacles to new nuclear build in many countries, often associated with public perceptions and financing costs for new reactor construction.

Realizing the need for nuclear growth, the MIT (2018) study provided suggestions to overcome the high cost of nuclear plant construction, one of the biggest hurdles. These include modularization in construction, improved plant (rather than just reactor) design and international alignment of regulatory requirements. All of which are addressed within this SRIA.

Individual countries are entitled to make their own decision on the sources of energy that they wish to use. As a technical organisation, SNEPT's contribution is to provide reliable and accurate information of the benefits, costs and detriments associated with the use, or not, of nuclear power and to articulate these within the European society and its policy-making structures. To that end, relevant activities to that end are contained within this SRIA.

2.2 Benefits and Potential of Nuclear Energy

Nuclear energy is an important contributor to all three main pillars of EU energy policy set out in the SET-plan (EC, 2017): environmental sustainability, security of supply and economic competitiveness. Nuclear provides 26% of the EU's electricity and about half of the EU's low-carbon electricity. Nuclear has one of the lowest life-cycle climate impacts of any energy source. According to the IPCC (2018), greenhouse gas emissions from the nuclear cycle average around 12gCO_2equivalent/kWh, which is similar to wind power and only one quarter of the emissions of solar photovoltaics, for example.

Environmental sustainability

When compared with other sectors, the nuclear industry generates a very limited amount of waste. The average EU citizen generates about 1.4 tonnes of waste per year, of which 54kg is toxic waste and only 54g is classed as radioactive. Unlike other sectors, the nuclear industry segregates and manages its waste safely, with dedicated funding set aside for its ultimate disposal. Because nuclear is energy-intensive, the area of land occupied by a nuclear power plant is, for example, less than one-hundredth of the area required for a wind farm of equivalent electrical output. Nuclear reactors provide both heat and electricity. Waste heat can be used for district heating, desalination or to power industrial processes. High temperature reactors hold the promise of being able to link directly with energy-intensive cement making or metallurgical plants, or to produce hydrogen from water without the need of fossil fuels. Direct linkage provides benefits by eliminating otherwise unavoidable losses associated with energy conversion or carbon emission from conventional high temperature heat sources.

Security and flexibility of supply

In terms of security of supply, nuclear is beneficial to the European electricity grid because it has high availability, can operate flexibly and helps with frequency stabilisation. Because it uses so little fuel, fuel for multiple years of operation can be stored at a reactor site. Uranium can be sourced from a variety of politically stable countries around the world, meaning that fuel imports are not subject to potential disruption. Identified exploitable resources of uranium will last for well over 300 years on current projections using slow-neutron, light water reactors. Next-generation fast-neutron reactors could increase this to thousands of years, when fully deployed.

Economic competitiveness

IEA (2015) comparisons of levelized costs of electricity (LCOE) for new-build production facilities in 2020 for a range of sources at 10% discount rate show that nuclear and onshore wind are the two most competitive low-carbon generation technologies, with similar median electricity prices. However, long-term operation of existing nuclear power plants, when the capital cost has been depreciated, will produce considerably cheaper electricity than new build – even three times cheaper according to IEA. Nuclear is therefore an economically competitive source of low-carbon electricity. In the future, as the share of intermittent renewable electricity grows and nuclear will be required to operate more flexibly, the costs of curtailment, back-up and system balancing for renewables will become more significant. It is likely that different market models based less on marginal costs and more on capacity will need to be introduced. Nuclear will remain competitive in this situation, especially in markets where full system costs and externalities are taken into account.

The sector also provides other benefits. Deloitte (2019) recently published the nuclear sector employs more than 1.1 million people, generating a gross domestic product of the order of 0.5 trillion euro per year.

OECD (2018) concludes that direct employment during site preparation and construction of a single unit 1000 MW advanced light-water reactor is approximately 1200 professional and construction staff, or about 12000 labour years in total; during a conservative 50 years of operation, approximately 600 administrative, operation and maintenance, and permanently contracted staff are employed annually, or about 30000 labour years; for up to 10 years of decommissioning, about 500 people are employed annually, or around 5000 labour years; over an approximate period of 40 years, close to 80 employees are managing nuclear waste, totalling around 3000 labour years. When indirect and induced employment is added, the total employment in the nuclear power sector of a given national economy is therefore roughly 200000 labour years over the life cycle of one gigawatt of nuclear generating capacity.

Looking ahead towards 2050, an article published in SETIS (2014) foresaw that approximately 100 of the EU's nuclear plants would have their operational lives extended for between 10 and 20 years and that 100 new NPPs would be built. The associated engineering and construction works would entail investments of around €90 and 500 billion respectively. The EC (2017) PINC communication puts the expected LTO investment figure at €40-50 billion and the new build investment at €350-450 billion. Whichever set of figures you take, the resulting investment in jobs and the local economy is very significant. On top of that, jobs in nuclear generally require higher levels of qualifications, training and skills than comparable jobs in other energy sectors, meaning that the contribution to the EU's growth and prosperity is correspondingly higher.

Other benefits of nuclear energy

Apart from creating jobs and value for the economy, nuclear energy provides many other benefits to society. The radioisotopes produced in Europe's reactors have widespread use in medicine, industry, agriculture and research in all Member States. More than 500 million diagnostic procedures using x-rays or radioisotopes are carried out in Europe each year, and more than 700000 European healthcare workers use nuclear and radiation technology on a daily basis. One should also not underestimate the benefits of nuclear energy reliably providing more than one quarter of the EU's electricity without emissions of noxious gases and with very low life-cycle discharges of greenhouse gases. Kharecha and Hansen (2013) estimate that, since the 1970s, nuclear power has prevented nearly three-quarters of a million deaths in OECD Europe that would have otherwise been caused by air pollution from fossil fuels. In countries that produce or import nuclear electricity, the flexibility of nuclear reactors to vary their output is increasingly being used to balance the intermittency of variable wind and solar, thus providing a genuine contribution to maintaining Europe's security of energy supply.

2.3 European Deployment Strategy

The purpose of the Deployment Strategy in 2015 (DS 2015) is to define the programme for delivery of SNE-TP's global vision and alignment with the challenges and planning assumptions for nuclear energy. This is achieved by providing:

- R&D programs up to 2050 that deliver progress towards the SNETP vision, consistent with the European energy context and policy,
- Clearly defined technical objectives within the R&D programs for each nuclear system to which R&D projects of high technical value can be aligned,
- Transversality, through identification of cross cutting issues, not only within SNE-TP but also with other European technology platforms,
- The basis for defining funding resources required to deliver the vision, with an equitable share between public and private contibutions.

The Deployment Strategy is periodically reviewed to ensure that it represents the optimum path to meeting the SNETP vision for delivering societal benefits from nuclear technologies and provide relevant prioritisation to guide delivery of EC framework programmes.

2.3.1 Challenges and planning assumptions for nuclear energy

Nuclear system technology drivers: safety & performance

Nuclear energy generation is a mature and reliable technology, operating under established legistative codes and scrutinized by independent safety authorities. Electricity is supplied at stable and competitive prices, generating low greenhouse gas emission, and with established and secure supply chains for fuel, maintenance operations and new build. For maintaining a leading role in electricity production, nuclear energy systems need to comply with both a safety and performance vision and to continually improve in the delivery of both of these. Examples include:

- Safety review and monitoring, including the consequences of the future energy mix with increased share of renewables and the demands this puts on the flexibility of the network,
- Improving economics for initial investment, operating cost, back end costs,
- Increased sustainability: optimization of resources use and minimization of nuclear waste,
- Minimization of environmental impact: minimizing discharges, waste management, fuel cycle.

Technology evolution of reactors

The European fleet is approximately 30 years old. The original design lifetime of nuclear power plants (NPPs) is around 40 years. Therefore, if current national policy regulations are applied, because of NPP ageing many reactors will be shut down and decommissioned in the next decades in Europe. However, utilities are investing in plant lifetime extension beyond the 40 year limit, as a highly cost efficient strategy, which is enabled by the highly conservative design of NPP components, under the supervision of the safety authorities. Currently, 5 to 10 year extensions are being validated on a case by case basis by national regulators. For the moment, however, no plant has ever been operating for 60 years in Europe. Besides long term operation, in the countries that have selected nuclear energy for electricity generation and intend to build new ones, Generation II reactors will be replaced with Generation III technology, which implements new and innovative features for improved performance and safety, while extending the design lifetime to 60 years. It is therefore expected that Generation III reactors will be key players for electricity production throughout the 21st century. In addition, light water cooled Small Modular Reactors (SMRs) are more and more flagged as an attractive option to improve the flexibility of nuclear energy, by offering better integration with renewables, with reduced infrastructure and siting costs as well as, to some extent, safety improvements in terms of reduction of the emergency planning zones. SMR concepts based on light water cooling are ready for mid-term commercial deployment.

The fourth generation of reactors is under preparation, with a clear objective to provide a sustainable nuclear fuel cycle. This will be achieved with fast neutron technology which allows fuel multi recycling and offers capabilities for waste minimization and/or transmutation. Challenges related to safety and economic competitiveness are still key drivers to cope with, as well as increasing resistance against proliferation risk.

Sodium-cooled fast reactor development is part of several national programs at different levels of advancement: the post ASTRID R&D program in France in tight connection with Japan, the VTR project in the USA, the CFR600 project in China, the PFBR (Prototype Fast Breeder Reactor) in India, and industrialization proceeding in Russia where the BN800 reactor has reached criticality in 2015 and produced 5,8 TWh on the grid in 2017. The Belgian Government decided in 2010 to select and support the Accelerator Driven System (ADS) project, called MYRRHA, and decided in 2018 to allocate a special endowment of 558 M€ for the realization of the MYRRHA installation at the SCK•CEN Mol site. The lead cooled fast reactor is considered as a short-term alternative Generation IV technology, with the ALFRED demonstrator selected to be built in Romania and a large R&D program ongoing in Europe in its support, along with the BREST300 reactor development in Russia. The gas cooled fast reactor is the longer-term alternative Generation IV technology, proceeding with the intermediate objective of building the small demonstration reactor ALLEGRO.

The industrial deployment of such fast reactors in Europe is not foreseen before the second half of the 21st century and will likely be progressively introduced at a slow pace in order to take benefit from lessons learnt from prototype and from research reactors operations throughout this century. The availability of dedicated fuel for fast neutron reactors, which requires LWR fuel reprocessing and adequate fuel cycle facilities, is another strong constraint.

In addition to electricity generation, nuclear systems can offer process heat generation with low-carbon emissions. It is worth recalling that fossil fuel combustion is the main source of heat supply to European energy intensive industries, which represents around 20% of Europe’s CO_2 emissions. Other process heat applications have been identified: large-scale hydrogen production, district heating, sea water desalination, and coal gasification or liquefaction. Although not widespread, nuclear cogeneration is already a reality. Depending on the targeted temperature range, different reactor technologies are envisioned, among which the High Temperature Gas-cooled Reactor.

Small Modular reactor

The concept of a Small Modular Reactor (SMR) applies equally to LWR and advanced reactor systems. It will therefore be useful to identify any design, component fabrication or construction issue that is common to different types of SMR. Materials issues, especially concerning advanced manufacturing, modelling and partially qualification are also common through reactor generations, like explained by EERA-JPNM (2019). The main barriers to new build and reactor deployment are political decisions and public acceptance. It is important that through reactor generations a common position is taken, promoting under the umbrella of SNE-TP actions directed to dispelling wrong myths about nuclear energy, to dialoguing with other energy technologies and to discussing in full openness real pros and cons of nuclear energy with the civil society.

Fuel Cycle

Whatever the reactor technology, the fuel cycle remains an important consideration. Regarding fuel resources, uranium supply is currently more than adequate to meet demand up to the middle of the 21st century and beyond. New uranium sources are being investigated (sea, phosphate…) and at the same time, new extraction processes are being developed for improved economics. The spent nuclear fuel from the operation of nuclear power plants needs to be managed in a safe, responsible and effective way. Several possibilities exist to deal with the spent fuel, and the strategy adopted by the country depends strongly on its overall energy strategy and its national policy.

- Open fuel cycle: the spent fuel is disposed in geological repository. This option has been selected by Finland and Sweden.
- Closing the fuel cycle: the spent fuel is not considered as a waste, and is recycled following adequate processing. This option has been selected by France.
- Waste management: the quantity, level of radioactivity and lifetime will depend on the fuel cycle strategy i.e open, partially or fully closed fuel cycle.
- Transmutation option for high level waste: Minor actinides could be burned in fast neutrons reactors, reducing that way the volume of high level ultimate wastes to be stored.
- Sustainability: fuel recycling offers a step towards sustainability, dependent on the number of recycling operations. In principle, multi-recycling in fast neutron reactor would result in a self-sustaining cycle.

Cross cutting issues:

Once the Generation IV reactors technologies considered in ESNII are available and mature, the transition from current LWR technology to fast neutron reactors will strongly depend on fuel cycle capability and capacity. Initialization of fast neutron reactor deployment relies on the plutonium produced in LWRs and requires reprocessing and recycling facilities to make this plutonium available for fast neutron reactor fuel fabrication. It turns out that the transition from current reactor technology to the next reactor technology requires a similar transition for the fuel cycle facilities, from LWR to fast neutron reactor reprocessing, and with required plutonium throughput increasing step by step, as new fast neutron reactors are started and their fuels are being reprocessed.

The pace and extent of this transition to fast neutron reactors may vary greatly depending on the global energy and political situation. A regional approach scenario, as well as prospective studies could shed light on possible transitions and identify the key industrial risks and success factors.

Decommissioning and dismantling

Given the ageing of the European nuclear fleet (around 27 years on average today) and given the phase out decision in several European countries, such as Germany, Belgium and Switzerland, decommissioning and subsequent dismantling, followed by site declassification or new construction will bring forward many nuclear projects and activities. New characterization, cleaning and cutting technologies are being developed, as well as new waste forms commensurate with the level of activity, the chemical or physical nature of the waste, and the local or national regulations. Technologies such as digitalization, simulation, augmented reality or advanced robotics will mature and offer new opportunities.

Energy mix

In a wide range of scenarios mentioned earlier, nuclear energy is currently recognized as the least-cost option for base-load centralized generation, but the cost of renewables is decreasing, leading to a new and complex situation for the network. Given the increased deployment of renewable energy sources, which are intermittent, stability of the overall electricity system will increasingly require new load-following modes for the nuclear capacity. In fact, the transmission system operators, gathered under the ENTSOE, have built new rules for the connection of electricity producers to the grid. These rules, called Gridcodes, may lead to more severe stresses under steady state conditions, and to stability issues. This will be a real challenge for nuclear power plants. New technical requirements for both installed capacity and new build will arise and open routes to innovative technology development for nuclear reactors.

A proper integration of nuclear energy in the energy mix importantly also requires that the currently existing barrier between renewables and nuclear is broken through open dialogue, in such a way that, beyond computer-generated scenarios, a consensual view is reached about the role, realistic possibilities and actual contribution of each technology in connection with the goal of reaching climate neutrality in Europe by 2050.

2.3.2 Strategic vision for R&D program deployment

SNE-TP's structure has been endorsed for providing a collaborative R&D framework to its participants, for covering three main pillars for nuclear energy system development: light water reactors, fast neutron reactors and co-generation of heat and electricity. For each system, progress has been made in refining the technical objectives and challenges for supporting nuclear product development and for defining R&D topics in depth.

NUGENIA

NUGENIA features an integrated framework for Gen II-III light water reactor technology development, with the general objective of securing the safe operations of nuclear power plants while increasing their competitiveness and reinforcing the role of nuclear energy as a reliable contributor in the decarbonized energy mix. The overall program is described in the NUGENIA Roadmap document and the portfolio of R&D projects is managed by experts achieving excellence in nuclear fission research.

The NUGENIA research program has been organized in eight technical areas (TA) with their own fields of expertise:

1. Plant safety and risk assessment
2. Severe accident
3. Improved reactor operations
4. Integrity assessment of systems, structures and components
5. Fuel development, waste and spent-fuel management and decommissioning
6. Innovative LWR design and technology
7. Harmonization
8. In-service inspection, inspection qualification and non-destructive examination

The installed base as well as newly built reactors are considered within the European fleet, mostly using LWR technology. As a complementary approach, eight high level objectives have been identified for reinforcing the synergies between TAs specific challenges while giving a clear visibility of Generation II-III system challenges:

- 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 into the energy mix
- Prepare the future to avoid technology obsolescence
- Performance and ageing of NPPs for long-term operation

NUGENIA program prioritization

The NUGENIA research program is planned for the next 20 years. Prioritization of the program was achieved with different and complementary approaches:

- Prioritization of technical objectives for meeting the requirements of the high level objectives
- Evaluation of R&D topics according to the TAs challenges and processes, to national and individual needs, and outcome of finished collaborative projects.

Technical objectives, specific challenges and major milestones to be reached within the next 20 years have been listed in the NUGENIA roadmap available through the website, with a view to highlighting the main orientations of NUGENIA program. This covers basic technology and methods for structural components, fuel, operations (normal – ab-normal and accidental) and systems, to be developed along with the aim of improved safety, performance, harmonization and innovation as well.

Emphasis is given to mid-term technical challenges since they mainly apply to current LWR design and operations. They should be revised and extended for the next generation of new build, or in case of new regulatory demands, harmonization, or for up-scaling innovative technology development to on-site application.

Funding resources: public/private

The current collaborative R&D project portfolio in the scope of the NUGENIA research program is equivalent to nearly 80 M€ with a share of 40% coming from the European Commission and 60% from national programs and industry. The projects are carried out by industry, research organizations or technical safety organizations through their own programs, national programs or European calls for proposals.

The overall cost of R&D in support of Generation II- III, is difficult to be evaluated. For giving an order of magnitude, the overall cost for the 2015 – 2030 period would range from €5 – 10 billion, mostly supported by Industry. Additional funding should be sought, especially for the research infrastructure, the maintenance of the existing large testing facility and/or the construction of new ones.

ESNII

Concerning fast reactor technologies, four projects have been promoted within the European Sustainable Nuclear Industrial Initiative (ESNII) in the last years:

- MYRRHA: a lead-bismuth Accelerator Driven System to demonstrate transmutation of high-level waste in a double strata fuel cycle approach.
- ASTRID: a sodium cooled prototype reactor to demonstrate the sodium-coolant technology for electricity production in a closed fuel cycle. However the French government sponsoring the project has made in early 2019 strategic decisions which are analyzed in section 3.3.2.
- ALFRED: a lead-cooled demonstration reactor to demonstrate the lead-coolant technology for electricity production in a closed fuel cycle.
- ALLEGRO: a gas-cooled demonstration reactor to demonstrate electricity production in a closed fuel cycle.

ESNII Program Prioritization

In 2019, ESNII analyzed the status of the ESNII project and system maturity based on the prioritization criteria of technology readiness level and the advancement or impetus of European projects. MYRRHA was judged as is the most advanced ESNII project having the highest potential to reach full maturity, thanks to the increased technology level in liquid lead-bismuth technology, pre-licensing activities and the continued strong support of the Belgian Government. With regard to the developments of the fast reactor technologies in Europe, sodium and lead cooled reactor technologies have achieved a significant degree of maturity. However today, there is not yet sufficient state support to realize a demonstrator for these technologies in the short-term. Therefore Sodium and Lead fast reactor R&D will continue in Europe in the medium term. Finally, the Gas Fast Reactor technology concept still needs conceptual design and basic R&D efforts to demonstrate the viability of the concept.

Funding resources

The R&D projects in support of the prototypes' construction are mostly supported by national programs and European Commission calls for proposals. Industry is currently committed through in-kind contribution as well as funding of R&D national laboratory programs. Long-term R&D requested for the deployment of ESNII systems is expected to come from EC and public – public partnership, since the realization of such prototypes and demonstrators aims at implementing, in a pre-commercial and operational environment, the last stage of an R&D program, for future technology deployment. For the period 2015–2030, the overall cost for ESNII R&D and for prototype, research facility and demonstrator construction is evaluated at around €10 – 15 billion. More specific, the Belgian Federal Government allocated 558 M€ for the period 2019 – 2038 for the realization of MYRRHA.

NC2I

The EU currently generates 11.2% of its electricity using cogeneration. In Latvia and Denmark, cogeneration makes around 45% of total electricity generation. Today, cogeneration installations are dedicated to individual buildings, industrial factory and district heating systems. In Europe there are about 5000 district heating systems, which are mainly located in the Northern and Eastern part of Europe. Furthermore, the market share of district heat is about 10% of the heating market.

The main objective of nuclear co-generation is to make nuclear power suitable for the large and growing global market of non-electrical applications, for instance:

- District heating/cooling
- Seawater desalination
- Industrial heat supply

Achieving these goals requires significant changes in the design philosophy of nuclear reactors. The main criterion is the temperature at which the energy is consumed. However, another important parameter is the amount of heat consumed by each of the processes. In Europe, individual industrial processes require less than a few hundred MW_{th}. So that the best answer for nuclear electricity cogeneration is a reactor of small to medium power. HTRs fit here well, with power ranges up to 600 MW_{th}, very good safety parameters, and ability to provide heat at temperatures utilized by the “steam” market.

While the HTR overall technology challenges have been solved, the main issue hampering a broad market introduction of nuclear cogeneration is a lack of demonstrated technical and commercial success with applications above 240°C and beyond several tens of MW_{th}.

The action toward a broad implementation of nuclear cogeneration should therefore concentrate on developing and building demonstrator(s), which would serve as prototype for the next units, as well as examples of commercial success to follow.

The high temperature markets are very promising, since large quantities of fossil fuels could be replaced. However, due to certain challenges this is a longer term objective. These challenges include the development of high temperature materials and heat transfer fluids, and where applicable, the adaptation of chemical reactors at relevant size.

NC2I program prioritization

Prioritization of the NC2I R&D program is defined for supporting the construction of an HTR demonstrator plant featuring a cogeneration facility for steam supply.

In Europe, typical large industrial sites require a heat supply capacity between 100-1000 MW_{th} with an equally wide range of electricity supply. In the past, nuclear cogeneration projects were limited to steam delivery at approximatively 240°C and below, mainly for paper factories, district heating or other applications in this temperature range.

The demonstrator construction program would have to consist of several steps:

- Detailed design of the reactor;
- Site selection and siting studies;
- licensing the demonstrator on the designated site in accordance with both nuclear and process heat system regulations;
- financial commitment of industry and public stakeholders;
- construction of prototype and supply of critical components;
- demonstrator start-up, tests and subsequent operation.

For the fast-track demonstration, the HTR could be operated on core outlet temperatures around 750°C, which is largely sufficient for the targeted large process steam market <600°C. As a result, the demonstrator plant would be converted into a marketable commercial solution with a large domestic and export potential.

In the longer term, it is expected to venture into operation at higher temperatures; likewise the German test reactors (AVR and HTTR) have been operated for extended time at helium outlet temperatures of 950°C. For the future, another demonstrator plant using high temperature materials and coupled to a high temperature process heat application would probably need to be constructed.

Funding resources

The major obstacles to implementation of nuclear cogeneration are the costs of the design and construction of the prototype and the acceptance by heat using industries of being supplied by a nuclear reactor, with the subsequent licensing and public acceptance challenges. The key for establishing the landscape of the HTR’s industrial usage is the first demonstration with a prototype reactor coupled to an industrial process heat application in the near future

Engineering, construction and commissioning are the most important costs for each prototype nuclear plant. A consortium formed from various partners could be envisioned as follows:

- Technology Supplier – design of the prototype and licensing the demonstrator;
- Constructor (can be the same company as the technology supplier) - responsibility for the construction of the prototype;
- R&D centers – assistance with technical matters;
- Heat end-user – interest in an affordable and stable heat source;
- Demonstrator operator – interest in an affordable and stable electricity source;
- Financial institutions (national and international) - providing appropriate financial backing for prototype.

The project can proceed in two steps. The first step will be specifically developing the prototype and predicting potential obstacles and in the second step, the prototype will be licensed and constructed. In each step, the consortium may consist of different members. Lastly, it is worth noting that the collaboration with US partners could accelerate the construction of an HTR in both the USA and Europe.

2.3.3 Integrated vision and global deployment for SNE-TP program

Given the lead time required for the industrial deployment of the different nuclear systems, it turns out that an overlapping period is expected before the end of this century between existing Generation II-III operations, Generation III new build, and other potential new systems: SMR using LWR technology, Generation IV fast reactor systems namely SFR, LFR, GFR, and ADS. A common strategic agenda helps to identify technical and cross cutting issues which should be resolved in order to facilitate a smooth integration of different nuclear systems (towards a potential switch from one technology to another). The definition of a common research agenda is intended to cross the boundaries of SNE-TP, to liaise with other stake-holders, such as EERA-JPNM (Joint Programme on Nuclear Materials of the European Energy Research Alliance) and IGD-TP (Implementing Geological Disposal of radioactive waste Technology Platform), which deal with materials for sustainable nuclear energy and geological disposal of radioactive waste.

Transverse issues and clustering

For optimizing R&D project implementation of the three SNE-TP pillars, synergies between the nuclear systems and with other energy technology platforms should be refined and continuously sought for.

- A memorandum of understanding was signed in 2017 between SNE-TP and EERA for a joint undertaking in the area of new and innovative material solutions for nuclear. This will be renewed taking into account the changed legal status of SNE-TP, acknowledging the importance of exchanging information and dialoguing with other low carbon energy technologies, all of them represented in EERA, through the action of the EERA-JPNM. Moreover, a single, joint SNETP/EERA-JPNM strategic research agenda on nuclear materials will be produced. This agenda will cover the needs of all nuclear reactor generations and types.
- A working group has been formed to liaise with IGDTP on spent-fuel management
- A working group has been established with the MENAE group on radioprotection
- A practical agreement has been signed with the IAEA
- Many international organizations are willing to develop further collaborations and contacts such as WNA, COG, EPRI, MENAE, …
- Basic technology development open routes for the identification of common trunks for Generation II, III, and IV and cogeneration application notably in areas such as: material – structural integrity – manufacturing and assembly technology – instrumentation and control – digitalization – I&C – cyber-security
- Research infrastructures are essential instruments for the validation and qualification of technology development and any possibility of use for different applications should be considered
- Fuel cycle and waste management is an essential layer for nuclear system deployment whatever its specific technology
- Methods should be shared among the SNE-TP pillars for facilitating nuclear systems construction, deployment and operations, in an evolving context where technology is continuously improving,

while policy regulation is being updated and safety requirements are becoming more and more stringent.

- Finally, common to all nuclear technologies is the crucial aspect of dialoguing with other energy technologies in view of identifying the best strategy to achieve climate-neutrality by 2050, as well as with civil society at large, in order to promote nuclear energy as a friendly source, on the same footing as renewables as part of the solution to face climate change.

SNE-TP tentative roadmap with an integrated vision

For giving a global vision to the SNE-TP program, highlighting nuclear product evolution over the time scale 2015-2050, and considering the European nuclear capacity for electricity generation, different layers have been identified with milestones to be reached. Common trunks between Generation II, III, and IV and cogeneration have been set out in these layers for reinforcing the synergies between the SNE-TP pillars:

- European current fleet
- Prototype construction
- Fuel cycle and waste management
- Methods
- Basic technology

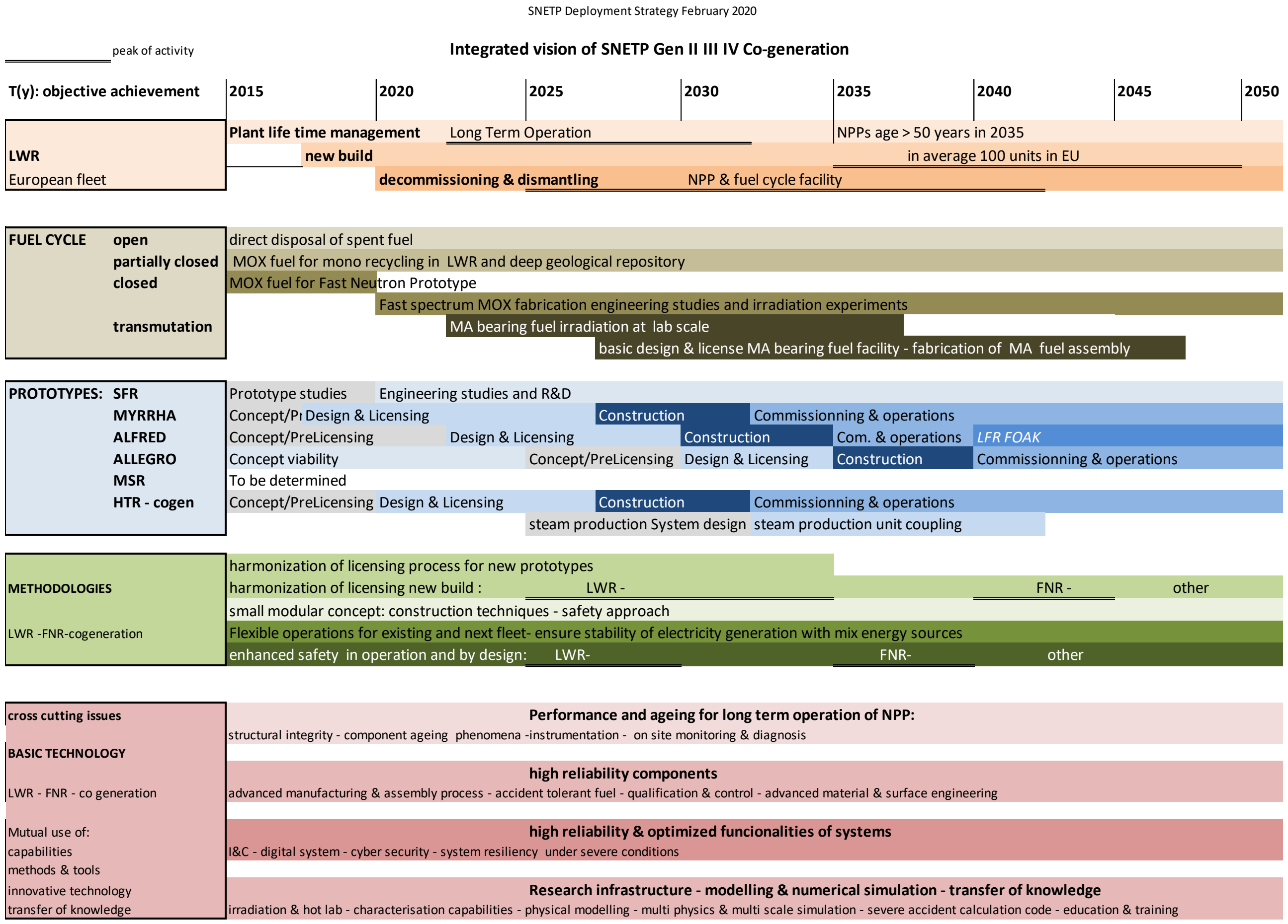
The SNE-TP deployment strategy is illustrated in the updated roadmap below which was firstly introduced and explained in detail in SNE-TP (2015), and which seeks to illustrate the consistent connection between the industrial nuclear panorama, the technology R&D program (from laboratory scale to prototype construction), transverse methods in support, and the time to achieve these objectives.

Light water reactors (Gen II) form most of the current European fleet, now 30 years old on average, which is expected to be renewed with a potential peak of activity between 2035 – 2050. This clearly identifies a first time period prioritizing long-term operation-related R&D projects followed by new build (Gen III +) which should benefit from the innovation and progress made in various technical domains.

Prototypes of 4th generation are being studied, with different maturity levels, as well as an HTR cogeneration demonstration plant. For MYRRHA, a planning for construction of the facility was discussed with the Belgian Governnement and the envisaged date of start of construction is 2027 while the envisaged date for end of construction is 2033. For the other facilities ALFRED demonstrator and HTR cogeneration demonstrator the planning will primarily depend on the securing of the appropriate financing whereas for ALLEGRO the planning will depend on the outcome of the feasibility phase.

Commissioning of new prototypes should be supported by harmonization of the licensing process for prototypes. Likewise, MOX fuel processing and re-fabrication, i.e multi recycling for fast neutron reactors, needs to be aligned with the prototype operations. Transmutation in FNRs, as an option for waste management, is envisioned too and requires minor actinide-bearing fuel fabrication and irradiation at reasonable scale.

In Europe, the construction of MYRRHA, the execution of Sodium Fast Reactor engineering studies and the execution of Lead Fast Reactor Engineering studies, possibly followed by ALFRED construction will provide sound experience to prepare the industrial deployment of LFR technology around 2040 and SFR technology later in the second half of the 21st century.



Methodologies dealing with licensing and safety assessment could strengthen interfaces between the different nuclear systems and assist with the suitable integration of different energy sources in the European mix . Harmonized licensing process for LWR new build should be ready before the expected peak around 2040. Construction techniques and innovative design developed for small modular concepts should benefit to all reactor systems. Considering the rapid evolution of the future electrical landscape, with an increasing share of renewables, nuclear power generation will have to adapt and reconsider objectives if needed.

Finally, mutual use and transfer of knowledge and expertise gained in basic technology should help to achieve high reliability and performance of components (structural and fuel) and optimized functionality of systems for Generation II III, and IV plus cogeneration, while opening routes for innovation.

3 Reactor Technology

3.1 Operation and Construction

3.1.1 Objectives and Motivation

Low-cost baseload electricity supply is a critical enabler of economic and social development. According to IAEA (2019), in total 449 civil power reactors are in operation and 52 reactors are under construction as of 2019 worldwide. Construction mainly takes place in China, India and Russia. Nuclear power has played a key role in delivering such supply for decades in many countries and will probably do so in the upcoming years. Therefore maximum and efficient utilization of the existing portfolio of nuclear reactors is an actual priority in Europe.

The current global fleet was developed with plant design lives that were typically either 30 or 40 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 plants to supply reliable, competitive and low-carbon baseload power. Once built and commissioned, and assuming a good operational performance, nuclear power plants 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 nuclear plants fall substantially with increased output. It is therefore vital for nuclear operators to achieve high plant capacity factors for long-term operation.

To reduce operation and maintenance costs, the nuclear industry has taken advantage of digital technologies to automate much of its testing and maintenance activities. In particular, the industry has begun to transition from traditional time-directed, hands-on, and reactive maintenance procedures to condition-based, risk-informed, and automated maintenance strategies. This is partly because the current generation of nuclear power plants has passed its mid-life, and increased monitoring of plant health is critical to their continued safe operation. This is especially true now that license renewal of nuclear power plants has accelerated, allowing some plants to operate up to 60 years or more. Furthermore, many utilities are maximizing their power output through uprating projects and retrofits. This puts additional demand and more stress on the plant equipment such as the instrumentation and control (I&C) systems and the reactor internal components making them more vulnerable to the effects of aging, degradation, and failure

The components, systems, and structures in NPPs are in general categorized in two classes: active or passive. Active components are managed under a maintenance rule, and this covers items such as pumps, motors, valves, and compressors. Passive components, which include the reactor pressure vessel, piping, core internal components, the containment structure, and cables, are managed using in-service inspections (ISI) performed in the context of an aging management plan (AMP). Degradation found under an ISI program is managed through mitigative actions, changes in designs, and repair or replacement of degraded components. This reactive, find and fix, approach has maintained the safety of operating reactors but it is becoming increasingly expensive as plants age. Attention is now moving to consider the potential for more proactive management of both active and passive components.

For passive component assessment, researchers have investigated NDE technologies that are sensitive to degradation precursors due to mechanical fatigue, thermal aging, and radiation effects. Most research to date has resulted in empirical relationships between precursor phenomena and NDE measurement parameters. More work is needed to fully understand the separate effects of multiple microstructural phenomena on NDE signals and to develop physical models correlating microstructural changes, induced by aging, to macroscopic NDE measurements.

Quantification of uncertainty through the measurement and prediction process is essential to bounding the confidence of diagnostic assessments and predictions. Uncertainties are associated with the NDE measurements, interpretations of the degree of damage, stressor history, future stressors, and the models used to integrate factors and extrapolate and bound predictions moving forward in time.

3.1.2 State-of-the-art and Challenges

Owners of nuclear power plants, 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 huge initial investment cost 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 nowadays that is incomparable with former regulated markets where utilities provided complex service with inclusion of all reasonable costs. Another aspect is that nuclear power plants 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 nuclear power plants will be quite important.

It should be noted that operators of nuclear power plants continually improve their assets by various measures, notably:

- power uprate (design reserves utilization, efficiency,…)
- optimization of maintenance and outages
- upgrade and more efficient utilization of nuclear fuel (increased cycle length, enrichment, burn-up, reload patterns,…..)
- flexibility of operation (load-following mode,..)
- impact of Gridcodes and integration of nuclear plants in the energy mix (Rioual et al., 2017),
- impact of new equipment in the power plants with respect to:
    - large equipment,
    - electrical distribution network,
    - instrumentation,
    - stability,
    - development of new tools.

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 aspects of operation of nuclear power plants. 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 nuclear power plants operation could be divided into management, organizational and human performance measures on the one hand and technical measures on the other hand.

Human and organizational factors are key subjects of analysis made with the aim to improve safety, performance and efficiency characteristics of nuclear power plants operation. After the Fukushima accident, the focus of studies on human and organizational factors has been moved towards the importance of the preparedness for emergency management, but the area of prevention also needs attention (safety culture, safety versus efficiency, impact of automation etc.). Important challenges are to strengthen the objectivity of safety judgments by using methods of risk-oriented decision making in the human reliability area, to improve the effectiveness of safety provisions, to harmonize operational principles across Europe and to minimize the negative impacts of complexity on operation and safety. Since organizational safety culture and operating practices strongly influence the safety level, new research should help in defining of the conditions required for ensuring the robustness of the organizations in charge of operating NPPs, based on a deep understanding of work practices and safety culture.

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.

Surveillance, diagnostics and monitoring techniques allow acquiring information and better knowledge about condition of material, equipment and systems which is prerequisite for management of life-time, increase of reliability, minimization of failures and optimized maintenance. Systems, structures and components of a nuclear plant could be divided into two general classes: those that are active components (such as pumps, motors, turbo-generators, valves, compressors, sensors and actuators) and those that are passive components (such as the reactor vessel, piping, reactor internals, containment structure, cables). For active components (e.g. rotating machinery), there are plenty of SDP techniques, with the exception of prognostics, that are proven and routinely used. For passive components, periodic in-service inspections are implemented in accordance with ageing management plans, using non-destructive examination techniques, such as eddy current testing and ultrasonic wave measurements (IAEA, 2013).

Advanced materials are needed for construction of components and systems with improved functionalities and reliability to be replaced during maintenance and upgrade (also to be prepared to LTO) or to be prepared for new generation of NPPs. A first issue concerns the development of new reactor materials which encompasses new steel grades with improved properties, the study of surfaces engineering techniques such as machining, heat treatment, and peening, to mitigate stress corrosion cracking and fatigue (see also section 5.2).

More innovative solutions are to be investigated in the area of coatings (mainly sprays), multilayers or composite materials as well as surface engineering improvements (heat treatment, peening,..) giving to materials improved characteristics (corrosion, resistance to load,..).

Recent studies have shown evidence that combining different materials and **manufacturing routes** may result in multi-functional materials. Large power generation components are commonly fabricated using conventional methods, such as forging, casting and grinding as a finishing operation. Recent research has highlighted the major attributes of powder metallurgy technology, especially high isostatic pressing and additive manufacturing with, for this latter route, different emerging technologies: 3D printing, laser deposition, cold spray. New manufacturing methods are also considered for improved assembly technologies: advanced welding (electron beam…) or bimetallic junctions by high isostatic pressing. Fabrication procedures such as sitable thermo-mechanical treatments are also of use, especially in view of improving the properties of existing classes of steels.

In association to these scientific and technological developments, improvement of computational tools is a challenging field in order to predict materials microstructure, metallurgical properties, residual stresses, deformation and macroscopic behaviour of this newly elaborated reactor components. At last, an important work regarding codification of these new materials/technologies is to be envisaged.

Digital transformation represents one of the most important challenges to nuclear power plants operation as for industry, services and society in general (see also section 5.1). A lot of activities worldwide are focused on the digitalization of nuclear plant activities. “Digital” includes the use or virtual (3D) or augmented reality (virtualization of real world with added information), the use of most advanced data analytics techniques such as machine learning, neural network learning and other forms of artificial intelligence, implementation of digital twins, high level of automation and robotization, and a vast deployment of Internet-of-Things technologies for sensoring and control of processes. The final goal is to improve optimization of maintenance and repairs of equipment, preparation of outages, training of the personnel with the aim to reduce and/or eliminate human failures and on-site assistance to maintenance and operation staff, accessing to procedures and technical documentation from portables and wearables devices.

The goal of the management of a LWR **core** with **fuel assemblies** and associated systems is to maximise cycle energy production with minimal fuel cost while maintaining sufficient margins to relevant improvement of precision of core calculations and better estimation of their uncertainties. Improvements of in core management are currently based on the continuous updating of the design and analysis tools, with the aim of achieving higher accuracy with well-established uncertainty evaluation, through a strengthened understanding of the underlying physics and associated modelling requirements, combined with enhanced computational efficiency. This task can be directly translated into large challenges in basic nuclear data, neutronics, material science, thermal hydraulics, fuel fabrication and fuel storage. Coupling all these aspects (multi-physics) with the help of up-to-date advanced software is the driver for replacing the current systems of codes used for simulation of processes related to reactor operation (see also section 5.1). Advanced instrumentation and measurement methods, and efficient signal analysis, can increase reliability, performance and competitiveness.

Water **chemistry** and low level waste (LLW) management activities have the main target in optimization of chemical parameters of the primary, secondary and auxiliary cooling systems and in development of the optimum technologies for LLW treatment. Water chemistry is actually one of the most powerful tools that operators can use to improve the lifetime of plant components and systems. Suitably designed water chemistry can significantly reduce operational problems, including corrosion, erosion, deposition of corrosion products, etc.

Concerns on radiation exposure of the workers as well as on the radioactive releases into the environment require constant improvement of processes and technologies for LLW treatment and for conditioning of liquid waste. Priorities are to obtain higher decontamination and volume reduction factors, lower both on-site and off-site processing costs, and reducing solid radioactive waste generation rates.

Radiation protection is a specific area to protect both human beings and environment against negative impact and/or consequences of ionization radiation. The main goal is to keep the ALARA principles, i.e. to limit the exposure "as low as reasonably achievable". A strong focus put on radiation protection recently has led to the establishment of the CONCERT European Joint Programme integrating effort in individual platforms and associations – MELODI (Multidisciplinary European Low Dose Initiative), NERIS (European Platform on Preparedness for Nuclear and Radiological Emergency Response and Recovery), ALLIANCE (European Radioecology Alliance Association), EURADOS (European Radiation Dosimetry Group) and EURAMED (European Alliance for Medical Radiation Protection Research) along with activities in social sciences and humanities. Cost effective solutions and application of new tools are highly demanded including more accurate dosimetry. Risk remains in the potential tightening of radiation limits for personnel and the environment leading to further new measures and requirements for new measurement tools.

Apart from the measures mentioned above, measures to ensure safe and reliable **long-term operation** under ageing conditions of the plant are very important. An effective ageing management of systems, structures and components (SSCs) is a key element in plant life management (PLiM) for the safe and reliable long-term operation (LTO) of NPPs. PLiM can be defined as the integration of ageing and economic planning for the purpose of maintaining a high level of safety and optimizing plant performance by dealing successfully with extended life ageing issues, maintenance prioritization, periodic safety reviews, education and training,

The LTO for 60 years and beyond necessitates a consistent PLiM programme that includes technical and economic assessment to:

- Maintain a high level of safety;
- Optimize the operation, maintenance and service life of SSCs;
- Maintain an acceptable level of performance;
- Maximize return on investment over the service life of the NPP;
- Provide NPP utilities/owners with the optimum preconditions for achieving the desired LTO.

Although each country and each reactor technology may have its particular needs and LTO justification methods, they can be classified in three main categories:

- The periodic safety review method, which is typically used in European member states with unlimited or continuing licences;
- limited term licence and a licence renewal concept;
- A combination of the previous two approaches.

In all cases, the preparation for an LTO permit application, implies the conduction of a thorough ageing management review to establish the current state of critical SSCs and their usage factor for fatigue assessments, in order to determine their fitness for prolonged service to the end of the LTO permit duration.

The equipment in a NPP has 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, NPP equipment also needs to function under postulated conditions beyond DBE and DBA. Such postulated conditions are denoted Design Extension Conditions (DEC) and under such conditions may the reliability 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 NPP SSCs. This is ensured via appropriate maintenance, replacement and repair strategies through an appropriate 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.

The PLiM analyst needs to look into the past history of the SSCs, making use of all available records, including those generated by on-line monitoring and diagnosis systems, wherever available. On-line monitoring systems, if selected and set-up for the purpose, can provide a precise record of any deviations from the SSC technical specification by recording changes in parameters and variables, such as peak values, Fourier spectra, vibration residues, critical speeds and chemistry values, among other things. Monitoring can also provide information on the ageing assessment of SSCs, such as pressure boundary leak tightness, number and entity of pressure and thermal transients and functional anomalies in components. Monitoring systems can also provide information on unaccounted stressors and interference with the functionality of systems and components, including cases such as the inadvertent introduction of loose parts. Data, in the most advanced on-line monitoring systems, are post-processed, and recommendations are automatically issued to help operators optimize the planning of maintenance activities and, in special cases, design upgrades and system improvements can be suggested. On-line monitoring systems allow analysts to follow and trend the equipment behaviour and provide meaningful data for an LTO feasibility analysis

To address the R&D needs towards long-term operation, various national and international programs have been initiated and major reports and databases developed by both regulators and industries. The international community has also focused on the issues with the IAEA’s PLiM committee, OECD-NEA’s committee on the Safety of Nuclear Infrastructure (CSNI), European Groups through the NUGENIA association and Euratom program, the Materials Aging Institute in France, proactive management of materials degradation (PMMD) programs in Japan and Korea, and related work in a number of other countries that are all recognizing the challenges faced in extended LTO for NPP.

The past collaborative projects (too many to be listed) have been structured along three main paths:

a. Projects aiming at providing laboratory tests results regarding various degradation mechanisms in order to construct empirical trend curves to support the engineering decisions;
b. Projects aiming at analysing in-service or surveillance programs from various decommissioned or operating reactors both to complemented and to verify the databases;

c. Recently, some projects have been initiated to use the existing experimental knowledge to formulate physically-based predictive models for a specific degradation mechanism.

However, only very few projects are now on going to apply the existing knowledge to develop in-service monitoring strategies accompanied with preventive maintenance to predict or mitigate the residual life time of some safety related components.

Construction and putting in operation of nuclear power plants represent ones of the most complex infrastructure projects in human history. Recent projects usually have taken huge delays and investment cost overruns (Mochovce, Flammanville and Olkiluoto in Europe; Vogtle and VC Summer in the USA), otherwise some projects are in time schedule and budget (mainly in Asia). Another aspect is the sometimes very long preparatory period due to comprehensive approval processes (national laws, international obligations) complemented by extensive public consultations. Potential approaches for keeping the cost plan and time schedule have been analysed recently by the Energy Technologies Institute (ETI, 2018) with the following recommendations (reflecting the UK situation, but results are generally valid):

- Complete plant design prior to construction start
- Follow contracting best practices
- Develop multiple units at a single site
- Develop alignment with labour around nuclear projects
- Government should encourage systematic application of best practices and cost reduction measures
- Develop a national program to maximise and incentivise learning
- Government support to financing process
- Regulatory interaction should be transformed to focus on cost-effective safety.

A possible solution to the current challenges with construction of nuclear power plants could be designs for smaller generated thermal power and modular construction techniques.

3.1.3 R&D Topics

The identification of the SSCs that are subject to ageing is a key issue for plant life management. 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 codes & standards, regulations, specifications & guidelines and scientific knowledge of the ageing mechanisms.

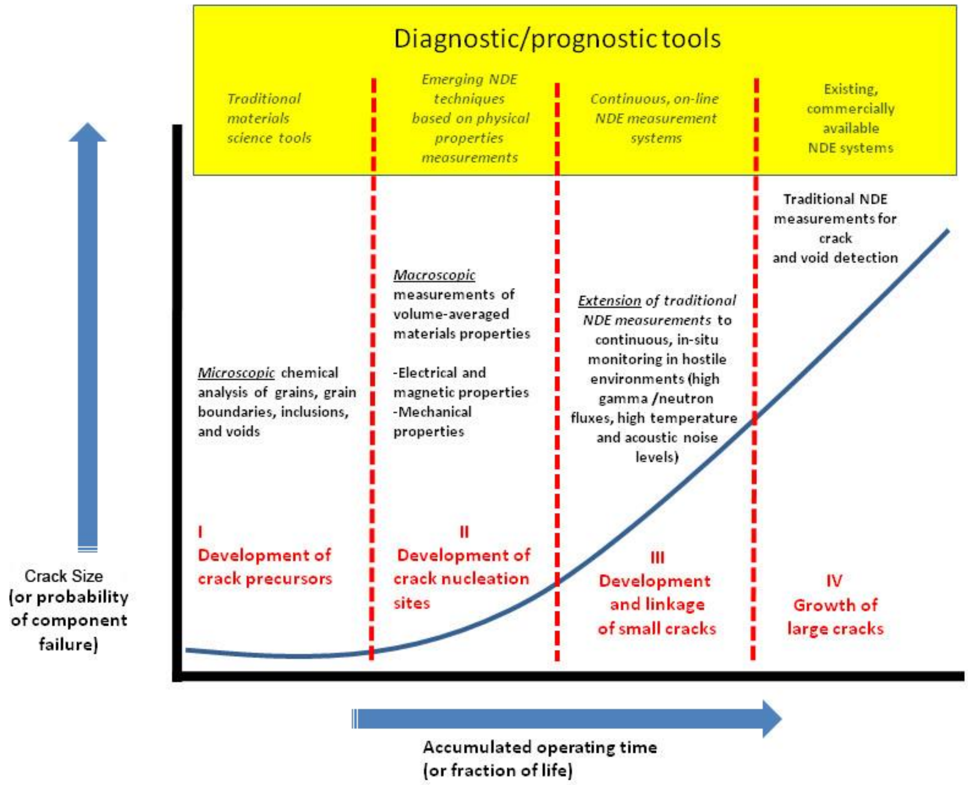
Degradation in metallic components

Degradation in metal components in its early stage is characterized by the development of crack nucleation sites and then small cracks, which are below the detectability threshold size of current NDT. Laboratory techniques can be used to study crack initiation. However, in deployed systems the early detection of degradation will increase the probability that corrective actions are timely planned and implemented. Earlier knowledge of degradation also has the potential to provide plant staff with greater flexibility in taking resolutive measures, thereby avoiding failures or leaks, rather than merely delaying or mitigating its negative effects.

The four stage evolution of degradation in passive components is illustrated in Fig. 1, together with an assessment of the maturity of technologies that are suitable for their identification. Traditional NDE technologies are only sensitive to the most severe stages (stage IV) of degradation, while early degradation (stage I) is typically observable only using recently developed materials science tools. There is a need to investigate phenomena between these two extremes, so as to provide field deployable technologies and assessment methods (theoretical or numerical) that are sensitive to stage II-III degradation.

The development of early-degradation sensitive methods requires the identification of suitable observables that correlate with changes in material condition. Such changes should ideally be local variations in electrical, mechanical, or thermal properties that are detected before initiation of a macro-defect, which could later evolve into material loss or a crack. The measurable property variation should therefore result from microstructural modifications (precursors) that lead to defect formation. Examples include changes in dislocation density, grain size/orientation/shape, precipitation of second phases, and others. For instance, gradual loss of fracture toughness may result from generation of dislocations and voids preceding failure due to mechanical-, thermal-, or irradiation-induced phenomena. To be useful from a plant aging management perspective, precursors should be detectable and quantifiable using either non-invasive measurements and/or robust predictive numerical tools. This may be achieved by understanding and linking the underlying microstructure property changes to measurable bulk material properties (elastic, magnetic, and electrical).

However, for these systems to be effective, the influence of the microstructural modifications on measurable bulk mechanical properties, as well as on originating measurable elastic, magnetic or electrical property variations, has to be assessed in detail.



Monitoring systems and predictive numerical tools should be in place to reliably follow the SSC ageing process caused by known degradation mechanisms, including:

- Irradiation embrittlement (particularly reactor vessel and its internals);
- Creep;
- Corrosion (water chemistry control);
- Wear;
- Fatigue;
- Flow accelerated corrosion and environmentally assisted corrosion, wall thinning of housings and piping (on-line detectors);
- Elasto-plastic thermal deformation phenomena including residual stresses

Other parameters that need to be monitored include vibrations and thermal stratification (thermocouples and dilatometers).

Special attention should be paid to stress corrosion cracking of steam generator tubes from the safety and economic point of view for LTO. Critical components with perhaps difficult access, such as certain RPV base metal sections, reactor supports and reactor structures and other components not included in normal in-service inspection (ISI) programmes, such as buried pipes and underground pipes, should also be included in ageing evaluation for LTO.

One of the challenges then becomes detecting and characterizing small local changes from among natural variability in a nominally homogeneous material using a modest number of sensors to interrogate critical regions. This challenge can be thought of in terms of determining what to measure, how to measure it, where to measure it, and how many measurements to make, all using sensors and instrumentation that will not be significantly impacted or degraded by the operating environment (temperatures, radiation, and chemistry) during extended periods. Any measurement on-site will have to be thoroughly validated, calibrated and qualified properly. In addition progress has to be made regarding the on-time analysis of the huge amount of data yielding from the automatic and in-situ measurement of all implemented sensors.

Secondly, diagnostics and monitoring simulation tools that can greatly increase the ageing management efficiency have to be developed based on the physical understanding of the underlying degradation mechanisms. This challenge necessitates an in-depth knowledge of the environmental stressors (load, temperature, water chemistry, irradiation, …), the materials properties as well as a profound experimental validation programs at appropriate time and space scale for each ageing mechanism.

The main challenge is to develop multi-scale and multi-physics methodologies (see also section 5.1) that take simultaneously into account the load history experienced by any and each critical component during its previous service lifetime and all known and properly assessed ageing induced degradation mechanisms to predict the reliability limits of any components under flexible operating conditions.

Some topics that need further R&D are:

- Adapt existing codes & standards and methodologies to specific operating conditions (e.g. LTO, seismic loading) or creation of new methodologies;
- Deepen the knowledge of degradation mechanisms and their possible impact on the integrity of SSCs;
- Treatment of secondary and residual stresses (including elastic follow-up, crack closure and load history effects);
- Treatment of non-crack like defects (Corrosion, thinning, pitting, erosion, flow induced corrosion, crevices);
- Fracture mechanics for thin sections;
- Integrity of RPV internals for long-term operation;
- Benchmarking of safety assessment methodologies including comparison of outputs from deterministic versus probabilistic methods and integration into the safety assessment;
- Validated models for the assessment of structural integrity of in-vessel components under high doses of irradiation.

Concrete structures

Typical safety-related concrete structures contained in LWR plants may be grouped into four general categories: primary containments, containment internal structures, secondary containments/reactor buildings, and other structures. Primary containment structures, in particular, have significant safety responsibilities including serving as a final barrier to the release of radionuclides, providing protection from severe external anomalies such as missile attacks or natural disasters, and also providing shielding for the external environment from radiation. As a consequence, primary containment structures must satisfy functional requirements for structural integrity and leak tightness. It is necessary to understand the relevant aging mechanisms, their impact on the lifetime of the NPPs, and the adequacy of aging management plans for discovering and mitigating the effects of primary containment degradation.

A variety of phenomena can compromise the functional integrity of concrete structures, including aging degradation, collapse of soils under the raft of the nuclear island which impacts load distribution, seismic activity, and long-term or transient fluctuations in pressures and temperatures during an incident. Leak tightness can be compromised by degradation of welds and seals at joints or through-thickness corrosion of liner plates. Structural integrity is impacted by many forms of degradation associated with both the cement-aggregate mixture and supplemental metallic hardware. The porosity and permeability of the concrete significantly influences susceptibility to degradation through impact on transport of moisture and chemical species through the interior of the member. Degradation of the cement-aggregate mixture can occur by chemical or physical attack, which is ultimately manifest as cracking and loss of strength. Some forms of chemical attack include alkali-silica reactions, carbonation, and sulphate attack. Examples of physical attack include freeze/thaw cycles, shrinkage, creep, and drying. Corrosion of metallic hardware embedded in the concrete can lead to cracking in the concrete. Loss of tension in the tendon system is a concern associated with pre-stressed containments and can occur by shrinkage or creep of the concrete, tendon relaxation, or corrosion of tendon cables and anchorage hardware.

Concrete structure degradation is a function of many factors, including constituent materials, location (e.g. coastal or inland), climatic conditions (e.g. temperature and moisture) and the presence of external agents (e.g. aggressive ionic species). As structures age, incidences of degradation, primarily related to environmental effects, increase.

In addition to the development and assessment of the reliability of NDE methods applicable to the various type/location of concrete structure, a robust modelling strategy will have to be deployed using the following enablers:

- Using decommissioned plants to further compile material data and evaluate long-term concrete performance in an NPP environment;
- Evaluation of long-term effects of temperature and radiation;
- Developing damage models and acceptance criteria;
- Non-intrusive methods for inspection of heavily reinforced thick walled concrete structures and basemats;
- Inspection methods for metallic pressure boundary components including containment liner backsides;
- Utilization of reliability theory to address time dependence changes in structures to demonstrate operability and to estimate end of life;
- Applying probabilistic modelling of component performance to provide risk based criteria to evaluate ageing impacts on structural capacity;
- Determining impacts of refuelling cavity and spent-fuel bay leakage on concrete and embedded steel;
- Development of 'first principle' accurate models to allow for interpolation and extrapolation to stringent conditions.

Cable condition monitoring

Cables are a part of power, instrumentation, control, and communication circuits in NPPs and are essential to both normal and post-accident plant operations. Thousands of kilometres of cables, of a variety of classes, are routed throughout NPPs. Most cables were selected and tested to have a nominal 40-year life. However, LTO is now seeking operation to 60 and even 80 years. In many cases, cables are difficult and expensive to replace. It has even been suggested that it is the economics of cable replacement that could be the determining factor in the economic assessment for the feasibility of plant LTO.

The aging degradation of a cable will be governed by the polymeric system, environmental conditions, and the time scale for which age-inducing stressors are applied. Exposure to high temperatures, moisture, and radiation are key aging stressors for cables. Polymeric insulation and jacket materials can embrittle with sufficient exposure to high temperature and radiation while moisture intrusion can reduce the dielectric integrity of the cable. Exposure of cables to boric acid and mechanical vibrations are also potential ageing factors. In addition to the main cable body, splices and connectors can also be potential locations for degradation and failure.

Localized degradation ("hot spots") can disrupt the function of the entire cable. Thus, consideration of cable architecture, connectors, potential environmental stressors, hot spot phenomena, and the desire to perform measurements in-situ impose a complex set of requirements on cable condition monitoring systems. Condition assessment techniques are generally visual, mechanical, chemical, or electrical in nature. Visual, mechanical, and chemical techniques can provide detailed characterizations of damage but are often localized or destructive in nature. Further, in-situ evaluations in extreme environments, such as within containment, are unlikely if sampling requires direct human interaction. Electrical techniques can sample larger sections of cable, they are non-destructive, and some techniques can be performed online. However, electrical techniques are most sensitive to damage in the conductor and are limited in their ability to characterize damage prior to a failure that impacts electrical function. The application of several condition monitoring techniques is often necessary to form a comprehensive assessment of cable condition. Thus, efforts should continue in the development of in-situ online cable monitoring tools that are able to provide a more holistic assessment of cable condition.

Concluding remarks

New tools and new methods are needed to improve structural health monitoring for LTO:

- Knowledge on behaviour at different scales (materials, specimen, real structures);
- Non Destructive Tests / monitoring devices;
- Methods to combine all the records and use them in predictive modelling to build a relevant diagnosis (digital twins).

3.2 In-Service Inspection, Qualification and Non-Destructive Examination

3.2.1 Objectives and Motivation

In-service inspection (ISI) is a preventive maintenance measure to guarantee the integrity of safety relevant components in a nuclear power plant, and as such is closely related to the safe long-term operation of plants. Throughout the last 25 years, nuclear power operating countries have established inspection qualification frameworks, which govern the qualification of Non-Destructive Testing (NDT) methods prior to their application on site.

In Europe, the European Network for Inspection and Qualification (ENIQ), established in 1992, deals with the reliability and effectiveness of non-destructive testing (NDT) for pressurized metallic components in nuclear power plants and is a network driven by European nuclear utilities working mainly in the areas of qualification of NDT systems and risk-informed in-service inspection (RI-ISI).

In 2010, the ENIQ Steering Committee (SC) recognized that the European nuclear industry was entering a period of significant change and thus initiated an internal discussion to determine its vision and objectives regarding ENIQ's future role and activities. This exercise resulted in the issuing of a strategy document, entitled the "ENIQ 2020 Roadmap" and the decision of ENIQ voting members to integrate ENIQ into NUGENIA, making ENIQ the 8th Technical Area of NUGENIA.

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 optimize and harmonize 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 and new build;
- Promoting ENIQ approaches outside Europe and in non-nuclear industries;
- Maintaining links with other NUGENIA Technical Areas, especially TA4 and TA6.

The Non-destructive Testing methods this chapter is concerned with are Ultrasound, Eddy Current and radiography, since these are still the subject of major innovations, as opposed to techniques such as dye penetrant or magnetic particle testing.

3.2.2 State-of-the-art and Challenges

In service Inspection

Since the creation of the ENIQ sub area inspection effectiveness, ENIQ is actively promoting the transition from traditional ISI to risk informed in service inspection. Traditional ISI relies on accumulated operator experience and engineering judgment to define inspection requirements, while risk informed ISI combines risk-informed data with deterministic information to justify the ISI program scope, and to focus inspection on safety relevant components. To that end, ENIQ published the second issue of "European Framework Document on RI-ISI," in 2019 and before that ENIQ has been developing a series of supporting recommended practices and initiating a number of other work-streams to advance the principles of RI-ISI and maximize the overall risk benefit. Amongst these are recommended practices on the verification and validation of structural reliability models and guidance on the use of expert panels together with discussion documents on the application of RI-ISI to the inspection of reactor pressure vessels and updating of RI-ISI programs. Also ENIQ members were heavily involved in a benchmark project on RI-ISI that was organized by OECD-NEA, and completed the a NUGENIA project, looking at risk reduction through ISI.

The present challenges in the field of risk informed inspection are RI pre-service inspection for new build and modifications of existing plants, as well as RI-ISI for new build in general, establishing acceptance amongst relevant stakeholders of the developed methodologies and extension to a broader scope of components.

Inspection Qualification

The ENIQ Methodology for Inspection qualification approach assembles theoretical and experimental evidence and combines this with formal practical demonstrations to ensure that specific performance objectives are met, in order to provide assurance that NDT of nuclear safety critical components is fit for purpose.

The ENIQ sub area for qualification responsible for having developed the inspection qualification methodology that is now being used as a basis for all European methodologies and for CANDU type reactors. The ENIQ inspection qualification methodology is also accepted by the IAEA as recommended practice to be followed for nuclear inspection qualification all over the world. After publishing the third issue of the European Qualification Methodology Document in 2007, ENIQ issued a recommended practice on personnel qualification and a document giving an overview of inspection qualification for the non-specialist. In particular, ENIQ has progressed NUGENIA projects in computed and digital radiography, the mutual recognition of qualifications between countries and recently launched a new project into the usability of inspection procedures.

Previously, a separate task group for inspection qualification bodies had been established in recognition of the importance of the correct functioning of the inspection qualification bodies as a recognized assessment organization (generally second or third party assessment organization in accordance with ISO 17020) in providing the necessary confidence of NDT results in supporting Structural Integrity claims for safety critical components on NPPs.

At present, the main challenges for qualification are mutual recognition of qualification approaches between countries and the qualification of new NDT systems such as those based on phased array ultrasonic testing, time of flight diffraction ultrasonic testing and computed radiography. The methodology is considered to be sufficiently flexible to qualify NDT techniques on non-metallic components, and interest would be taken by ENIQ in examples of such applications, such as concrete or high density polyethylene. The accuracy and validity of NDT inspection simulation software will continue to be an important area of activity due to its increasing role in NDT design and qualification.

Non-destructive Testing

The current challenges faced in Non-destructive testing (of metallic components) are either due to paradigm changes in the industry, or the technical maturity of new inspection solutions which can now be considered as replacements for established techniques:

- For the majority of the existing Generation II plants with an original design life of 40 years, a lifetime extension to 60 years has become economically viable. This is in part due to the increased capital cost of Generation III reactors, which now target essentially the new build. The long-term operation of Generation II plants beyond the initial design life requires the non-destructive evaluation of components which up to now received little attention, such as piping in the tertiary loop. This is often buried or otherwise difficult to access, and raised an interest in guided wave techniques.
- New materials and new manufacturing techniques (additive manufacturing such as hot isostatic pressing and powder bed fusion) lead to components with different metallurgical characteristics, requiring (or enabling) new NDT designs.
- Continuous monitoring of the structural health of components has demonstrated its added value in other industries (such as aviation/aerospace) as a complement to in-service inspections at programmed intervals.
- The automated analysis of NDE results is becoming technologically feasible, at least for NDE methods where the influence of the human factor is negligible, and remains highly desirable for methods where the human factor cannot be neglected, in particular radiography. Some of the methods proposed or currently under consideration pose challenges from a qualification point of view, if they employ artificial intelligence/deep learning strategies, for which deterministic validation is challenging.
- The industry aims to replace radiography as a highly disruptive inspection techniques with different inspection methods allowing virtually unlimited co-activity, or with digital radiography methods with shorter exposure time and reduced energy, in order to reduce the inherent risks of ionising radiation.
- The limitations of computer models to predict the performance of NDT methods are not always well understood. Current models are unable to provide error margins for produced results, which would be highly desirable for studies on complex structures with some uncertainties, or when covered zones need to be determined.
- Full matrix capture as an acquisition technique and total focusing as an imaging technique have established themselves as state of the art techniques, allowing to maintain a virtual focus at all inspection depths, as opposed to fixed delay law inspections. However, it is still difficult to maintain

crucial real-time imaging capability for complex cases where focal law calculations must take both component geometry and material heterogeneity into account.

- The most challenging material structures for ultrasound NDT have always been cast austenitic stainless steel and dissimilar metal welds. The success of the inspection of these structures strongly depends on the knowledge about the structures at hand. In-situ material characterization is making its first appearance as a means to adapt the inspection method in the field to local microstructure variations, or to confirm the representability of a component's microstructure with the assumed microstructure that served during the inspection qualification.

3.2.3 R&D Topics

In Service Inspection

The following R&D issues have been identified by ENIQ for in service inspection:

- Communication with stakeholders.
- To review risk informed pre-service inspection for new build and modification of existing plant.
- Extension of RI-ISI to all mechanical components, i.e. beyond piping

Inspection Qualification

The following R&D issues have been identified by ENIQ for inspection qualification:

- Benchmarking for computed radiography qualification and Phased Array and guided waves ultrasonic testing qualifications under ENIQ type Methodologies
- Understanding the technical (or other) barriers that preclude the transport of qualifications between countries and find methods or procedures on how to overcome these.
- An independent assessment to verify the accuracy of NDT inspection simulation software. This R&D topic is of particular relevance due to the increasing use of modelling results, not only for ISI planning and design, but also for inspection qualification, and also implies determination of scope of applicability of such software.
- Explore possible frameworks for defining inherent capability for generic applications or evaluating the reliability of commercially available inspections
- Maintaining validity of qualification e.g. through equipment obsolescence
- Simulated indications for operator qualification and /or maintaining proficiency of the operators
- Harmonization on the design of practical trials and production of test pieces for qualification of ISI procedures and personnel
- Inspection considerations for the design of new plants ("design for inspectability").
- Usability of inspection procedures

Nondestructive Testing

The R&D issues in NDT are directly derived from the challenges identified before:

- Explore different mechanisms of excitation of guided wave modes as a means to inspect inaccessible sections of pipes, and access performance in terms of sizing, positioning, dead zone, and robustness with respect to external contact and surface coatings
- Explore the potential on nonlinear acoustics as a means to assess fatigue damage before crack initiation
- Explore the potential of structural health monitoring techniques to complement or substitute scheduled in service inspections (including before mentioned NDE techniques).
- Demonstrate the potential of automated analysis techniques for automated NDE techniques, explore the limits of applicability for methods with high human factor, and develop qualification methods for automated analysis techniques involving artificial intelligence.

3.3 Advanced Reactors and the Next Generation

3.3.1 Objectives and Motivation

The current and projected fleet of NPP's consists largely of water-cooled, water-moderated reactors. These reactors have over time achieved a high degree of maturity in terms of economic performance and safety. To achieve major steps in terms of sustainability (reduced high-level waste production, better use of resources and higher thermal efficiencies) and to open the way for high-temperature non-electricity applications, new types of reactors based on other coolant technologies should be envisaged combined with more advanced fuel cycles. Thorium fuel cycles (especially in liquid fueled molten salt reactors) theoretically offer some potential advantages in terms of sustainability, but at the short term economic drivers are lacking to justify the industrial deployment of a thorium-based fuel cycle, whereas significant progress with regard to sustainability can be made as well through advanced uranium-plutonium fuel cycles.

The use of fast reactors in a closed fuel cycle approach will allow a large decrease in natural resource (uranium) consumption, at least by a factor of 50 allowing therefore a more sustainable implementation of nuclear energy. One of the major concerns of society regarding the implementation of nuclear energy is also the high-level nuclear waste. Fast spectrum reactors with closed fuel cycles will allow a significant reduction in high-level nuclear waste radiotoxicity and volume. Advanced reprocessing and fuel manufacturing techniques are needed to recycle the minor actinides.

For those countries phasing out nuclear energy in Europe and willing to reduce the legacy high-level waste from LWR NPPs, also dedicated advanced reactors can be considered for transmutation of the high-level waste. For the transmutation of high-level waste in a double strata fuel cycle approach four building blocks need to be addressed: the reprocessing of current spent fuel, the fabrication of dedicated minor actinide containing fuel, the dedicated burning of MA-containing fuel and the reprocessing of these irradiated MA-containing fuel.

With advanced reactors, also non-electricity production related applications such as hydrogen production, desalination of salt water and high-temperature heat applications are envisaged. Fast reactors with a higher outlet temperature than current LWR NPPs can address most needs of industrial steam supply while higher temperature applications are presently well suited for the future High Temperature Reactor, operating at elevated temperatures.

Of course, these advanced reactor technologies could also be deployed as Small Modular Reactors, combining the specific properties of SMRs and advanced coolant technologies.

3.3.2 State-of-the-art and Challenges

Concerning fast reactor technologies, four projects have been promoted within the European Sustainable Nuclear Industrial Initiative (ESNII) in the last years:

- MYRRHA: a lead-bismuth Accelerator Driven System to demonstrate transmutation of high-level waste in a double strata fuel cycle approach.
- ASTRID: a sodium cooled prototype reactor to demonstrate the sodium-coolant technology for electricity production in a closed fuel cycle.
- ALFRED: a lead-cooled demonstration reactor to demonstrate the lead-coolant technology for electricity production in a closed fuel cycle.
- ALLEGRO: a gas-cooled demonstration reactor to demonstrate electricity production in a closed fuel cycle.

With **MYRRHA**, Europe will again operate a flexible fast spectrum research facility in support of the material development of fast reactor technologies or fusion. Since MYRRHA will be conceived as a lead-bismuth cooled Accelerator Driven System, it will be able to demonstrate the ADS technology, thereby allowing the technical feasibility of one of the key components in the double strata strategy for high-level waste transmutation to be evaluated. In the period 2010-2018, the Belgium government supported the MYRRHA-project with a total special endowment of 100 M€. In 2015, the staged approach for the implementation of MYRRHA was adopted and in September 2018, the Belgium government decided to continue the funding of the MYRRHA-project with 558 M€ covering the needed investments for the construction of the first part the accelerator up to 100 MeV and its target stations (called MINERVA), the design of the extension to 600 MeV and the design of the lead-bismuth cooled reactor, in total 402 M€ for the period 2019-2026, as well as the exploitation costs for MINERVA for the period 2027-2038, being 156 M€. At the same time the Belgian government decided to set up an international non-profit organization for inviting international partners to join the MYRRHA project.

ASTRID was developed to demonstrate Europe's capability to master the mature sodium technology with improved safety characteristics as defined by WENRA. The design of ASTRID (600 MWe) integrates operational feedback of past and current reactors. It is seen as a full Generation IV integrated technology prototype. An associated R&D program was performed to accompany and support the development to increase the robustness of this technology, and allow the goals of the 4th generation to be reached, not only on safety and sustainability, but also on economics and proliferation resistance. In the period, 2010-2018, the ASTRID project benefited from a state-support of 650 M€ that resulted in a basic design that was thoroughly discussed with the competent safety authorities in a licensing trajectory. Recently, the French government however decided not to continue the ASTRID-project and to envisage a much larger horizon for the industrial deployment of fast reactors, namely towards the end of the century. Therefore, large investments for realizing a sodium-based demonstrator are not expected in the coming years, but the large acquired technology base will be maintained in view of potential future deployment. The French Long-term Energy Plan ("Programmation Pluriannuelle de l'Energie") promotes the extension of the industrial closed fuel cycle on the basis of MOX fuel in PWR reactors, in particular in the 1300 MW units until 2040 and beyond. The MOX fuel technology both for thermal and fast spectrum reactors will therefore be maintained through industrial developments and long-term R&D. Fast spectrum MOX R&D should include European collaborative projects as well as member states and industry projects.

The **ALFRED** project is conceived to progressively increase the maturity level of the LFR technology through the design, construction and operation of an Advanced LFR European Demonstrator (ALFRED), as part of a pan-European distributed research infrastructure gathering main experimental facilities for the research, development, qualification and demonstration of the LFR technology. ALFRED, serving the role of the European technology demonstrator reactor, will be operated in multiple stages, starting with low temperature conditions, and progressively increasing performances based on gained operational experience, and on new technological options. The R&D will advance in parallel, feeding the demonstration program with the basis for advanced technological choices and design options. The role of ALFRED is an essential step with a two-fold implication: thanks to its SMR-oriented features, it will increase the confidence in LFR technology as a medium-term competitive option for the future Nuclear Power Plants and will demonstrate the LFR technology can fully meet the goals set out by Generation IV International Forum (GIF). The development of ALFRED will largely benefit also from the R&D performed in support to the reactor part of the MYRRHA-project. The ALFRED Project is promoted by the FALCON Consortium, Fostering ALFRED Construction in the Mioveni nuclear platform. In 2017 and 2018, through the signature of strategic governmental documents at local and national level, Romania has strengthened its political commitment for the construction of the demonstration infrastructure.

Whereas both the sodium cooled fast reactor and the lead cooled fast reactor have as primary objective to produce electricity, both could be used for combined electricity-heat production. While the output temperature for sodium technology is limited by boiling, for lead reactors, the outlet temperature is presently constrained by having high temperature materials mitigating the coolant corrosion. Medium temperature heat applications are however possible based on currently known technologies.

A Gas cooled Fast Reactor (not to be confused with other gas cooled reactors like HTRs due to completely different implications in terms of core design and safety) has the long-term potential of combining high temperature heat applications with electricity production, provided that suitable materials are found resistant to high temperatures, pressure and irradiation, and the additional advantage of possibly combining Brayton and Rankine cycles for an improved overall efficiency. As such, the GFR can be viewed as a sustainable fast reactor for high temperature process heat production. In this respect the goal is to reduce the industrial consumption of fossil fuels to produce high temperature process heat and hydrogen. However, the feasibility of GFR has still to be demonstrated and for GFR to become an industrial reality, an intermediate objective is the design and construction of a small demonstration reactor. This reactor has been named **ALLEGRO** and its role, apart from being the world's first gas cooled fast reactor, is to demonstrate essentially the GFR specific safety systems. To fulfil the above goals five participants from Hungary, Czech Republic, Slovakia, France, and Poland have set up a V4G4 Centre of Excellence for ALLEGRO project coordination.

In 2019, ESNII analyzed the status of the ESNII project and system maturity based on the prioritization criteria of technology readiness level and the advancement or impetus of European projects. MYRRHA was judged as the most advanced ESNII project having the highest potential to reach full maturity, thanks to the increased technology level in liquid lead-bismuth technology, pre-licensing activities and the continued strong support of the Belgian Government. With regard to the developments of the fast reactor technologies in Europe, sodium and lead cooled reactor technologies have achieved a significant degree of maturity.

However today, there is not yet sufficient state support to realize a demonstrator for these technologies in the short-term. Therefore Sodium and Lead Fast Reactor R&D and engineering studies will continue in Europe in the medium term. Finally, the GFR technology concept still needs conceptual design and basic R&D efforts to demonstrate the viability of the GFR concept.

Due to pending issues about the feasibility of the GFR concept in terms of heat removal capabilities in LOCA events and developments needed for the optimal fuel, **HTR** reactor concepts are considered a more realistic option for mid-term deployment, although not able to compete with fast reactor technologies in terms of sustainability goals. Several EU countries have expressed at ministerial level their support for further development of nuclear high temperature cogeneration, as one of the main objectives of the Nuclear Cogeneration Industrial Initiative (NC2I). Poland, currently a heavy consumer of coal, is financing the national project HTRPL paving the way for the demonstration of HTR cogeneration in the country to decrease its CO2 emissions and to enhance its competitiveness. The HTR technology was successfully proven in Germany, the UK and the US, and test reactors are currently operated in Japan and China. In the US, the Next Generation Nuclear Plant (NGNP) program targets an objective of licensing an HTR first-of-a-kind in the next decade. The NGNP Industry Alliance gathers industrial companies interested in the technology. In 2014, the NC2I and NGNP Alliance have established a transatlantic cooperation framework called GEMINI.

In the recent EC (2019) report, the **MSR** has been identified as one of the potential radical innovation breakthroughs of the future that may exert a strong impact on global value creation and offer important solutions to societal needs. GIF (2018) comprehensively describes the technological challenges underlying the development of MSRs. These challenges are confirmed by EC (2019) in generic terms. The main challenges for MSR development start from obtaining fundamental knowledge about physical and chemical characterization of (fueled) molten salt compositions. Especially knowledge needs to be gained with respect to the effects of irradiation. Once this is known, liquid fuel behavior and its interaction with structural materials should be studied. Supporting deployment of a demonstrator unit, instrumentation and control of liquid salts requires attention, as well as design rule modifications for components, on-site fuel processing and construction of out-of-pile and in-pile test facilities.

3.3.3 R&D Topics

The important technical choice of pelletized fast reactor MOX fuel should lead to the harmonization of fast reactor fuel R&D in Europe, which is not the case in the rest of the international R&D community (GIF) – where metallic and nitride/carbide fuel are also considered. Some fast reactor communities also use MOX fuel compacted using vibration techniques. The comparison of pelletized MOX and compacted MOX at the international level will be a useful exercise.

MYRRHA R&D topics

Because of the maturity that MYRRHA has reached over the past decade, the next main milestones of the project are the construction and commissioning of the first part of the accelerator (MINERVA), bringing the development of the reactor to a level that a detailed engineering design can start and finally obtaining a construction license. These milestones are planned to be realised by the end of 2026. For the former, commissioning of MINERVA should start early in 2025 while for the latter, the Preliminary Safety Assessment Report (PSAR) must be completed by mid-2024 to allow the licensing authorities sufficient time for review. The short and medium term focus of the R&D programme for MYRRHA focussed on supporting the achievement of these milestones. Due to the similar behaviour of the coolant of ALFRED and the common use of pelleted MOX fuel in current European designs for LFR, SFR and MYRRHA it is clear that in principle several synergies can be found. On the other hand, the focus on the PSAR for MYRRHA makes that some of the research will be coolant and design specific.

The R&D programme of MYRRHA is split into several main areas. These include fuel and materials qualification, chemistry control, thermal hydraulics, component tests, accelerator reliability and instrumentation and reactor control. Code validation and safety studies should be mentioned separately since many of the fields mentioned above run across the two latter in the sense that safety and validation touch all aspects of the project and therefore relate to all research fields. Specific topics in research for MYRRHA are detailed below. As usual it should be stressed that this list is not exhaustive and as the work progresses, priorities might change.

- Fuel and Materials qualification

MYRRHA will use MOX as its driver fuel. This allows to use the vast database that has been built up in previous sodium cooled fast reactor programmes. The R&D work in this field is concentrated on extending the information where needed and re-establishing fuel fabrication. A particular effort is put on MYRRHA (coolant) specific issues such as the fuel-coolant interaction, the failure limits of the fuel pins in transients and corrosion behaviour of the cladding. The latter is one of the main topics of the materials programme. Besides corrosion and erosion studies of the clad material and the structural material of the reactor, also the mechanical properties of the materials in the LBE coolant must be thoroughly investigated. This includes accident conditions and the study of welded joints.

Materials coating to mitigate corrosion is also a relevant topic. However, in view of the rather low operation temperature of MYRRHA and the short deployment time relative to the required qualification time of coatings, the focus should be put on coatings for which an established industrial production procedure exists. Of course this does not exclude that newly developed solutions are applied in MYRRHA at a later stage. It should also be stressed that proper attention must be paid to QA and standardisation of test procedures since only in this way the work can be used in a licensing process.

- Coolant chemistry control

  The coolant chemistry control programme of MYRRHA is centred on three main topics. The first is the control of the coolant itself which includes mastering the oxygen concentration but also mass transport and managing impurities. The main source of the latter are corrosion products from the structural materials. The chemical interaction between these, the coolant elements Pb and Bi, and dissolved oxygen, on the one hand and the dissolution, precipitation and deposition kinetics of the reaction products and filtering and removal techniques on the other hand need to be studied. The second main topic encompasses the release and capture of radioactive materials from the reactor system. This involves spallation products from the interaction with the proton beam, activated elements where polonium is the most prominent, and fission products that are potentially released from the fuel pins. Both evaporation and aerosol formation need to be considered as release mechanisms. Capture tests should involve both deposition on reactor vessel surfaces as well as the interaction with dedicated getter materials. It goes without saying that both normal operation as well as accident conditions need to be looked into. The third topic that is related to coolant chemistry control is related to component cleaning and decontamination. This is relevant for the reactor maintenance programme and the eventual decommissioning plan. It should be mentioned here that for both materials and chemistry control, but in particular for the latter, long-term investigations i.e. the investigations for the long-term safe state are important as well.

- Thermal hydraulics

  The thermal hydraulic research activities for MYYRHA mainly serve as input for code validation although several topics are also related to components tests. The work firstly includes system and pool thermal hydraulics investigating flow patterns and potential flow stagnation, striping and stratification. A further major issue is turbulent heat transfer modelling that is required to gain an optimal reliability of thermal-hydraulic computer simulations of the system, and the study of the secondary side of the cooling system to further improve its modelling. A topic directly related to the safety assessment of MYRRHA is the study of thermal-hydraulic effects of earthquakes and the potential effects of the induced sloshing. Finally, thermal-hydraulics also covers the investigation of the progress of a potential coolant freezing.

- Component tests

  Because of the novelty of the coolant applied in MYRRHA in comparison with the established light water reactor technology, an important part of the work supporting the design and licensing process is necessarily dedicated to component tests. In this effort operational and safety related behaviour of all important parts of the primary system is studied. The fuel assembly and reactor core obviously form the centre of MYRRHA. The basic task regarding the core is to demonstrate its integrity and coolability in all operational and transient conditions. Furthermore, it is essential to assess the failure risks in accident scenarios. For this purpose experimental and numerical evaluation is needed of the pressure drop and the vibrations possibly caused by fluid structure interaction. Particular attention must be paid to the heat transfer to the coolant under all circumstances including forced and natural convection, (partial) channel blockage, and pin and fuel assembly deformation. Finally inter-wrapper flow must be assessed to quantify its contribution to fuel assembly cooling and as an input of the assessment of potential propagation of failure to a neighbouring fuel assembly in some severe accident cases. The safety rods and control rods, which double as redundant and diverse safety rods are essential for the control of the reactor in critical mode and for fast shutdown in emergencies. They perform a safety function and consequently a proper assessment of insertion times, reliability and behaviour in abnormal circumstances, e.g. seismic tests, is paramount. The primary pump and heat exchanger form the core of the cooling system. For the former, because of the high mass flow rate required, the hydraulic design of the pump should at least undergo a proof of principle test. Secondly, key LBE submerged parts need to be looked into which means for example that it is important that the impeller material is sufficiently tested against erosion in the coolant and that submerged bearings are tested under relevant conditions. Regarding the heat exchanger besides the thermal hydraulic behaviour, the integrity under normal operation (e.g. due to flow vibrations) and accident conditions (e.g. tube rupture propagation) needs to be addressed. The fuel handling machine is an innovative component in MYRRHA as the fuel assemblies will be loaded from below the core. As a result, proof of principle and reliability tests of LBE submerged remote handling tool needs to be performed. Before this, tests of basic building blocks of the machine such as bearings, gears, cabling, and springs need to be done. Subsequently proof of principle tests of main components such as the gripper need to be performed and finally an integral operational test.

- Accelerator reliability

  For an Accelerator Driven System like MYRRHA the accelerator reliability is critical. Parallel to construction of MINERVA, further improvement of the reliability of components of the accelerator and development of a fast fault tolerance recovery scheme is needed.

- Instrumentation and reactor control

  The work on instrumentation and reactor control involves tests of standard reactor instrumentation that is modified of shows different behaviour because of the LBE coolant. This includes temperature, flow, pressure and level metering, subcriticality monitoring, radiological release monitoring, fuel pin leak detection and impurities monitoring. Reactor control evaluation is based on work performed in a zero power mock-up of MYRRHA.

- Code validation

  For a large part of the evaluation and safety assessment of MYRRHA simulation tools are needed since it is impossible to address everything experimentally. Aspects that need to be addressed involve thermal-hydraulics, chemistry, neutronics, mechanical properties or most often, a combination of any of these. As a result an extensive validation process needs to be carried out where the input for validation should come from existing data and the R&D programmes discussed above. For some aspects, for example in turbulent heat transfer, coolant chemistry, materials and multi-physics modelling, model and code improvement would be relevant as well.

- Safety assessment

  Safety assessment is obviously crucial part of the licensing progress and must play central role in any step of the development of MYRRHA. For this reason, R&D supports for safety is interwoven in each of the research fields by including investigations covering accident scenarios. In extreme cases, e.g. for severe accidents, additional efforts are needed to cover these as well.

SFR R&D topics

- Design and safety studies

  The ASTRID project has accumulated a large basis of technological and engineering SFR studies. These studies will be pursued to define a functional description and a sketch of a commercial industrial French Sodium Fast Reactor of 1000 MW, extrapolated from Astrid design. As a complementary approach, SMR designs will be studied to see if and how they can reach economic competitiveness with respect to large scale reactors. Both studies will participate to maintain the skills on SFR reactors and SFR technologies.

- Simulation and code validation

  As explained in section 5.1.2, the general objective is the continuous improvement of physical models and the integration of these models in multi-physics simulation platforms. Another challenge is uncertainty quantification for the intended field of application i.e. considering nominal and accidental situations, conventional or innovative reactor designs. The strategy is to make the best use of the available experimental databases and to complete them when needed (for instance, ASTRID needs are well identified and should be addressed in the coming years).

  For SFR, this work encompasses the following items:

  the modelling of core multi-scale and multi-physics phenomena : natural circulation of primary sodium taking into account the connection with other circuits (secondary loops, dedicated decay heat systems), core behaviour with sodium boiling taking into account all the phenomena induced by the double-phase flows and the coupling with the neutronics.

  the modelling of physical phenomena encountered during severe accidents : mechanistic models of corium-sodium interaction (developments based on small-scale experiments and/or by simulating experiments, experimental capacities to be developed), corium behaviour on the core catcher, debris bed coolability, materials interactions, …

also the accurate assessment of chemical risks:

- description of sodium leakage and spray fire, aerosol transfer, loading on the containment, atmospheric release ;
- the modelling of the sodium-water reaction in a steam generator: the evolution of the initial defect, the kinetics and the mechanisms of propagation to neighbouring tubes, induced phenomena such as shock waves and mass transfer ;

- Fuel and material qualification

  The general objective is to increase the knowledge on both the $UPuO_2$ fuel at high burnup (10<BU<20 at%), also the assessment on the in pile behaviour of the austenitic stainless steel as the cladding material.

  The strategy is to make the best use of the available experimental mater: analyses of experimental irradiations performed in Phénix should be continued.

  More generally, the decommissioning of the Phénix reactor is a good opportunity to get specimens of various materials that were more or less characterised in the former programs (B4C pellets in the control rods, coatings …) and thus, to increase our knowledge on these materials.

- Instrumentation and inspection technics

  A challenge is the development of sensors and technics directly operable in the sodium. The following needs are of particular importance:

  - velocity measurements with eddy-current flowmeters (primary flow measurements)
  - neutron measurement with high temperature fission chamber positioned as close as possible to the core,
  - defectometry and target visualization in the sodium with acoustic sensors.

  The development program will address the following items:

  - performances and robustness of sensors with program of design, manufacture and test of prototypes ; performances should be determined for the whole system : sensor + signal treatment + carrier ;
  - proof of principle of the carrier innovative equipment.

The program will benefit of the ASTRID developments (specification of needs, operating conditions, experimental platform already existing …)

ALFRED technology topics

For the LFR technology the first priority is still related to the development of strategies and techniques to face the coolant corrosion, especially for higher temperature operation envisaged in the long-term. The present approach is to tackle the topic from multiple sides, including: material developments, coolant chemistry (coolant purification and oxygen control), surface treatments (coatings, double walls etc.). Simulations of coolant- material interaction may play also an important role in the understanding of basic corrosion phenomena and help the identification of new approaches to be object of investigation. Such investigation should obviously be complemented by the verification of the irradiation effect on materials immersed in the lead coolant environment.

Other specific topics of investigation are related to the fuel handling technology and operation (given the high temperature of the “cold” reactor shutdown) as well as In-service inspections and repair (in an opaque, high-temperature and high-density fluid environment). Seismic impact, buoyancy effects and lead-water interaction have been already object of investigations that should be however further pursued, although preliminary results are considered very promising .

Specific topics of interest are related to fuel coolant interaction, retention of fission products in lead (including Polonium behaviour) and severe accident progression and phenomenology. Additional point of interest are also related to operational and maintenance aspects of LFR like the coolant toxicity and lead cleaning process to be developed at industrial level. The implementation of passive safety systems is presently object of projects with the aim to assess system behaviour and expected performances.

It is important to point out that the ALFRED project shares with other European fast reactor initiatives the choice of using MOX fuel for which cross cutting actions should be carried out and leverage on important synergies with other liquid metal based technologies, MYRRHA and ASTRID.

The above description of the main topics of interest for the technology development should be used a s a starting point of the activities. In fact only the realization of a demonstrator will be able to raise all the relevant aspects of an industrial project, allowing a real and measurable advancement of the LFR technology.

GFR technology topics

Development of an acceptable fuel system is a key viability issue for the GFR system. It is necessary to develop an initial cladding material that meets the core specifications in terms of length, diameter, surface roughness, apparent ductility, level of leak tightness (including the potential need of a metallic liner on the clad), compatibility with helium coolant (plus impurities), and the anticipated irradiation conditions. The needs include fabrication capacities and material characterization under normal and accidental conditions for fresh and irradiated fuel.

The target criteria are:

- Normal operation clad temperature of 1000°C,
- No fission product release for a clad temperature of 1600°C during a few hours,
- Maintaining the core-cooling capability up to a clad temperature of 2000°C.

The GFR also requires a specific dense fuel element that can withstand very high temperature transients, due to the lack of thermal inertia of the system. Ceramic or refractory metal clad should be selected, developed and qualified. Such a programme requires material properties measurements, selection of different materials, their arrangement and their interaction, out-of and in-pile tests up to qualification, demonstration tests

Existing calculation tools and nuclear data libraries have to be validated for gas-cooled fast reactor designs. The wide range of validation studies on sodium-cooled fast reactors must be complemented by specific experiments that incorporate the unique aspects of gas-cooled designs, including: slightly different spectral conditions, innovative materials and various ceramic materials. In addition some unique abnormal conditions (depressurisation, steam ingress,…) must be considered.

The need to ensure robust decay heat removal (DHR) without external power input, even in depressurised conditions is now regarded as a requirement. Previous concepts used electrical (battery) driven blowers to handle depressurized DHR while there are no diesels in the design that had to accommodate potential flooding, integrity of the electrical infrastructure following an extreme event is still required. Work is required on two fronts; first to reduce the likelihood of full depressurization and second, to increase the autonomy of the DHR system through the use of self-powered systems. While these self-powered systems cannot be considered passive, they do not require any external power input.

Finally, the strategy to deal with severe accidents is to be established

HTR technology topics

Given the relatively high technological readiness level of the HTR as a type of small modular reactor, R&D topics concern chiefly those needs that are related to near-term demonstration and licensing of reactors with a typical coolant outlet temperature of 750-850°C. In the area of computer tools, uncertainties related to fission product transport in the reactor must be further reduced both in operating and accidental situations. Codes and Standards for structural materials need to be completed on the reactor and on the end-user side. For this purpose, a suitable materials database needs to be kept available reliably. The supply chain for materials and components needs to be revived, and manufacturing capability needs to be recovered where necessary. Some components are likely to undergo qualification tests before commissioning thus requiring specific test facilities in combination with a qualification plan. Specific attention should be paid to the manufacturing and qualification of innovative instrumentation to enable the demonstration reactor to draw full benefit from digitalization. Other specific material subjects include for instance thermal insulation material between RPV support struts and concrete, RPV surface tailoring for maximized radiative heat transfer or material for instrumentation to enhance longevity. Importantly, measures to accelerate deployment and cost reduction approaches should be implemented. Examples may be below-grade construction, simplified design or the creation of a competitive supply chain for materials and components along with harmonized licensing.

Being particularly suited for cogeneration, topics encompassing the coupling to a variety of end-user applications are also of importance which implies different heat transfer fluids on the secondary side (steam, gas mixtures, molten salt…) and thus specific novel heat exchangers, valves and pumps. If an HTR is used in some sort of load following, components need to be adapted to new dynamic requirements. Some cogeneration applications such as thermo-chemical hydrogen production involve aggressive fluids and require specific corrosion-resistant materials. A number of industrial processes using process heat from HTRs could benefit from re-optimization and reduction of process temperature, e.g. by new catalysts. Knowing that industrial processes which can use the heat supplied by HTR are steadily evolving, in particular for optimising their efficiency and minimising their CO_2 emissions, interactions in this field with the R&D performed on these processes is desirable.

Following first successful deployments, it is likely that new fuel production capacity will need to be built. This fuel will require high-performance low-cost quality control for manufacturing. Therefore, it is crucial to maintain related test facilities and know-how for irradiation testing and post-irradiation examinations. Other longer term topics include alternative fuel cycles (closed Th-U, symbiotic U-Pu) or the development of the Very High Temperature version of this reactor type with coolant outlet temperatures above 850°C for maximized efficiency and versatility. This calls for development and qualification of new types of structural and functional materials, in particular refractory metals and ceramic composites for which Codes and Standards need to be prepared.

Techniques to minimize waste volumes need to be perfected, such as the decontamination and recycling of irradiated graphite (in synergy with existing waste management programs), or the separation or recycling of TRISO particles from their matrix graphite.

MSR technology topics

The following R&D topics related to molten salt fuelled (both uranium and thorium) MSRs have been identified by GIF (2018) and EC (2019):

- Physical and chemical characterization of (fuelled) molten salt compositions.
- Liquid fuel behaviour analysis and development.
- Qualification of structural materials.
- Instrumentation and control for liquid salt systems.
- Pre-normative research recommendations for component design rule modifications in support to prototypes for MSR.
- Development of on-site fuel processing concepts.
- Development of out-of-pile and in-pile mock-ups.
- Development of a molten salt fuelled MSR demonstrator.

3.4 SMR

3.4.1 Objectives and Motivation

As mentioned in the IAEA (2018) booklet, there is an increasing interest in small modular reactors (SMRs) and their applications. SMRs are defined as power reactors up to 300 MWe, whose components and systems can be shop-fabricated and transported as modules to their designated sites for installation as demand arises. The most promising SMR designs adopt inherent safety features and are deployable either as a single or multi-module plant.

The key driving forces of SMR development are fulfilling the need for flexible power generation for a wider range of users and applications, replacing ageing fossil power plants, providing the opportunity of cogeneration, supplying energy to remote areas or developing countries with small electricity grids, and enabling hybrid nuclear/renewables energy systems (IAEA, 2018).

The small size offers potential advantages when compared to large NPPs, in terms of design simplification and potential to use passive systems, increased resilience against external hazards and terroristic acts as well as potential to reduce emergency preparedness zones. Through modularization, SMRs aim for economics of serial production and shorter construction time; this, along with the reduced capital investment per unit and the generation of revenues from initial units while constructing the follow-up ones, is also a key enabler for a significant decrease of the investment risk.

Many different countries (Russia, USA, China, France, India and, notably, EU) have governmental strategies supporting the development of SMRs (many are integral PWRs, but also HTRs, LFRs, GFRs, MSRs) with projects led by both research centers and industries.

In the European context, one main potential application of SMRs is represented by installations having power in the order of 100 MWe for the compensation of renewables, due to the policies supporting the increase of share and priority of dispatch of this intermittent energy source. However, the consequent reduced capacity factor would have a detrimental impact on the return of investment making SMRs even less attractive, unless the loss in competitiveness is compensated by national policies. To face such situation, also low-cost thermal energy storage solutions coupled with small-size nuclear energy systems are under consideration and would represent an invaluable asset for the integration with intermittent renewable energy sources, without compromising the financial viability of nuclear power plants in a regulated energy market.

On the other hand, multi-unit sites with a total power in the range 350-700 MWe will represent an option for the replacement of fossil fuel power plants and the supply of process heat to industrial clusters as well as cogeneration of heat for residential areas. In this case, SMRs should be demonstrated to match the temperature needs of the specific industrial application and be safely co-sited close to the end-user. It has finally to be noted that. when considering co-generation application, an additional set of challenges emerges from the coupling to industrial (e.g. chemical) installations:

- Decoupling of accidents and accident initiators in nuclear and industrial parts
- Following variable power demand of industrial installation or coupling through heat storage

The implication of the specific coupling mode and consequences on both nuclear and industrial plants should be obviously carefully analyzed in close cooperation with regulators and potential users.

New standards need to be developed and integrated in the existing licensing and certification regimes (ENCO, 2017), with more chances for knowledge sharing and implementation of lessons learned. Although initiatives are ongoing worldwide, licensing regimes in place for the last few decades represent a barrier to meet the ideal goal of internationally harmonized standards. The EU has the opportunity to develop a legal framework for SMRs (if not for all of Europe, at least for member states embarking on a new nuclear power generation capability), compatible with standardized designs and international certification. The long-term advantage will be the possibility to deploy an internationally certified module in any country adhering to the certification program. EU’s commercial prospects in deploying a certified technology will improve the competitiveness of the local nuclear supply chain. Modular construction of factory built Systems Structures and Components (SSCs) for a standardized SMR designs will centralize the return of experience, with a progressive improvement in quality. Moreover, the associated costs and time schedules will be constantly optimized, for an on-budget and faster delivery.

Finally, from an economic point of view, some not-easily-measurable advantages of smaller NPPs could give the SMRs a competitive advantage. Complexity linked to the large size might be a reason behind recent failures to deliver large-NPPs on-schedule and on-budget. SMRs are expected to be easier to manage from the EPC point of view, thus improving the “actual” performance of smaller units, as far as a size reduction might increase the number of equipment suppliers, as far as modularization should enable the parallelization of fabrication and installation activities, as far as higher factory fabrication options might reduce the chance of non-compliance with the quality standards.

3.4.2 State-of-the-art and Challenges

LWR

Among the 50 SMRs designs reviewed by IAEA, the short-term deployable SMRs are relying upon the most mature technology: water-cooled reactors. Around the world, various companies offer specific water-cooled SMR designs. Far to be an exhaustive list of designs, the followings can be cited as examples for the LWR technology:

- Russian KLT-40S reactors are installed on a barge, have been transported to their destination, and connected to the grid;
- In Argentina, a prototype CAREM reactor is under construction;
- NuScale is in the middle of the licensing process in the USA;
- Discussion is ongoing in Saudi Arabia for the construction of South Korean SMART design;
- The French industry have formed a consortium to promote their own innovative water-cooled Nuward SMR design (see schematic view).

Among the different concepts, the so-called integrated designs, in which steam generators and pressurizer are located inside the pressure vessel, are the most promising ones. They indeed offer simpler design and inherent safety advantages. Furthermore, these designs rely on passive systems for residual heat removal during hypothetical loss of coolant accidents or station black out scenarios.

Advanced Modular Reactors

HTR

High Temperature Gas-cooled Reactors (HTR for short) are SMR candidates closest to deployment after LWR. They have two important advantages for specific applications:

- An inherent safety feature based on silicium-carbide coated fuel particles makes possible to install them in proximity of industrial installations and residential areas.
- High outlet temperature (over 500°C, up to or even exceeding 1000°C) makes them especially useful for industrial heat applications.

In contrast to electricity, heat cannot be transported over long distances. Therefore, reactors providing heat must be located in proximity of user facilities and their power should match the user demand. An optimal size for European market is around 200 MW_{th}. In order to compete economically with larger reactors, one has to find a way to break the economy of the scale. This could be achieved by economy of numbers if HTRs are produced in a repetitive way in a factory, and by supplying heat for industry in addition to (baseload) electricity. This requirement and the relatively small power bring HTRs to the SMR class.

Currently, three basic kinds of applications are considered.

- **Electricity (and possibly heat) production for remote sites.** “Micro-reactors” of 10-50 MW_{th} are being considered for such applications e.g. in Canada, to power remote mines. Military bases are another possible application.
- **Processing heat for industry.** Reactors up to 200 MW_{th} producing steam of 550°C could be an exact replacement of coal- and gas- fired boilers commonly used today. They could be installed without any changes in industrial installations, as they usually have their own steam distribution networks. Reactors with higher temperature output are especially suitable for chemical processes like hydrogen or synthetic fuel production.
- **Cogeneration of electricity and heat for residential areas.** Typical cogeneration power plants today are based on coal- or gas-fired boilers producing 550°C steam. The steam drives turbines producing electricity and the “waste heat” in form of ~200°C steam is used to feed district heating

networks. Reactors of 100-300 MW_{th} producing steam of 550°C could be again a good replacement for such power plants.

LMFR

Main challenges to (advanced) SMR deployment in Europe are the lack of SMR consensus, the decrease of gas prices, the “nuclear fear” and lack of “nuclear vocation”, the dense European electric grid and the lack of a licensing framework specifically applicable to advanced SMR technologies. Improved safety, sustainability, proliferation resistance and economics of Generation4 fast reactors are considered key factors to mitigate the identified societal, economic and environmental threats, thereby opening new perspectives for Small Modular Fast Reactors (SMFR).

More than twenty years of experimental activities on heavy liquid metal coolants have significantly increased the knowledge and experience on this subject across the EU. The large databases of physical, chemical, thermal-hydraulic properties of lead coolant have allowed designers to develop technical solutions that simplify the plant design, thus reducing capital cost, while simultaneously achieving a very high level of safety progressively closer to the elimination of outside containment consequences. Thanks to such constant advancements, the LFR technology has now actual perspectives for a short-term deployment of SMFRs implementing the so-called closed fuel cycle, allowing not only a full use of the uranium resource (sustainability) but also contributing to a strong decrease of the production of high-level waste and hence to the size reduction and needs of the geological repository.

In favor of this choice there are many aspects inherent to the LFR technology such as the high boiling point, exceeding 1700°C, primary system operating in atmospheric conditions, the extensive use in the designs of passive safety features as well as the high retention capability of lead respect to fission products providing an inherent barrier to external radioactivity release, strengthening Defense-in-Depth and supporting reduced emergency preparedness requirements thus facilitating siting near populated or industrial areas.

Lead-cooled SMFRs feature significant export potential in light of their compatibility with small remote electricity networks, intermittent energy sources and, through their higher operating temperature relative to LWRs, cogeneration applications (steam side temperature are presently as high as 450-480°C, but further enhancements can be expected with technology improvements on corrosion compatibility of materials with molten lead).

These features, which supplement the previously mentioned advantages in terms of multi-unit siting and siting in proximity of populated or industrial areas, are cornerstones of the SMR philosophy and result in the LFR being an optimum candidate for global deployment. Moreover, when combined with modular design and construction techniques, plant characteristics such as a high core power density and compact containment as well as reduced releases to environment represent important assets for compensating the small design scaling factor and achieving economic viability. Design and modularization factors around 0.8-0.85, respectively (i.e. 20% and 15% saving factors compared to reference costs for large scale reactors), are necessary for the SMR-LFR to achieve a profitability in line with PWR technology. Profitability is sustained by the shorter deployment time of each SMFR compared to larger plants, anticipating the revenue stream and the pay-back time.

- As already noted in the introductory section, some not-easily-measurable advantages of smaller NPPs could give the SMFR a competitive advantage especially because they are easier to manage from the engineering, procurement and construction point of view. Moreover, the enhanced sustainability in terms of natural resources and the minimization of spent nuclear fuel brought by LFRs, are peculiar features of the technology that shall be factored in, since they could determine potential savings at system level and higher public acceptance, when a broader view is considered.
- Within the SNE-TP advanced reactors initiatives, both the MYRRHA and ALFRED developers are seriously considering an industrial deployment in terms of SMFRs, as a natural and short time frame possibility to implement the technology advancements already achieved. Due to the lack of operational experience in western countries, the commercial deployment of the SMFR technology shall be previously supported by the construction and operation of a demonstrator.

MSR

With respect to small modular versions of MSRs, the challenges are similar to the challenges mentioned for MSRs in general.

3.4.3 R&D Topics

LWR

The dynamic development of integrated light water (LW)-SMRs requires R&D regarding:

- The core
  - use of burnable poisons specifically in the case of soluble-boron-free designs. The challenge is to smoothen the local power distribution while moving from a homogeneously distributed neutron absorber configuration to a heterogeneous neutron absorber distribution.
- The vessel and its internal parts
  - development of compact heat exchangers and associated fabrication processes. The design of these compact heat exchangers will fulfil different conditions, their ability to exchange heat from primary to secondary circuits and their capability to remove the reactor residual heat under natural convection conditions.
- The use of passive safety systems to cope with different accidental scenarios
  - understanding the heat transfer in natural circulation mode and ensuring the function of safety features relying on natural circulation are of primary importance. In order to reduce uncertainties, thermal-hydraulics codes and associated correlations need to be improved, in particular in the field of boiling and condensation at intermediate or low pressures. In specific cases, additional experiments are required.
- The management of hypothetical severe accident:
  - SMRs offer potential advantages like significantly reduced emergency planning zones in case of a severe accident. In order to demonstrate such capacity, special attention will be paid on the in-vessel core retention strategy with the associated improvement of core degradation and corium progression codes.
- The reduction of on-site construction time:
  - this goal is achieved thanks to a large use of modular construction techniques.
- Human Factors:
  - in most cases, SMRs designers propose multi-module SMR plants monitored via a single control room. Such an option raises issues of control room staffing and human factors.
- Probabilistic Safety Analysis:
  - the development of methodologies regarding safety probabilistic safety analysis in order to take into account the reliability evaluation of passive systems, the dynamic aspect over long periods, the monitoring of several units per site with shared systems and operators.
- Licensing:
  - the market addressed by LW-SMRs is clearly worldwide including currently non-nuclear countries. To foster the development of such market of SMRs at large scale, the development of a common methodology for safety analysis of water-cooled SMRs and/or European or internationally accepted generic design assessment scheme is a key advantage.

Advanced Modular Reactors

The technology of advanced modular reactors is either well proven and it does not require any generic R&D, or it requires similar R&D as their larger scale alternatives mentioned already in the previous chapter. Specific research and development is, however, needed for SMR kind of applications. Basic challenges are related to “mass production” of the reactors:

- Simplification of the design
  - Benefits from small power and never-melting fuel
  - Simplified shutdown systems
  - Containment vs confinement, simplified reactor building, etc.
- Compactness of the design
- Making design suitable for manufacturing
- Using commodity components

As already noted, another set of challenges emerges from coupling to industrial (e.g. chemical) installations:

- Decoupling of accidents and accident initiators in nuclear and industrial parts
    - Ensuring that nothing in industrial part can influence operation of the nuclear part and vice versa
- Following variable power demand of industrial installation
    - Load following mode
    - Heat storage (to enable the reactor to run full power all the time)
    - Varying the ratio of produced heat and electricity

Such kind of research should be done in close cooperation with regulators and potential users.

4 Enabling Conditions

4.1 Safety of Nuclear Power Plants

4.1.1 Objectives and Motivation

Safety of nuclear installations belongs to absolute priorities from the very beginning of nuclear reactors construction in 1940-ies. During the nearly 80 years of designing, construction and operation of research reactors and commercial nuclear power plants, the concept of nuclear safety has developed into a complex and sophisticated system, where the very core of it is the defense-in-depth approach. Nuclear safety is a critical condition for sustainable NPPs operation and therefore SNE-TP puts 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's why support of nuclear safety programs and harmonization of approaches to nuclear safety is another imports aspect of nuclear safety effort.

With appropriate site risk evaluations, plant designs and management, current Gen II and future Gen III NPPs show high levels of robustness and low probabilities for severe accidents. The deployment of advanced Light Water Reactors (LWR) for electricity production could valuably make the bridge between the ageing nuclear installations currently in operation, the Generation III reactors now under construction, and the Generation IV reactors, proposed by the Generation IV International Forum (GIF). But, despite the highly efficient accident prevention measures, some accident scenarios may, with a low probability, result in a severe accident, as emphasized by the events in Fukushima. A nuclear severe accident can result in core melting, plant damage and dispersal of radioactive materials outside of the plant containment, thus threatening public health and the environment. For innovative reactor concepts of non-LWR type, the application of the LWR severe accident methodology cannot be simply transposed from the LWR technology due to different phenomena that play a role and engineering features. For all reactor types, inherent and passive safety should be continuously assessed and improved.

The deterministic safety assessment of NPP is being extended in several directions, mainly to design extension condition area (based on previous works of the European Utility Requirements organization and WENRA). More systematic assessment of vulnerabilities to defence-in-depth is another important field of application of modern deterministic tools and methods. Probabilistic analysis was also strongly influenced by the events in Fukushima and work in areas like external hazards (including extreme events), multi-unit PSA, human factor, fragility analysis have been initiated or strongly extended:

- 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.

4.1.2 State-of-the-art and Challenges

One of the most important parts of nuclear safety is the NPP safety and risk assessment. It serves not only in phase of licensing of a new plant, where the safety analyses are the very core of the preliminary Safety Analysis Report (SAR). The deterministic and probabilistic analyses are widely used in the phase of NPP design, licensing, start-up, support of operation, periodic safety assessment, validation of accident management guidelines, and support of NPP modifications. The tools and methods utilized in NPP safety assessment experienced dynamic development in last decades. The original approach with deterministic analyses of a spectrum of transients and accidents up to maximal design basis accident (DBA) performed with conservative computer code and documented in the SAR has been gradually extended by probabilistic risk assessment, application of best-estimate computer codes, severe accident analyses, human reliability analysis, assessment of external hazards, quantification of uncertainties of safety analyses, analyses of design extension conditions etc...

The extension of plant safety and risk assessment is accompanied by progress and development of computational tools which are utilized for safety and risk assessment. Advanced computer codes utilized for DBA analyses are continuously being developed. Shift from 1-dimensional hydraulic models and point kinetics to 3-D modelling of the reactor core and the cooling systems, coupling of system thermal-hydraulic codes with core physics (multi-physics coupling) and/or computational fluid dynamics codes (multi-scale coupling) are the tasks being solved at present. Methods and programs utilized for probabilistic risk assessment have developed to complex computational tools enabling quantification of plant risks in both nominal and shutdown conditions including a.o. human reliability analysis, external hazards, and grid impact. Combining of deterministic and probabilistic methods is also a very promising direction of plant safety assessment. However, as always simulation tool development and experiments to provide data for development and validation need to go hand in hand. The ever increasing computational capabilities put a challenge to the usage of more sophisticated measurement techniques. Moreover, also the instrumentation and control systems of NPPs could represent a challenge both in term of safety application and during the licensing process.

Considerable knowledge has been gained about severe accident phenomenology for LWRs through research carried out during the last 40 years, for instance in the international project Phébus FP on in-pile experiments, and in the SARNET Euratom projects from 2004 to 2013. More recently, many international R&D projects have started in diverse frames such as Euratom collaborative projects and OECD/NEA. One can underline the importance of projects launched in the latter frame and led by Japanese organizations about the interpretation of the accidents in Fukushima. For the advanced reactors and in particular for the sodium-technology, severe accident phenomenology has been defined in the past and has been further studied during the ASTRID-project. For lead-technology, the severe accident phenomenology leads to a significant different concept and needs specific development. The same is true for high temperature and molten salt reactor technology which like lead-cooled reactors relies on different principles.

For each of the six main objectives defined for severe accident analysis, challenges have been identified:

With respect to in-vessel corium/debris coolability, the objective is to reduce the remaining uncertainties on the possibility of cooling the reactor core structures and materials during a severe accident, either in the core region or in the vessel lower head. This should limit the progression of the accident. Substantial knowledge exists concerning cooling of intact rod-like core geometry. Significant progress occurred in the recent years about the core degradation late-phase, in particular on the behaviour of corium and debris in the vessel lower head. This is currently being completed.

With respect to ex-vessel corium/debris interactions and coolability, the major safety challenge after vessel lower head failure is to preserve containment integrity against rapid failure (e.g. due to steam explosion) or slower failure by basemat melt-through (Molten-Core-Concrete-Interaction (MCCI)) and/or containment over-pressurization. Significant new knowledge was obtained in the past years on the premixing phase of steam explosion and on MCCI phenomena but main remaining issues have recently been synthetized in OECD/NEA reports.

With respect to the mitigation of gas explosion risk in containment, significant knowledge was gained in the past years on containment gas distribution and on the efficiency of passive autocatalytic recombiners during severe accidents.

The source term to the environment refers to the amount, chemical speciation and isotopic speciation of all radio-elements that can be released to the environment. A significant progress to this respect came from recent R&D international projects in European and OECD/NEA framework but some knowledge gaps remain to be addressed.

In addition to NPP safety concern, severe accident R&D activities target the improvement of emergency preparedness and response and of the prediction of the environmental impact. Associated needs will have to be discussed in the frame of the memorandum of understanding signed in 2017 between NUGENIA and the radioprotection European platforms. Fast-running tools are necessary in the emergency preparedness phase and in the response phase. Improving on-site atmospheric transport and dispersion models of radionuclides will allow a better interface between the in-reactor source term evaluation tools and the atmospheric transport and dispersion tools that mostly consider mid-to-far fields.

With respect to the management of severe accident scenarios, integral codes (or system codes) are essential for simulating severe accident scenarios including the evaluation of the source term into the environment, as well as the evaluation of severe accident management measures and the efficiency of mitigation systems. In addition, the accidents in Fukushima have underlined the importance of the behavior of spent-fuel pools in case of loss of cooling. And finally, the consolidation of shared databases for methods and tools for severe accident management guideline assessment and improvement will be necessary in the future.

4.1.3 R&D Topics

The advanced methods and tools for plant safety and risk assessment enable upgrading of reactor safety systems to handle new safety demands, effective replacement of obsolete components, power uprates, improvement of economic parameters of NPP operation, support of LTO etc.

Major challenges and related R&D topics in the area of plant safety and risk assessment are as follows:

- New approaches to safety assessment:
  - Methodologies extending the scope of existing probabilistic safety assessment (external events, cascading/conjunct events characterization, fragility / operability / technical resilience analyses, human organizational factors and risks, etc…);
  - Long-term and multi-units loss of safety functions from internal or external event or combinations of both conceivable at the plant site, including station black out, loss of the ultimate heat sink or both,
  - Development and validation of advanced tools and methods for deterministic safety analysis, including multi-scale and multi-physics capabilities;
  - Integrated deterministic-probabilistic safety assessment;
  - Simulation tools for fire modelling;
  - Methodology of safety assessment of design extension conditions (DEC) and performance of diverse and alternative means and measures;
  - Further progress in quantification of uncertainties of safety analyses. Application of uncertainty methods to further areas (neutron cross sections and 3D neutron-kinetic calculations of transients, pressurized thermal shock, sub-channel calculations, etc…);
  - Support to continuous operation of remaining European experimental facilities with emphasis on design extension conditions accidents and shutdown conditions (essential condition for computer codes development and validation).
- Development of safety requirements, criteria and rules for passive systems:
  - Credibility of passive systems activation and load-up to required capacity,
  - Safety and reliability assessment of the capability of passive safety system to perform the assigned function,
  - Dependence on external energy sources for initialization and execution of the assigned function,
  - Assessment of different phenomena that could lead to the loss of assigned function,
  - Uncertainties and safety margins associated with passive systems,
  - Methodology for the reliability evaluation of passive systems and its integration into probabilistic safety assessments,
- Development of more sophisticated instrumentation and control systems for safety applications:
  - Implementation and safety assessment of electronic and programmable devices as more use of such devices in NPPs can be expected in the near future,
  - Methodology for the reliability evaluation of digital instrumentation and control systems and its integration into probabilistic safety assessment,
  - Implementation and safety assessment of wireless technologies for data transmission.

With respect to the six main objectives defined for severe accident analysis, the following R&D topics are identified:

- In-vessel corium/debris coolability
  - Coolability of a degraded core/corium with particulate debris during reflooding by water injection
  - Transient corium/debris behaviour in the vessel lower head
  - Integrity of an ablated vessel lower head with external cooling
- Ex-vessel corium/debris interactions and coolability
  - Debris formation during melt relocation to the ex-vessel cavity
  - Corium/debris coolability by top flooding during MCCI, in particular for metal-rich melts;
  - Consequences of ex-vessel steam explosion, in particular for stratified configurations with corium spreading under water
  - Long-term cooling of corium/debris, including efficiency of the coolant recirculation systems.

- Mitigation of gas explosion risk in containment
  - Containment atmosphere gas combustion, with deflagration to detonation transition, and corresponding modelling improvements, in particular for extrapolation (e.g. scaling) to actual NPP geometry
  - Evolution of containment leakages due to severe accident conditions up to the long term.
- Source term assessment and mitigation
  - Improvement of predictability of iodine and ruthenium chemical behaviour in reactor cooling system and containment, in particular all remobilization and revaporization phenomena for delayed source term linked with severe accident long-term management.
- Severe accidents linkage to environmental impact and emergency situations
  - Improvement of in-reactor liquid source term and associated releases paths;
  - More accurate atmospheric transport and dispersion models, in particular near–field models and impact of physical and chemical transformation of radionuclides
  - Improvement of severe accident management evaluation tools for accident progression, including mitigation actions, and consequences (e.g. effect of different severe accident venting strategies);
  - Improvement of fast-running tools, including instrumentation and information transmission, either based on severe accident evaluation codes or validated by comparison with these codes.
- Management of severe accident scenarios
  - Continuous capitalization of knowledge in the integral codes and of their capabilities to support improvements of severe accident management guidelines;
  - Extension of the current crosswalk exercises among the major severe accident integral codes;
  - Development and qualification of specific instrumentation for supporting the management of all severe accident phases, including long term;
  - Accidents in spent-fuel pools (thermal-hydraulics, fuel cladding oxidation, criticality risk, accident and source term mitigation..), and improvements of applicability of the integral codes.

Note that for non-LWR's, the safety approach used for LWR's cannot be adopted straightforwardly. An interactive process with the safety authorities is necessary in order to agree on a safety approach and underlying guidelines and rules that take into account the specific characteristics of innovative reactor concepts and coolants.

4.2 Development of Fuel, the Fuel Cycle, and Spent-fuel Management

4.2.1 Objectives and Motivation

For the LWR-fleet of NPP's, the currently adopted fuel cycle is the open fuel cycle with final direct disposal in geological repositories or mono-recycling of plutonium via the production of MOX fuel loaded in LWR reactors. For these LWR's, fuel development and spent-fuel management research and innovation topics cover the development of nuclear fuel for existing, advanced and innovative core designs including

- assembly and control rod considerations;
- within assembly instrumentation;
- manufacturing;
- transport;
- use within reactors (nuclear fuel behavior mechanisms including post-irradiation examination);
- pre-disposal management of spent fuel (which may include wet storage, transport, drying, dry storage and repacking);
- reprocessing;
- the production of recycled fuel from the products of reprocessing.

This includes the safety issues linked with fuel behavior in normal operation, transient and accident conditions in addition to the safety of the fuel cycle including criticality prevention, heat management and containment. Of particular importance is that the lessons from the accident in Fukushima are taken into account to propose research, development and innovation to improve the safety and resilience of the existing and new build LWR reactor fleet.

Nuclear fuel production and use in commercial reactors have reached a relatively mature state. Nevertheless there is motivation to improve existing fuel types and to develop innovative fuel. Research on fuel behavior mechanisms and computational codes research is focused on behavior in both normal operation and accident conditions, performed experimentally and with simulation models (computer codes). An understanding of fuel behavior is underpinned by fuel R&D, which must address new safety requirements and design innovations such as Accident Tolerant Fuel or Advanced Technology Fuel (ATF) and advanced recycled fuels, high burn-up, high linear power, SMR fuels, long refueling intervals, and flexible operation. It must also address differences in behavior engendered by more incremental changes of the fuel pellets, cladding and assembly structural components.

The improved understanding of fuel rod behavior mechanisms is enabled by experimental observation, measurements complemented by physical models, and facilitated by modelling using physics based simulation tools. This improved understanding and the results of physical modelling can be used to improve fuel performance codes, as is pursued within the fuel sub-programs of the EERA-JPNM as outlined by EERA-JPNM (2019), with which SNE-TP signed a memorandum of understanding to ensure collaboration. Fuel performance codes are essential for fuel design and licensing. A fuel performance code calculates the evolution of the thermo-mechanical and thermo-chemical state of a fuel rod during its irradiation (and potentially also during any post-irradiation storage) as well as, potentially, the fission gas and fission product behavior.

Fuel treatment, transportation and interim storage (spent-fuel management) research satisfies the need to fully understand the challenges faced by managing the extended storage periods of the spent (used) fuel and their storage systems following reactor utilization. Management activities include handling of the spent fuel, associated diagnostics (determination of fuel assembly and storage system condition), storage in spent-fuel pools at power plants, transport, interim storage in either wet or dry conditions before either reprocessing and recycling or transfer for final disposal, all need to be qualified and validated. Recycling of UO_2 and metallic fuels is well established within some countries in the EU. The continued development of fuel and the effects of higher burn-up irradiations raise the potential for changes in recycling process parameters.

Although with open fuel cycles or partially closed fuel cycles based on mono-recycling of plutonium the sustainability in terms of resource utilization and high level waste minimization can be gradually increased as mentioned above, major progress can only made through closed fuel cycles with fast reactors. Fast nuclear reactors can be designed to reach conversion ratios equal to or even greater than one, in such a way that no more natural fissile isotope is needed to sustain nuclear energy production since the reactors generate more fissile isotopes than they consume to produce energy. These reactors, also called “breeders”, need to be fed only with fertile isotopes (^{238}U or even ^{232}Th) which are available in plentiful amounts, both in nature and as leftovers from the present enrichment of the nuclear fuel in ^{235}U.

To optimize high level waste management, two generic fuel cycle scenario exist:

- A fleet of fast neutron critical reactors that simultaneously produce electricity and transmute all the actinides. The only input into the system (reactors and fuel cycle facilities) is natural or depleted uranium and the output is electricity and residual intermediate level waste (ILW) plus high level waste, including the fission fragments, activation products and actinide reprocessing losses. In this option, the minor actinides (MA) could be homogeneously diluted within the fuel or separated in the form of dedicated targets. However the core design of these reactors has to be optimised from the point of view of neutron economy and safety performance, and the feasibility of the associated fuel cycles should also be addressed.
- A “double strata” reactor fleet. The first stratum is a set of critical reactors dedicated to electricity production using “clean fuel” containing only uranium and plutonium. The reactors in this stratum can be either present or future thermal reactors or fast reactors. Some European countries may want to consider long-term plutonium multi-recycling R&D both in fast spectrum reactors and in thermal spectrum ones in the first stratum. The second stratum is devoted to transuranic elements or minor actinide transmutation and is based on special fast reactors or subcritical fast systems, Accelerator Driven Systems (ADS), loaded with homogeneous fuels with high minor actinide content.

The evaluation of this type of scenario indicates that while maintaining the safety of operation, they should ultimately be able to significantly reduce the long-term uranium consumption, making the present reserves last for several thousand years. At the same time, the high level waste long-term radiotoxic inventory could be reduced by more than a factor of 100 and its heat load by more than a factor of 10, at medium and long term. According to these studies the last figure will allow the deep geological repository capacity to be increased by factors from 3 to more than 10 (in hard rock, clay and tuff geological formations).

4.2.2 State-of-the-art and Challenges

The main nuclear fuel suppliers in Europe are currently Orano, Westinghouse, ENUSA, GNF and TVEL. The existing theoretical and experimental knowledge base consists of the vendors' own R&D, the operational experience of utilities, research entities such as national laboratories, technical service providers, universities and international organisations, in particular the IAEA, OECD/NEA and WNA. Experimental facilities including research reactors, hot cells and hot laboratories need to be available for research and testing, supported by extensive modelling and simulation capability using state of the art computer codes.

Uranium dioxide (UO_2) enriched up to 5% in the form of solid or annular pellets in zirconium alloy cladding remains the most widely used fuel in European reactors, primarily LWRs. MOX (mixed uranium-plutonium oxide) fuel also is used in limited quantities, mainly in France, where large scale reprocessing and manufacturing facilities are available. For LWR fuel assemblies, the main construction materials are again zirconium alloys, with nickel alloys and stainless steels also used for some assembly components. Control rods are currently manufactured primarily from either silver-indium-cadmium (Ag-In-Cd) alloys or contain boron carbide (B_4C).

The properties of all these materials and fuel assembly design are relatively well established. However, the drive for continuous improvement in safety, reliability and performance through improved understanding and evolutionary adjustments necessitates further studies and ongoing development. Fuel performance and reactor physics codes have been developed over a number of years and validated using data from operation and dedicated experimental programs. These are routinely used for simulation of normal operation, transient conditions and accident scenarios. Nevertheless, enhancements in simulation methods, enabled by ever improving computing capabilities, are continually sought as there is a desire for better mechanistic understanding of fuel behavior in-reactor. This endeavour, with a projection towards fuels for advanced reactors by centering on MOX and MA-bearing fuels, is especially the focus of the fuel activities within EERA-JPNM.

Spent-fuel management of the various nuclear fuel types from both commercial and research reactors is a mature practice benefiting from the accumulated knowledge and experience acquired over more than fifty years. Nevertheless, there is room for improvements in safety, security (proliferation resistance), economics and environmental aspects. Spent-fuel management is carefully regulated by national regulators, usually reflecting recommendations of international organizations, in particular Euratom and the IAEA. Within the EU, a range of spent-fuel storage arrangements are employed, in some countries fuel is stored primarily at the reactor site where it was irradiated, whereas in other countries, centralized facilities exist for interim/long-term storage following an initial cooling period at the reactor site.

The reprocessing of UO_2 and metallic fuels has been well established within some parts of the EU. However, there is the potential for the extension of existing reprocessing techniques to more challenging fuels, such as high burn-up fuels and multiple recycled MOX, as well as development of advanced reprocessing techniques such as pyro-processing. In addition, the reprocessing of potential novel LWR fuel compounds such as those proposed for ATF, needs to be considered in particular by linking with Gen IV programs where there is currently greater experience of some of the proposed materials. In addition, there are many exotic fuel forms which been produced in Europe as a result of past development programs including Gen IV pre-cursors which are difficult to reprocess but may not be suitable for direct disposal in a geological repository.

The deployment of advanced fuel cycles involves large technological challenges:

- synthesis of new fuels (targets) and fuel assembly designs bearing significant amounts of MA, and their fabrication technology (this is a major focus of the research on nuclear fuel performed within the EERA-JPNM);
- the technologies of fast neutron reactors and ADS, including new materials, thermal-hydraulics, simulation tools, nuclear data and, in the case of ADS, the coupling of an accelerator with a subcritical core
- new recycling technologies based on advanced aqueous and pyro-metallurgic reprocessing, adapted to highly active and hot fuels containing large amounts of plutonium and minor actinides, and minimizing the production of secondary wastes

For most of these topics, significant lab demonstration exists, but now the step towards larger scale demonstration needs to set.

Additional fuel cycle scenarios studies are required to complete the evaluation on the feasibility of sustainable solutions for the transition period from the present nuclear fleet until the deployment of fast nuclear systems, taking into account present perspectives for deployments of advanced thermal reactors and future fast neutron reactors. Similarly, the evaluation of the impact of these technologies in the deep geological repository designs, taking into account updated nuclear policies of EU Member States, technology deployment and different options for the fast systems deployments, needs still to be completed.

4.2.3 R&D Topics

The following R&D topics are identified, some of which overlap with activities on fuel coordinated within the EERA-JPNM:

- Increasing the safety margins of nuclear fuels and improving behavior under operation and accident conditions including the development of new ATF forms;
- Improved economics of nuclear fuels in particular through allowing high burn-ups, increased enrichment (beyond 5%), and potential new high density fuel forms;
- Increased nuclear fuel recycling through the use of reprocessed uranium and improved MOX fuels including multiple recycled MOX, high plutonium content and minor actinide bearing MOX;
- Improvements in assembly design and optimization including attempted elimination of grid-to-rod fretting and the prevention or mitigation of damage by foreign objects;
- Improvement of fuel performance and safety computer codes and their validation by quantifying and reducing uncertainties and extending qualified experimental data;
- Introduction and validation of more mechanistic and multi-scale modelling packages for the assessment of both existing and innovative fuel designs;
- Improvement of post-irradiation examination (PIE) methods
- Ensuring availability of key experimental facilities (research reactors, hot cells and hot laboratories) and expanding their capabilities to meet future requirements;
- Handling and storage of leaking fuel assemblies (spent-fuel pool and interim wet and dry storage)
- Understanding the evolution of spent-fuel and storage systems over multi decade or even longer temporary storage and development of effective means for monitoring compliance under nominal and off-nominal conditions.
- Optimization of storage systems to minimize handling of fuel and casks after longer term storage, including the interface to deep geological repository;
- Spent-fuel heat generation and burn-up credit challenges (code validation, uncertainty reduction and licensing issues);
- The reprocessing and recycling of challenging fuels (e.g. high burn-up, multiple recycled MOX) and advanced fuels (e.g. ATF) as well as advanced reprocessing technologies (e.g. pyro-processing);
- Use of advanced integrated computational tools for development of integrated waste management strategies;
    - new fuels (targets) and fuel assembly designs bearing significant amounts of minor actinides, and their fabrication technology, thus includes plutonium- and minor actinide-bearing fuels including thorium oxide (ThO_2) matrix (thorium MOX) and inert matrix fuels for plutonium and minor actinide burning applications;
    - new recycling technologies based on advanced aqueous and pyro-metallurgic reprocessing technologies, adapted to highly active and hot fuels containing large amounts of plutonium and minor actinides, and minimizing the production of secondary wastes

In Summary

The overall objectives with respect to the fuel cycle and spent-fuel management are to improve the operation of NPPs and the nuclear fuel cycle at large in the fields of in-reactor and out-of-reactor nuclear fuel management as to be more:

- Safe;
- Sustainable;
- Secure (proliferation resistant);
- Environmentally friendly;
- Reliable and Economic.

One key objective is to reduce the time to deployment of innovative new technologies across the whole technical area so as to realize the safety and economic benefits as soon as possible.

4.3 Dismantling & Decommissioning

4.3.1 Objectives and Motivation

Waste management and dismantling & decommissioning covers the management, treatment and disposal of waste arising from operations across the nuclear fuel cycle (including fuel fabrication, power generation and reprocessing). Beyond waste management, the area incorporates the dismantling and decommissioning of nuclear power plants and fuel cycle processing facilities as a last step in their lifetime. Finally it also considers waste minimization and recycling of non-fuel materials. The focus 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.

According to IAEA (2019), 178 nuclear reactors have been permanently shut down of which about 10 have been fully decommissioned; many other nuclear facilities have also been decommissioned (such as research reactors, radioisotopes production facilities, reprocessing plants, fuel fabrication facilities, and military reactors). Similarly, nuclear plants have operated successfully for many decades and the arising wastes managed safely, through treatment, storage or disposal. A significant amount of experience and knowledge has been accumulated and it is important that this is shared as the number of waste management and decommissioning operations increases. This body of knowledge will grow further as experience is gained and will define current best practice. This knowledge should also inform the design for future systems. The current challenges are to develop enhanced approaches to minimize waste arising, through design, operation and decommissioning, to enhance waste treatment processes and to develop technologies and approaches to deliver decommissioning safer, cheaper, faster and sustainably.

4.3.2 State-of-the-art and Challenges

A number of decontamination, waste treatment and conditioning methods and technologies have been developed over many years. These are used alongside the techniques for waste management of special categories of waste, such as Tc and C-14 waste, Be, irradiated graphite, mixed radioactive and toxic waste. Nevertheless, potential for technology improvements to reduce cost, reduce volumes for disposal and risks are not exhausted. Methods for decontamination and certification for reuse and recycling of various materials (metals, concrete) have been introduced. Experience from decommissioning and dismantling of nuclear facilities is being continuously accumulated allowing for the drafting of guidelines and best practices.

In the waste management area, the focus is on the implementation of the waste hierarchy in the context of radioactive waste. This involves characterization of waste, innovative approaches for treating waste (decontamination and waste revalorization), waste storage, waste form development, long-term condition monitoring and disposability. Innovative approaches can reduce the burden of waste management activities and disposal and lead to a more sustainable long-term approach.

As decommissioning and dismantling activities grow across the globe, significant experience is being gained. For the decommissioning and dismantling area, the focus is on development of pre-planning and programming for decommissioning, decommissioning strategies and the transition phases between operation and decommissioning. Key technical areas that underpin the D&D activities are plant characterization, decontamination techniques, dismantling equipment, remote operations (including robotics) and land remediation. Active demonstration of new technology is vital to increase the technology readiness and demonstrate the maturity of new approaches.

4.3.3 R&D Topics

The following R&D topics are identified:

- Minimization of waste production by design and material selection and operational measures and development of advanced waste treatment and conditioning technologies;
- Development of efficient dismantling technologies for structures and components including remote dismantling techniques;

- Waste minimization strategies for decommissioning including safe release of material to the environment, recycle/reuse, disposal to very low level waste repositories along with reliable and cost effective activity measurement techniques;
- Learn from current experience and identify and share best practice in waste management and decommissioning;
- Develop characterization techniques for waste inventory assessment and plant and facility assessment to aid planning for decommissioning;
- Innovate enhanced decontamination and dismantling technologies for structures and components, incl. remote dismantling techniques;
- Establish improved treatment technologies (thermal or other) to reuse/recycle materials, minimize waste volumes and to develop robust and passive waste forms;
- Accelerate the introduction of new technologies and technical approaches through inactive and active demonstrations.;
- Waste minimization strategies for decommissioning, including safe release of material to the environment, recycle/reuse, disposal to very low level waste repositories (landfills) along with reliable and cost effective activity measurement and assay techniques;
- Organizational aspects: Standardization of processes, Identification of synergy effects for multi-unit sites or fleet-wide D&D projects, optimization of post-operational phase,
- Change Management from operation to decommissioning organization

4.4 Social, Environmental and Economic Aspects for Research, Production and Use of Nuclear Energy

4.4.1 Objectives and Motivation

To ensure sustainability of nuclear energy production and its position at the future energy market, it is important to focus on the following key aspects and conditions:

- **Safe operation and minimum impact on environment**
  - to keep credit of nuclear power as a low-carbon and environment-friendly source of energy
- **Economy and competitiveness**
  - more exact prediction of safety margins, risk informed support of decision making, fuel cycle optimization, LTO
- **Social and political acceptability**
  - make use of existing and new ways of communication, open policy
- **Ability to survive in changing conditions**
  - NPP operation in changing energy-mix and under new grid codes

All these aspects and conditions are mutually interconnected and conditioned, e.g. safe operation and minimum impact on environment is the best argument in promoting nuclear power in social dialogue. There is number of other social, environmental and economic conditions and aspects important for sustainability and development of nuclear energy, like continuous effort in non-proliferation area, progress in nuclear waste storage field, harmonization of regulatory framework in EU, cooperation and synergies in R&D, ability to build new NPP with predictable costs and schedule, increase attractiveness for young people etc., but the conditions highlighted above are the most critical at present. The ability to adapt to different energy mix scenarios requires better interaction with other energy technologies, particularly with renewables, with a view to identifying an optimal energy system integration.

The major social, environmental and economic aspects are in good compliance with the more general priorities specified in the SET Plan (EC, 2017) for the nuclear energy sector:

- Safety to help securing the long-term operation of existing nuclear reactors
- Safe management of radioactive waste and decommissioning
- Efficiency and competitiveness of current and innovative technologies

Even wider view on the energy system and its 3 key pillars and issues gives the World Energy Outlook (IEA, 2018):

- Affordability
- Reliability
- Sustainability

The sad truth is, that after three flat years, global energy-related carbon dioxide (CO_2) emissions are rising since 2017, far from a trajectory consistent with climate goals. SNE-TP together with its 3 pillars (NUGENIA, ESNII, and NC2I), in collaboration with EERA and its JPNM, can substantially contribute to most of the key tasks listed above, maintaining the safety and competitiveness of today's technologies; developing a new generation of more sustainable reactor technologies; and developing new applications for nuclear power.

4.4.2 State-of-the-art, Challenges, and R&D Topics

Safe operation and minimum impact on environment

In order to achieve safe operation in any power plant and in particular in a nuclear power plant, the following three conditions need to be met:

- A well established and implemented **safety culture**
- Development and application of **state-of-the-art safety assessment tools and methods**
- Consideration of **retrofitting** of **state-of-the-art** (passive) **safety features**

Fission-based nuclear power has historically been one of the largest contributors of carbon-free electricity globally. The potential of nuclear power generation to contribute to the power sector decarbonization is significant. However, it should be noted that minimum impact on the environment must cover all phases of NPP lifetime and nuclear fuel cycle. Overall, EC (2012) shows that nuclear power generation has a low-carbon footprint and low direct plus indirect carbon emissions even considering the complete fuel cycle.

To that respect, the target to decarbonize Europe's economy by 95% by 2050, implying a major reduction in greenhouse gas emissions, calls for nuclear energy to remain a key source of electricity generation. The analyses of EC (2012) show that in all scenarios, centralized large-scale systems such as nuclear and gas power plants and decentralized systems will increasingly have to work together.

Economy and competitiveness

For the nuclear industry at large, it is a major challenge to make nuclear great again. In order to achieve this, long-term operation of existing reactors and deployment of new reactors should be facilitated. In principle, this should be achievable when modifications to existing plants and construction of new plants can be performed under a predictable schedule and costs. This will also mean that a level economic playing field should be created for all low-carbon electricity generation and heat source supply systems. On top of that, investment risks should be mitigated and on a national level investments should be facilitated. As an example, the strike price which is applied in the UK can be considered. On a levelized (i.e. lifetime) basis, nuclear power is an economic source of electricity generation, combining the advantages of security, reliability and very low greenhouse gas emissions (Deloitte, 2019).

In order to make nuclear more competitive from an economic point of view, the following R&D topics deserve attention:

- Deterministic and probabilistic safety assessments in support of enabling on-line maintenance with the goal to increase availability factors
- Advanced deterministic and probabilistic safety assessment methods enabling optimization of safety margins and power uprates
- Retrofitting of state-of-the-art (passive) safety features targeting better operational economy

Social and political acceptability

The SET Plan (EC, 2017) identifies nuclear fission as one of the key low-carbon energy technologies. The intention is to '*maintain the competitiveness in fission technologies together with long-term waste management solutions*'. To this respect, the benefits and drawbacks of nuclear fission should be presented, promoted and communicated in an open and transparent way such that the European citizens can educate themselves in nuclear knowledge and a continuous knowledge transfer takes place not only between experts and the public at large but also between generations. The public should be addressed on such a technical and controversial subject like nuclear fission in a professional way. Nuclear energy should be promoted and presented for what it is, i.e. part of the solution to the climate emergency, beyond prejudices, and in alliance with other low-carbon emission energy technologies, such as renewables, carbon capture and storage, hydrogen and fuel cells. To that respect the following R&D topic are identified:

- Collect technical facts and figures on benefits and drawbacks of nuclear fission. Obviously, a lot is already available, e.g. from organizations like the IAEA, OECD/NEA, SNE-TP and Foratom.
- Translate technical benefits and drawbacks into benefits and drawbacks the public at large can understand.
- Dialogue and ally with other low-carbon energy technologies in technical terms, identifying efficient and consensual ways of integration to be promoted together, as well as research issues of cross-cutting interest that can be faced together;
- Create a pan-European communication campaign allowing the citizens to educate themselves and take their own decisions.

Ability to adapt to changing conditions

Nuclear power plants can play an important role in a future energy mix given their compatibility with renewable energy sources and low-carbon footprint. This is underlined in many recent international studies including studies from EC (2011), MIT (2018), IPCC (2018), IAEA (2018), IEA (2018), and the OECD/NEA (2019).

Including nuclear power plants in such a changing environment, in which fluctuating demands play a significant role through the increased application of intermittent renewable sources such as wind and solar power, poses new challenges on the integration of nuclear plants in the electricity grid. R&D topics will be:

- The impact of intermittent external loads including grid disturbances on safety functions of existing and new nuclear power plants.
- Demonstration and further improvement of nuclear load following techniques.
- The impact of new hazards (e.g. drone attacks, stuxnet viruses) on safety functions of nuclear power plants.
- Dialogue and integration with renewables and other energy technologies that aim at reducing greenhouse gas emissions.

5 Cross-Cutting Technologies

5.1 Digitalisation, Modeling and Simulation

5.1.1 Objectives and Motivation

Digital technology is an essential tool for the competitiveness of the nuclear industry as it is for other industrial sectors such as aerospace or automotive. All the three SNE-TP pillars are involved in this digital transformation, while EERA is creating a whole joint program devoted to these issues, transversal to all energy technologies. The main objective of digitalization, modelling and simulation is to increase safety and competitiveness for the operation and maintenance of existing NPPs and for new build. It will also enable improved cooperation between partners of the nuclear research sector.

The development in the field of modelling and simulation has to reach three goals:

- adapt and accelerate the coupling between existing calculation codes by improving interoperability,
- Unify and make consistent numerical applications by linking the world of advanced expertise studies and industrial modelling;
- Benefit from breakthroughs in advanced visualization technologies (including virtual reality and augmented reality).

5.1.2 State-of-the-art and Challenges

Digital transition is not a totally new subject for nuclear. Digital tools have been widely used since the 1970s for the simulation and modeling of complex physical phenomena or for process control. Nuclear research has often been at the forefront of innovation mainly because of stringent safety requirements.

However, the current digital revolution encompasses new dimensions: the recent speed up of technological progress in terms of computing such as:

- **High Performance Computing** (HPC),
- **Artificial Intelligence**, a.o. machine-learning algorithms, deep artificial neural networks, gaussian processes and few-shot learning,
- **Virtual** and **augmented reality**,
- the extension of digitalization to the **entire life cycle** from the design stage up to the dismantling of nuclear units,
- the need for **digital continuity** to ensure that all stakeholders (i.e nuclear operators, academia, industry,..) can exchange information more efficiently.

Recent technological breakthroughs are for example the development of the Internet of Things and therefore the increase in data flow, significant development of Artificial Intelligence whether due to the efficiency of algorithms or to enhanced computing power. In terms of applications, digitalization will include reactor design (Generation III and IV) with advanced simulation tools, facility operation and maintenance via virtual imaging, augmented reality and artificial intelligence tools, and dismantling using robotic operations.

Considering modelling and simulations, the general trend can be summarized as **multi-scale, multi-physics, multi-phase plus uncertainty quantification**. Driven by progress in computational power and increasing understanding of separate processes, numerical simulations are expected to enter a domain of increased complexity. As a complement and enhancement or an alternative to physics-based simulation tools, data-driven modelling is currently booming, thanks to the progress made in data analysis using machine-learning techniques.

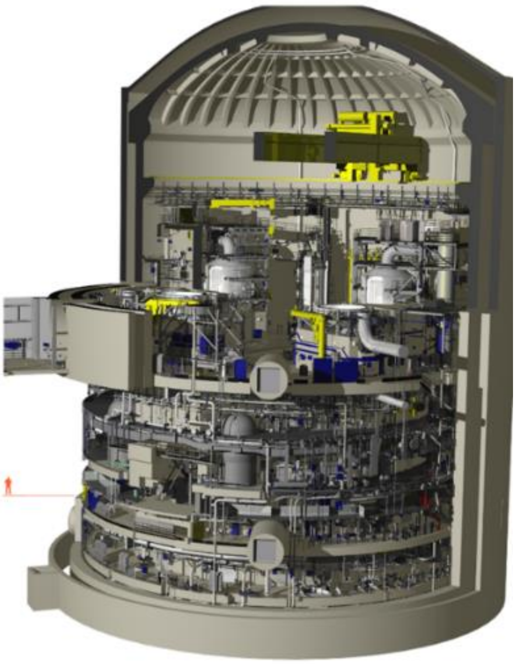
Multi-scale simulation refers to applying and possibly linking simulations of physical processes at the appropriate scales, e.g. atomic, microscopic, mesoscopic, component, system and plant scale. The development of tools operating at different scales aims at coupling simulation methodologies in single multi-scale packages. However, in this respect machine learning techniques offer the possibility of complementing a multi-scale modelling package, which will be most likely penalized by long computing times that are characteristic of high fidelity simulation tools, with a single artificial intelligence-based tool, to be trained on multi-scale physics-based suites of codes.

Multi-physics simulation refers to linking simulations of different physical processes and domains, e.g. neutronics, thermal hydraulics, structural mechanics, fuel performance and chemistry. Here the key issue to link models consists in the identification of the variables coming from one domain that are needed for another domain. Because of the mutual influence, iteration is necessary and may be a bottleneck. In addition, because of the often local type of information that needs to be obtained, there is a conceptually unavoidable overlap between multi-scale and multi-physics approaches.

Multi-phase simulation is mostly used with reference to thermal hydraulic simulations and refers to the simultaneous simulation of various phases in which a substance can be, i.e. gaseous, liquid, or solid.

Uncertainty quantification is becoming more and more important and is expected to be requested by regulators for all kinds of safety analyses in the future. Uncertainty quantification for advanced and complex simulations with long run-times needs to be developed. In particular, in the case of multi-scale/multi-physics simulation, the development of appropriate and efficient methods for the evaluation of the uncertainty related to the choice of key parameters and its propagation through different simulation tools and models remains a challenge.

Such developments can be summarized as a major challenge for the nuclear industry being the construction of a European **digital nuclear reactor** in order to model the design, operation and maintenance, in normal or accidental operation for all kinds of nuclear technology, ranging from Gen II and III LWRs, to SMRs, and Gen IV systems. In fact, the goal is to simplify modelling and secure safety margins by a demonstration approach based on simulation. The use of a multi-scale, multi-physics, multi-phase digital reactor from the design stage is an innovative approach. As such, **digital twins** will gather on a large base several numerical and physical schemes, optimization models or uncertainties quantification techniques. As a rule, the basic elements (1D or 3D codes) are available among the nuclear community even though development is an on-going process. Obviously **interoperability** of necessary modelling and simulation tools requires the development of simulation platforms, that should be provided with appropriate 'translators' to efficiently pass information between codes, possibly by-passing computing time bottlenecks by making use of artificial intelligence..



Human-Automation Collaboration for **Operation and Maintenance** is an open area for research by boosting digital innovation in support to the performance of nuclear operators in order to improve flexibility of nuclear units, prepare I&C upgrades, invent and test new operational concepts for new reactors such as SMRs. Challenges are technical with the development of digital twins reflecting the actual state of the facility as well as organizational (enhanced agility, resilience).

To analyze operation and maintenance data in order to optimize maintenance and replacement investments for large components in nuclear plants, **data analytics** tools have to be developed. Technical issues lie in the definition of robust indicators for the diagnosis of nuclear units (to obtain more reliable data and to process non-homogeneous and large data volume), and to determine duration of residual lifetime of components (monitoring data, physical degradation models). Developments in this area are of course connected with the capability of interpreting in a physically correct way the signals coming from sensors, which is in turn connected with the development of multi-scale and multi-physics models mentioned above.

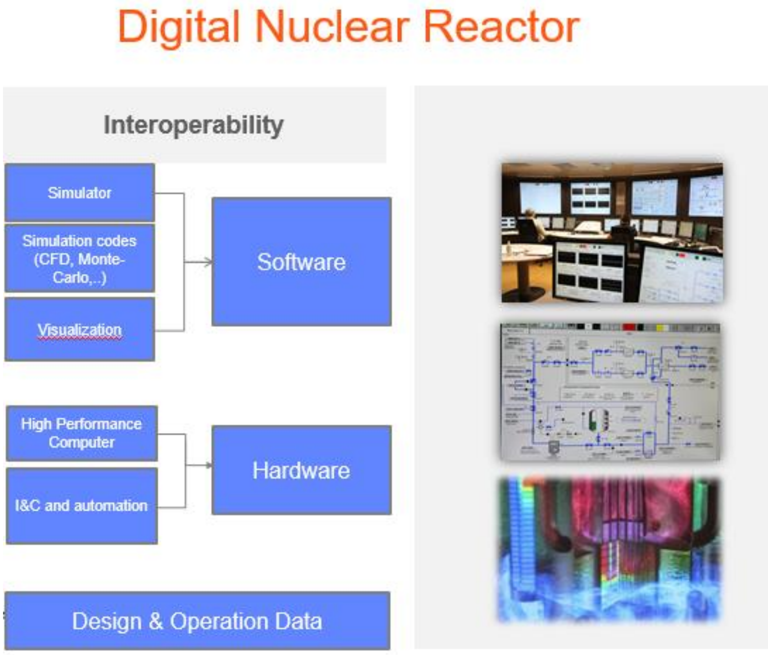
A key enabling technology to all digitalization challenges lies in **cybersecurity**, making digital systems secure. The ultimate aim is to integrate cybersecurity from the design stage (from idea to completion) and to eliminate digital risks. One of the challenges is to integrate cybersecurity into all digital technology steps. The major hurdles lie in the introduction of new intrinsically secure technologies (e.g. programmable logic integrated circuits, network diodes) and in the effective detection of unknown or complex computer attacks by the combination of big data analysis tools and Artificial Intelligence.

5.1.3 R&D Topics

Sharing experiences and best practices in this field of a '**European Digital Nuclear Reactor**' should remove major scientific and technical hurdles. From a technology standpoint, it implies:

- Development and validation of **multi-scale** analysis tools for various kinds of physics ranging from material science, to thermal hydraulics, and chemistry.
- Development and validation of **multi-physics** analysis tools, coupling different physical processes, e.g. neutronics, thermal hydraulics, structural mechanics (with input from microstructural evolution predictions), fuel performance and chemistry. In first instance establishing a multi-physics tool coupling two individual processes will be required, however, since nuclear systems are highly interdisciplinary, eventually the goal will be the interoperability of multiple (if not all) physics analysis tools.
- Development and validation of **multi-phase** analysis tools for better understanding of multi-phase flow and heat transfer in a reactor which is an essential element in nuclear safety analysis and as such also important in the design phase.
- Development and validation of **uncertainty quantification** methodologies especially for complex long running simulations including multi-scale, multi-physics, multi-phase platforms, and its propagation through scales and methods.
- Development of methodologies to ensure **digital continuity** over the complete **life-cycle** of a nuclear reactor, including methodologies in support of operation and maintenance.
- Determination of **robust indicators** through data-analytics for diagnosis of operation and maintenance of nuclear units and to determine duration of residual lifetime of components.
- Integration of **cybersecurity** in the digitalization process to eliminate digital risks throughout the life-cycle.
- Increasing development and use of **artificial intelligence** through machine learning techniques to enable progress in all above fields: link and interface between scales and physics, removal of bottlenecks related with long computing time of high fidelity simulation tools, development of artificial intelligence-based by-passes trained on physics-based packages, analysis of large quantities of data.
- Increasing development and use of **virtual** and **augmented reality** tools, particularly in support of design, operation and maintenance.

All these developments will enable the development of **digital twins** of nuclear buildings and facilities. The objective is to address challenges of site optimization and of operators training through immersive preparation. Associated challenges in terms of R&D are to add ever more intelligence into digital models by using artificial intelligence and to broaden its use as much as possible to operational issues, with enhanced interaction by the use of virtual reality.



5.2 Materials

5.2.1 Objectives and Motivation

Although the needs may be somewhat different, research and development on structural (and a few functional) materials is of utmost importance for both operating reactors and future reactors.

In the case of current GenII-III reactors, the materials are established and there is operational experience on their use for specific components, having therefore clearly identified most criticalities. There are precedents of replacement of materials in key components, such as steam generators. Moreover the materials for the fuel assembly, especially for the cladding, are likely to be evolving in the near future to improve accident tolerance (see section 4.2). Finally, advanced Gen III LWRs may adopt incrementally optimized structural materials, if identified and available. However, the interest in new materials for current generation reactors is limited, even though some specific metallic alloys raise potential interest in perspective. What is mainly needed is an ever deeper knowledge of the rate at which degradation during operation occurs in the materials that are used in the reactor, in order to estimate and predict the residual life with increasingly greater precision and to assess the degree of safety of extended operation. This knowledge will improve the schedule of inspections, while moving towards a more and more automatized and continuous monitoring (see section 3.2), which becomes crucial for irreplaceable components such as the vessel, the containment and, in practice, cables as well. This knowledge will also be useful in connection with the need for component replacement. As a matter of fact, in an LTO perspective there is a need not only to predict the component life time, but also to replace specific components. In order to optimize replacement and repair scenarios, reducing costs and possibly also further increasing the lifetime of the components replaced/repaired, advanced manufacturing routes are of specific interest. These fabrication methods are also expected to impact new LWR builds, reducing costs and including the possibility or modifying the design of some components for better efficiency. New builds may also adopt new types of concrete.

Regarding next generation reactor concepts, the development of new material solutions is crucial. This is so because of the use of non-acqueous coolants, with different compatibility features and requirements as compared to LWR, and the higher temperatures that are targeted (either for higher thermal-to-electricity conversion, or because of the goal of industrial heat production, or even simply as a consequence of the coolant requirements), as well as the high burnup that is aimed at. In the case of systems for which reasonable operational experience exists, e.g. the SFR or the HTR, the materials solutions are more or less defined, thus the needs are mainly related with selecting, qualifying and codifying existing materials for the conditions expected in those reactors (pre-normative research), even though of course materials with improved high temperature resistance properties would certainly be of use, especially if they can be timely codified. However, for technologies such as the LFR, which has already reached a sufficient level of maturity to be designed and constructed, the identification and development of suitable materials solutions to enable temperature increase, while guaranteeing sufficient resistance to coolant attack, are key both for improved safety and economic viability reasons (similar considerations may be made for the SCWR). Finally, the feasibility of systems such as the VHTR, the GFR, and largely also the MSR, the technological readiness level of which is still fairly low, depends crucially, among others, on the identification and development of suitable materials solutions to withstand the target temperatures, including of course accidental conditions, and/or the highly corrosive nature of the coolant. The development of new materials implies then the application of a (possibly accelerated) methodology for qualification and codification, as well as the development of equally qualified welding and joining techniques. The needs in the case of materials for future systems, particularly for fast reactors, are extensively discussed in EERA-JPNM (2019).

Concerning SMRs, while the materials issues are expected to be largely the same as in the case of their large-scale counterparts that use the same coolant and target the same operation temperature range, specific issues may arise in connection with the different size and the need for modularity. This may suggest material changes or require specific materials solutions, which should be identified and carefully looked into.

Irrespective of the different needs and challenges concerning current and future reactors, several aspects are of cross-cutting nature. These have been analyzed in some detail in EERA-JPNM (2019) and are summarized in section 5.2.3.

5.2.2 State-of-the-art and Challenges

LWR

The ageing management in view of LTO currently relies on four key stages:

1. Identification of systems, structures and components that are sensitive to ageing
2. Examination of all SSC/ageing mechanism pairs retained in the form of an Ageing Analysis Sheet (AAS)
3. Elaboration of a Detailed Ageing Analysis Report (DAAR) for most sensitive components and structures
4. Production of a Unit Ageing Analysis Report (UAAR) valid for the decade following the 3rd 10 year outage of each unit SSC long term O&M strategies;

These reports need to provide a diagnosis of the status of sensitive SCC and a maintenance planning, the prognosis for 60 years in view of LTO, including in particular the analysis of the risk of obsolescence (supplier loss, technology evolution, norm evolution…), SCC replacement and/or repair scenarios if relevant, and of course the corresponding investment planning. The challenge in connection with LTO is thus to improve the reliability of the prognosis to the number of years of life extension, while reducing conservatism and optimizing the replacement/repair scenarios in terms of investment needed. Relevant issues concern both replaceable and irreplaceable components. The strategy, repeats itself component by component: understand mechanisms and develop reliable predictive models of materials ageing, NDE and online monitoring, establish robust criteria for integrity and fitness-for-service assessment, and improve materials solutions (or design if possible) in the case of replaceable components. The **replaceable components** affected (and the relevant issues) are mainly: reactor internals (irradiation assisted stress corrosion cracking, swelling and wear), duplex austenitic-ferritic steel pipe elbows (thermal ageing) and steam generator secondary pipes (fouling, clogging, stress corrosion cracking). The **irreplaceable components** affected (and the relevant issues) are mainly: reactor pressure vessel (embrittlement) and concrete containment (creep, drying and subsequent leakage). Finally, although not structural materials and strictly speaking not irreplaceable, cables and specifically the polymers used for cable insulation need to be included in the list of sensitive components: they are in practice irreplaceable, due to the incredibly large number of kilometers of them that are laid out in each NPP.

The most promising advanced manufacturing techniques for the replacement and in general the fabrication of nuclear components, as alternative to classical forging or casting, are based on powder metallurgy:

- Hot Isostatic Pressing (HIP) allows shape and material homogeneity and composition to be controlled and is especially suitable for heavy components. It is therefore currently considered for the replacement of elbow pipes, that have been so far produced by casting. In the future this method may enable the fabrication of pipes with integrated nozzles (thereby minimizing the need for welds) and of components that need superior wear resistance (by suitably choosing the powder composition on the surface).
- Additive Manufacturing (AM) is especially suitable for components of complex geometry, but currently limited in terms of component size. It is therefore considered for small components with complicated shapes, for which suppliers are often difficult to find.

Both techniques offer the possibility of reducing manufacturing delays when obsolescence occurs, with the possibility of improving the design, because the shape of the component is not any longer limited by manufacturing. However, several R&D challenges remain before the application in nuclear industry can become a reality:

- Improve the controllability and reproducibility of the process, understand how the process limits the final component/materials properties and its correlation with the type of microstructure and thus properties obtained,
- Improve the component quality (especially in the case of AM), in terms of homogeneity, minimal porosity, correct density and microstructure, minimal residual stresses (by suitable post-treatment), etc.,
- Demonstrate compliance of the final product with nuclear requirements (regulators), verifying that the ageing behavior (e.g. resistance to irradiation and corrosion) is comparable to components fabricated with traditional methods

It has to be emphasized that these techniques make the material properties related to the type of component that is fabricated, because this will influence microstructural features, porosity, residual stresses. Therefore, the standards for the qualification need to be developed not really for the material as such, but actually for the component made with a certain material according to a certain process. The materials of interest are mainly austenitic stainless steels and nickel-based alloys, as well as, to a lesser extent, zirconium alloys.

In terms of improved nuclear safety, the main challenge for Gen II & III reactors is accident tolerance, which implies improved fuels but especially, in practice, cladding materials with higher thermomechanical stability. The objective is to design and qualify fuel casings that can remain intact for a sufficiently long time even when subjected to the high temperatures and mechanical stresses typical of a nuclear accident. Accident tolerance is intrinsic to HTRs and is being developed for LWR, but the concept will have to be extended also to fast reactors and other innovative reactors. The material solutions proposed range from chromium-coated zirconium alloys to refractory metals and ceramic composites. These materials require, in order to be adopted and used in reactors, all the necessary qualification, thereby calling for an accelerated qualification process.

Advanced reactors

The deployment of advanced reactors requires demonstrators and prototypes to be built as first steps. These are not expected to include all the features of true Generation IV systems, but are meant to be a step in that direction, generally through different phases. Since the main limiting factors in terms of component lifetime are temperature, coolant attack and irradiation, for which in most cases suitable materials are not available. The idea is to start with relatively modest temperature and also irradiation levels, to be increased in subsequent phases. In this way the research on materials can be split into several steps or stages from the initial one to the final one, which can be denoted as *near term* and *long term,* with intermediate stages in between. The classes of materials that are expected be used to design and construct advanced reactor demonstrators, prototypes and then commercial reactors, including the different intermediate phases, have been analyzed in detail in EERA-JPNM (2019).

In the near term, materials for which operational experience already exist will be used. These will be exposed, taking as example the LFR demonstrator, to temperatures not higher than 400°C, and negligible neutron damage, in the case of the main vessel, and to temperatures between 450°C and 500°C, subject to weak neutron damage, in the case of the internals of the reactor. Even the core structures, unavoidably exposed to intense neutron damage, will not exceed 550°C as maximum operating temperature. This approach allows material R&D in the first phase to be limited, the fuel elements being replaced with a frequency higher than the standard, in order to better control the damage evolution, allowing the qualification of materials for the next phases.

The materials of interest for all fast reactor demonstrators, on which the qualification and pre-normative research effort needs to be mainly focused, are austenitic stainless steels for structural functions, such as 316L nickel-based alloys are considered for some out-of-core applications, while for some specific components of specific designs, ferritic/martensitic steels have also been chosen. Ceramics composites (mainly silicium-carbide (SiC) fibers) will be necessary for the high temperature operation of e.g. a GFR demonstrator, but these materials are currently still far from being fully qualified, therefore even in this case for the demonstration lower temperatures and known materials will be most likely used. Surface protection may be necessary already for demonstrators to provide sufficient compatibility with coolants, especially in the case of the LFR.

Improvements of safety, performance and economy in future prototypes and then commercial reactors advises the exploration of improved (more swelling resistant) austenitic steels, advanced (creep-strength enhanced) ferritic/martensitic steels, refractory alloys, oxide dispersion strengthening via powder metallurgy, advanced surface protection methods (from ceramic coatings to self-healing protections by addition of aluminum to the steel compositions: alumina forming austenitic steels, and ferritic iron-chromium-aluminium steel) and, for the longer term, prospective materials such as high entropy alloys or so-called MAX phases. Especially challenging is the development of a methodology to accelerate material development, screening and qualification. In the absence of such a methodology, innovation in the field of nuclear materials will require decades, i.e. too long times to be flexible and competitive.

In the long term, the challenge for the materials is to bring the maximum temperatures of the thermal cycle of the reactor closer to the boiling temperatures that characterize the non-moderating coolants: ~880°C for sodium, ~1700°C for lead and further higher for the helium. An ambitious but reachable target for SFR and LFR could be placed at 750°C for core structures, and 650°C for internals. In the case of GFR, the target temperature should be set at 900°C. At this stage the R&D carried out during the previous stages will have allowed the complete qualification, even under neutron load, of at least some among the most promising materials mentioned above. The qualification must also include suitable welding and junction methods.

5.2.3 R&D Topics

LWR

In order to reduce conservatism in the margins currently used for the safety assessment of existing LWR components, it is necessary to develop advanced fracture mechanics approaches and new methods for environment assisted fatigue assessment, that guarantee transferability from specimen to component. The former applies especially to the reactor pressure vessel (RPV, see below), but also to the turbine blades and disks or to the cylinder heads of the diesel engines. The latter applies to hydraulic thermal mixing zones, stratification zones, flow distribution baffle of the steam generator, etc. In order to optimize replacement/repair scenarios, a number of challenges can be identified, that are related to specific classes of components:

- Reactor internals:
    - Model irradiation assisted stress corrosion cracking (IASCC) using a multi-scale, multi-physics approach, that should include thermo-hydraulics, neutronics, materials microstructural processes and mechanical conditions of the component (stress distribution). Models should allow IASCC susceptibility to be evaluated, especially in baffle bolts.
    - Develop an overall assessment procedure to guarantee the efficiency of tube guides, which should include test and modelling of swelling effects, test and modelling of wear and improved resistance against it (new materials solutions), as well as effects of vibrations due to thermal-hydraulics.
- Duplex austenitic-ferritic pipe elbows:
    - Develop a methodology that enables a correct residual lifetime prognosis, by designing 60-year-equivalent thermal ageing program and subsequent characterization and an appropriate NDE scheme (e.g. thermo-electric effect measurements).
    - Evaluate alternative solutions, such as: regeneration of material properties by thermal treatment, use of powder metallurgy (Hot Isostatic Pressing, HIP) for austenitic-ferritic cast iron elbow replacement.
- Steam generators and secondary pipes:
    - Extend the service lifetime by better understanding and modelling, and thus preventing, fouling/clogging, as well as stress corrosion cracking.

In order to perform a correct residual lifetime assessment for irreplaceable components, a number of component-specific challenges stand out as well:

- Reactor pressure vessel:
    - Develop physics-based models for RPV lifetime prediction in terms of fracture toughness degradation (embrittlement), as a consequence of irradiation and thermal ageing.
    - Use the knowledge of fracture toughness degradation to assess the RPV resistance to a pressurized thermal shock in case of a loss of coolant accident (LOCA)
    - Gain margins in terms of thermo-hydraulic loading, in case of a LOCA, by using 2-phase flow CFD simulation and crack analysis with warm pre-stress effect, as well as by improving NDE of RPV nozzle welding
- Civil engineering buildings (concrete of containment):
    - Guarantee long-term tightness by combining leak rate tests, cement and concrete testing, suitable NDE technology and appropriate maintenance strategies, while developing tools to simulate concrete ageing (creep, drying, ...) and the mechanical behavior of the reinforcement bars.

Concerning cables, in order to guarantee life extension beyond 40 years, tools need to be developed for a robust demonstration process. Similarly to the case of RPV and containment, these include physico-chemical modelling of polymer ageing due to temperature and irradiation, NDE and monitoring of cables and related diagnostic methods and criteria for qualification and fitness for service.

Advanced reactors

The R&D materials topics related with advanced reactor systems are necessarily broader and less specific than in the case of LWRs, because the relevant operational experience is limited. Thus what is needed is first and foremost the qualification of the candidate demonstrator materials (mainly austenitic steels of the 316L family, and 15Ni-15Cr titanium stabilized for the cladding), or materials solutions (e.g. ceramic coatings on top of traditional materials, for greater resistance to the chemical aggression of the coolants), for the correspondingly expected operating conditions. The construction of demonstrators is expected to be the crucial step that will subsequently trigger and open the way to the identification and qualification of materials that allow the following phases to be addressed.

In perspective, the requirement of 60 years design lifetime for non-replaceable components is the most demanding requirement, which includes under its umbrella several R&D issues, that are related with the reasonable prediction of long-term degradation processes. These include:

- High temperature processes (creep, fatigue, thermal ageing);
- Compatibility with (heavy) liquid metal and helium coolants;
- Effects of low flux prolonged irradiation.

Emphasis is on welded components in all cases.

In terms of testing, there is a need for standardization, especially for sub-size and miniature specimens. The modelling, from atomistic simulations, through mesoscopic approaches up to macroscopic constitutive models, supported by advanced microstructural and mechanical characterization, has as its main objective the development of suitable microstructure evolution models to be used as input to models for the mechanical behavior under irradiation and at high temperature, eventually linking with fracture mechanics. Specific developments are required for coolant compatibility models, as well as for models in support of the use of charged particle irradiation for the screening of new materials solutions.

Cross-cutting

Overall, the following R&D issues can be considered cross-cutting through different reactor generations:

- Advanced manufacturing in a broad spectrum methods will benefit both current and future reactors;
- Any activity related with understanding physical mechanisms and developing relevant models, by this meaning multi-scale modelling, use of artificial intelligence, application of accelerated exposure techniques such as ion irradiation for specific studies, and the relevant methodology, are common;
- Materials with better resistance to high temperature and corrosion after irradiation, which are a must for advanced reactor systems, can also be beneficial for future LWR, especially in an improved accident tolerance framework (most candidate ATF cladding material coincide with candidate cladding materials for advanced reactors, ranging from creep-resistance enhanced steels, ferritic or austenitic, to refractory alloys and ceramic composites);
- Methodologies related with materials qualification, especially of welds and joints, internal stresses evaluations and online monitoring at large, are beneficial for all reactor generations, despite differences in the specific application. Small specimen size testing can be included in this list, for better exploitation of limited irradiation facilities and limited space in them. The qualification of components fabricated using advanced manufacturing techniques require global qualification methods, given that the properties of the material are not independent of component manufacturing process, shape and type: here, too, the methodology to be developed and applied is common.
- The use, and therefore maintenance and coordinated planning, of nuclear materials exposure and testing infrastructures is also of common interest, notwithstanding neutron spectrum differences depending on the target technology (see section 6.1).

It is finally important to emphasize that many of the above reactor generation-common issues, as well as those related with compatibility with heavy liquid metals and gases for advanced reactor systems, are cross-cutting with nuclear fusion materials. Furthermore, structural materials with superior corrosion and temperature resistance that may be developed for nuclear applications have a potential, as happened in the past, to be of use for other energy technologies where high temperatures and corrosive fluids are part of the picture, such as concentrated solar power, geothermal energy, fuel cells and bioenergy.

6 Non-Technological Cross-cutting Aspects

6.1 Research Infrastructures

6.1.1 Objectives and Motivation

EC (2019) underlines the need to ensure availability of state-of-the-art research infrastructures (in particular for materials research and innovation, irradiation facilities, nuclear safety, research reactors and hot cells). Current initiatives in France with the Jules Horowitz Reactor (JHR, http://www-rjh.cea.fr/), in Belgium with the MYRRHA initiative (https://myrrha.be/), and in the Netherlands with the PALLAS reactor (https://www.pallasreactor.com/) should get political support from all SNE-TP members ensuring at the end of the day sufficient financial support to realize these capital intensive projects which have a large impact on the future of the European nuclear research infrastructure. An important boundary condition is a financially sound basis for the operation of the infrastructure. Current-day models do not sufficiently account for the increasing costs imposed by measures in the field of, among others, security and waste handling, endangering access and availability of these infrastructures.

6.1.2 State-of-the-art and Challenges

As a starting point, a ‘picture’ can be taken of the current situation. This describes the state-of-the-art. Such ‘pictures’ mostly result in a database of existing and (near) future infrastructures in certain domains of interest. Around the year 2010, the OECD/NEA took an initiative create a database of research infrastructures for gas and sodium cooled fast reactors documented in OECD/NEA (2009) and (2010). In parallel, the European collaborative project ADRIANA made databases of research infrastructures for fast reactors documented in ADRIANA (2011). More recently, an initiative was taken by NUGENIA to collect a database of research infrastructures for light water reactor applications which is available as NUGENIA (2016). This NUGENIA database contains more than 180 experimental facilities amongst which Material Testing Reactors, critical mock-ups, training reactors, hot cell laboratories, chemistry-corrosion labs, mechanics-materials labs, measurement labs, severe accidents setups, and thermal-hydraulics test loops. And finally the IAEA (2018) documents research infrastructures for liquid metal cooled reactors. With respect to these databases, the main challenge is:

- Collecting, updating and maintaining research infrastructure databases internationally at one place.

Nevertheless, a database is just a starting point. More important is to maintain and upgrade the facilities themselves and to construct new ones if there is a need to. As mentioned before, an important boundary condition and main challenge is:

- Creation of a financially sound basis for the operation and maintenance of these infrastructures.

6.2 Harmonisation

6.2.1 Objectives and Motivation

As stated in Nuclear Illustrative Programme (EC, 2017), the construction of new nuclear units will be necessary in the future in Europe to satisfy the energy objectives of the European Commission (EC). This program encourages vendors and suppliers to engage in an initiative to standardize their components and codes to a higher degree in order to ensure:

a. a faster procurement process;
b. higher compatibility and more transparent and higher safety standards;
c. increased capacity of operators to control technology and knowledge management.

Among them, the most challenging task is harmonization of safety standards. Because nuclear safety is a national responsibility, national regulators are independent and we face 29 different sets of safety rules in EU. It is not widely appreciated yet, that the independence of judgement does not exclude cooperation in preparing or harmonizing safety standards. Below we mention some initial efforts, but they are by far not enough and further cooperation between regulators should be encouraged.

This is especially important for Generation IV innovative reactors. LWR standards have been developed over many years from practical experience and therefore they are at least conceptually coherent between different countries. This is certainly not the case for advanced reactors. There is a risk, that regulations concerning advanced reactors will be so different that the EU market will be split into several regions requiring different designs. This might be an important barrier in deploying Generation IV reactors in Europe.

6.2.2 State-of-the-art and Challenges

EUR Requirements

One of the first initiatives in Europe to standardize nuclear reactors and harmonize safety requirements was launched in the early nineties when the main European nuclear utilities that were considering to build new reactors in the 21st century, convened to establish common design targets directed to potential reactor vendors interested in the nuclear European market and formed the European Utility Requirements (EUR) organization. Interested vendors submitted applications for their products to be assessed by the EUR organization through a comprehensive process to analyze the degree of compliance with these requirements. Several reactors types have been assessed including the reactors from AREVA, Westinghouse, GE, AEP Moscow, and most recently from Mitsubishi and CGN. The EUR document has been used by some utilities to define technical specifications associated with their call for bid of nuclear projects. It is regularly updated to integrate new knowledge, the feedback from the assessments and the evolution of regulatory requirements. The last version (revision E) comprises more than 4500 requirements and integrates the lessons learnt from the Fukushima accident.

WENRA Reference Levels

Another initiative came from the European regulatory side in the early 2000s, when the WENRA organization was created to define common safety requirements (termed Reference Levels) applicable to reactors operating in Europe. Although these safety requirements are not legally binding, all members of WENRA are committed to include them in their national regulation. In November 2010, WENRA published safety objectives of new nuclear plants so that the new plants will be even safer than the existing ones and these news plants will have very high and comparable levels of safety.

EU Nuclear Safety Directive

In 2009 the European Union issued a Nuclear Safety Directive that established high level safety principles and a common regulatory safety framework. This Directive was subsequently updated after the accident at Fukushima to include safety objectives consistent with the WENRA requirements as well as some new technical ones.

ENEF Roadmap Towards European Reactor Design Acceptance

In 2011, at the request from the European Commission, and in the framework of the European Nuclear Energy Forum (ENEF), a report was produced to make progress in harmonizing licensing processes in Europe. This report, entitled “Road Map Towards European Reactor Design Acceptance”, aimed at allowing deployment of standardized reactors in Europe through harmonization of licensing processes. This ENEF report makes recommendations to develop in national licensing regulations “stand alone design reviews” where a design could be assessed independently of a specific project, with a process similar to the Generic Design Assessment in the UK. It also suggests European regulators to closely work together in reviewing a design proposed by vendors and to conduct joint assessments. The report calls also to the European nuclear industry to harmonize industrial nuclear codes and standards. These industrial codes and standards define how to comply practically with safety requirements of higher level. Although design codes are mainly developed by industry, the regulators rightfully want to approve them as they are the basis of the detailed design and construction activities, or at least to assess their compliance with national regulations.

6.2.3 R&D Topics

The main challenges for SNE-TP in the harmonization field can be identified along several initiatives.

Harmonization of the codes and standards

Taking the nuclear codes of AFCEN (e.g. RCC-M) as a starting point, since 2014, AFCEN intends to explore a generic pattern for “Europeanized” codes that can be adopted for any nuclear project in the EU, primarily for new build but also potentially for improvement and life extension of existing nuclear facilities. The workshop is organized with three specialized “prospective groups” covering a specific technical area addressed by the AFCEN code and based on the above mentioned structures:

- PG1: mechanical equipment for Generation II and III reactors (with reference to the RCC-M code);
- PG2: mechanical equipment for Generation IV reactors (with reference to the RCC-MRx code);
- PG3: civil works (with reference to the RCC-CW code), covering Generation II and III as well as Generation IV.

Continuation of the work through a follow-up that will take into account the experience of the present phase in order to exploit the work done in phase 2 and further improve its process should be considered with a view to:

- Include more reference to non-nuclear high quality industrial standards;
- Enlarge the scope to take into account in service inspection and life management;
- Link between the safety class of Structures, Systems and Components and quality requirements.

In order to enhance the harmonization of the Design Codes at EU level, the AFCEN research and development proposals need to be taken into account.

Partnership with other industry

Modernization and optimization of the European nuclear industry supply chain

The European Commission held a seminar on 28th October 2016 in Brussels in order to support the project based on the modernization and optimization of the European supply chain for nuclear components. The 20th of March 2017 the task force examined the term of reference of the workshop. The goal of the proposals is to modernize and optimize the European nuclear industry supply chain by ensuring that the European nuclear industry benefits from the rapid developments and technological possibilities offered by the non-nuclear industries as well as the non-European nuclear industries, while still guaranteeing the harmonized European nuclear safety level. This requires a mutual recognition and presumption of conformity of simplified processes by which compliance can be shown, between the world of the safety requirements and the physical world of the safety class SSCs.

Greater use of High-Quality Industrial Grade Items in European Nuclear Installations

The trade association for the European nuclear industry, FORATOM established a Supply Chain Optimization Working Group (SCOWG) to explore challenges and current industry practices to optimise the supply chain. Throughout 2019 the SCOWG have conducted activities in this field and will in 2020 publish a report outlining how greater use of high-quality industrial grade items in nuclear installations via a common European harmonized way is a means to further enhance safety, competitiveness and availability of the nuclear industry.

Benchmarking Nuclear Technical Requirements

Benchmarking of nuclear technical requirements against WENRA safety reference levels, EU regulatory framework and IAEA standards should take place in order to contribute significantly to more rapid and generic licensing of nuclear new builds and to extend the operational life of existing reactors. To achieve this, the following initiatives are taken:

- Benchmarking of the EUR documents against all applicable WENRA reference levels IAEA standards and the of the amended directive on nuclear safety as detailed by the EC;
- A feasibility study to extend the ETC nuclear codes of AFCEN to other national legal frameworks and other type of reactors than the EPR;
- A detailed description of the technical content that **an EU common pre-licensing process** should include, taking into account the different types of reactors, the applicable safety standards and the diversity of Member States national framework;
- A set of **technical reference guides for LTO should be prepared covering in particular aspects related to the safety upgrades**. In addition, a benchmarking of national LTO programs against the amended directives will be defined and described particularly regarding art 8a and 8b of amended nuclear safety Directive, for future use by regulators.

This study has been submitted through a call for tenders in November and December 2016. The study started in July 2017.

Analysis to support implementation of Articles 8a–8c of Council Directive 2014/87/Euratom

This project is part of the European Commission's activities to support EU Member States, competent regulatory authorities, and licensees in the effective implementation of Council Directive 2014/87/Euratom by facilitating the sharing of experience, and to **promote more consistent and ambitious implementation of these provisions at the EU level**. For this purpose, the Commission is already working with Member States and competent regulatory authorities (notably through ENSREG) to discuss national approaches and to identify further work to support more convergence in the implementation of the nuclear safety objective. This project is complementary to the activities with ENSREG and designed to inform and identify future areas of work and priorities of the European Commission in that context. This study is ongoing since beginning 2018.

OECD NEA Nuclear Innovations 2050 (NI2050)

The goal of the exercise launched by the OECD/NEA is to identify areas of most needed or most promising innovations and to find a way to speed up their route to practical applications. The first goal has been already achieved, while the second one is just about to be addressed. Among the priorities identified by NI2050 are development of common licensing framework for High Temperature Reactors (HTR), and acceleration of procedures for new fuel qualification based on advanced modelling and development of suitable structural materials for advanced reactor applications. Following the contribution of SNE-TP/NC2I, a possibility of launching an international common project on the first issue is being considered by the OECD/NEA, while the activities concerning fuel and structural materials, the latter largely in connection with the EERA-JPNM, are mainly being addressed through fora devoted to coordinate irradiation programs, as well as delegating activities to NEA working parties.

IAEA activities

The International Atomic Energy Agency conducts several activities related to long term operation, safety of NPPs, and requirements for advanced reactors. Among them is the Technical Working Groups on plant life management, SMR's and others.

In 2017 IAEA organized with NUGENIA, JRC and EPRI an international conference on plant life management with more than 450 experts worldwide. In November 2018, the IAEA published a common report with GIF titled "Safety of High Temperature Gas Cooled Reactors".

Initiatives follow-up and Challenges

Support to the aforesaid initiatives emphasizing their potential contribution to the improvement of rules, practices and methodologies will be beneficial. The valorization by SNE-TP will include exploitation of these projects results. For doing that, SNE-TP will rely on a systematic and continuous dialogue among the stakeholders of the projects.

6.3 Education, Training and Knowledge Management

6.3.1 Objectives and Motivation

High quality education and training are vital aspects of any sustainable nuclear energy program. They require universities and training organizations to work together with industry and regulators, as well as governments in some countries, to ensure the required quality and quantity of the workforce. The first signs that nuclear higher education might be dwindling were noted and reported in high-level documents at the end of the 20th century. These documents included comprehensive sets of bottom-up and top-down recommendations to preserve and improve nuclear higher education and training.

Many initiatives followed, including the establishment of the ENEN Association in 2003, and enabled mainly bottom-up activities, including pooling the teachers, infrastructures and students. These initiatives did receive important top-down support. ENEN, for example, has been supported for 15 years through projects by the European Commission. Many of the suggested top-down activities were unfortunately never attempted.

Nearly 20 years after the first signs of dwindling nuclear education, the main concerns persist. It is noted that nuclear energy currently has varying degrees of support in the countries of the European Union but education and training is required across all three phases - construction, operation and decommissioning - of a nuclear plant. It is therefore imperative that education and training programs exist to support the full life cycle of nuclear power plants.

As well as the initial qualifications from apprenticeships to doctorates, lifelong learning through continual professional development is also very important to ensure that the nuclear workforce is suitably qualified and experienced.

6.3.2 State-of-the-art and Challenges

Over the last fifteen years one of the main drivers for the development of nuclear education and training programs throughout Europe has been the European Nuclear Education Network (ENEN – www.enen.eu). The seventy-five members of ENEN:

- promote collaborations to support high quality nuclear education;
- increase the attractiveness of nuclear education and training for students, researchers and professionals;
- promote life-long learning and career development at post-graduate or an equivalent level.

Organizations working together can provide more efficient and cost-effective educational programs that can be established far quicker than just one organization working independently. There may also be political drivers to ensure that funding is spread between organizations to create more opportunities either geographically to perhaps reduce the cost to students, or technologically, ensuring that all required courses and topic areas are developed equally.

This coordinated approach to the networking of nuclear education and training in Europe has now been mirrored in other regions. Asia, Latin America, Africa and the Eurasian Economic Community States, with the support of the International Atomic Energy Agency, have all established networks:

- ANENT – Asian Network for Education in Nuclear Technology
- LANENT – Latin American Network for Education in Nuclear Technology
- AFRA-NEST - AFRA-Network for Education of Nuclear Science and Technology
- STAR-NET - Regional Network for Education and Training in Nuclear Technology

Recent initiatives funded by the European Union to support the continuous growth and development of nuclear education and training have included ANNETTE (Advanced Networking for Nuclear Education and Training and Transfer of Expertise - www.annette.eu) and ENEN+ (plus.enen.eu).

A key aspect of ANNETTE is the coordination of existing activities in nuclear education and training in order to:

- connect E&T groups of existing Platforms (SNE-TP, IGDTP, MELODI, EAN, EURADOS, EUTERP, Alliance, NERIS, the medical platforms, EFOMP and others)
- make an inventory of existing E&T initiatives, mapping how different projects are connected in order to identify overlaps and gaps
- connecting existing singular databases into one database for E&T initiatives adapted to the needs of every Platform.
- Support education and training initiatives outside of the European Union, in connection with IAEA and other relevant groups

With these goals ANNETTE aims to enhance nuclear knowledge, skills, competences and thus enhance nuclear safety culture.

ENEN+ builds on the success of the first fifteen years of the European Nuclear Education Network (ENEN) and aims to convert the interest of the young generation into nuclear careers by pursuing the following main objectives:

- Attract new talents to careers in nuclear energy.
- Develop the attracted talents beyond academic curricula.
- Increase the retention of attracted talents in nuclear careers.
- Involve the nuclear stakeholders within the EU and beyond.
- Sustain the revived interest for nuclear careers.

The ENEN+ consortium focuses on learners and careers in nuclear reactor engineering and safety; waste management and geological disposal; radiation protection and medical applications.

ANNETTE and ENEN+ are the current activities in the two decade long EURATOM Fission Training Schemes (EFTS), which are strongly supported by the European commission. EFTS are built on the principles of common qualification criteria, common mutual recognition systems, and the facilitation of teacher, student and professional mobility across the EU. To date, they have already resulted in a wide range of measures targeting the development of nuclear E&T programs at universities, research institutes and industrial training providers.

However, despite the remarkable results obtained since the launch of the EFTS initiatives in early 2000s, it must be recognized that the enrolment of students to nuclear disciplines has not yet reached the desired level. A plausible explanation lies in the fact that rather than direct support to the recruitment most efforts have been directed towards creation, improvement and harmonization of E&T programs, establishment of adequate schemes and frameworks for professional development, pooling of resources and means at European level, organizational restructuring and capacity building. These initiatives were indeed greatly needed as a premise to reach expected goals, e.g., for maintaining and transferring the expertise of nuclear professionals. It is now time to consider at its very roots the pipeline of nuclear workforce, tackling the problems discouraging young students from selecting nuclear subjects as their choice for a future career.

Main Challenges

An in-depth analysis by Chung (2018) of Kyung Hee University in South Korea points to some very plausible reasons for the persistent concerns, including:

- Tendency to solve the easy problems first;
- Tendency to be more concerned about 'how' and 'what' then 'why'.

These reasons are consistent with the experience and observations of ENEN.

'Why' is usually associated with curiosity, knowledge, higher education, research, and academia. Similarly, 'how' and 'what' may be associated with needs, training, skills, experience, knowledge management, industry and knowledge communities.

High tech industry, including nuclear, depends on people with very diverse degrees of education and training. Search for efficiency, stimulated in part by pressures from competition, might guide the industry towards more internal training, directed naturally much more towards 'what' and 'how' than 'why'. In other words, dwindling of the higher education might be compensated for a short while with more intensive training by the industry. In the short term, such a focused approach may even increase the safety record of the industry.

In the medium and long term, too much focus on 'what' and 'how' may have some unexpected and unwanted consequences, which develop gradually and intensify with time. One consequence is the lack of innovation and the subsequent loss of competitiveness and the interest of young creative talents. Another is possibly the perception of poor transparency towards the public. This may develop when the institutions dealing predominantly with 'why' do not have sufficiently detailed insight in the activities of the industry.

One may also say that dealing predominantly with 'how' and 'what' is easy, as it mostly requires the stakeholders to follow the market conditions only. The 'why' may be seen as more difficult, as it must fit the boundary conditions dictated by the market, but also requires long-term strategic planning, communication, cooperation, strategic (long term) investment etc.

Attractivity or Complexity

Many 'knowledge communities' have developed over the decades of nuclear electricity production. Many of them have already approached ENEN for cooperation and coordination. These include nuclear engineering, radiation protection, management of radioactive waste, fusion engineering, medical applications, nuclear security, nuclear safeguards, nuclear materials, nuclear safety assessment, nuclear culture for safety, radio chemistry and decommissioning of nuclear installations. Some of them have not yet sought cooperation or coordination. The most important among those might be the nuclear regulatory community.

Increasing the complexity of technology and concerns about the existing education and training are among the main reasons leading to the development of the knowledge communities, which became more and more independent from each other. The possibly unwanted consequence is increased complexity - and reduced attractivity - of nuclear education and training.

Competition or Cooperation

Another possibly unwanted or unexpected consequence of the stronger and more independent nuclear knowledge communities is competition for talents between nuclear communities rather than cooperation of nuclear communities in competition for talents with other complex or high technologies.

Steady supply or highly cyclic demand

Experience shows that construction of nuclear power plants comes in waves (e.g., in Europe the vast majority of the facilities were built in the 1970s and 1980s). Consequently, the recruiting and development of personnel for operation and other stakeholders has also been done in waves (e.g., 1970 and 1980s for the first wave, 2010-2020s for the replacement of the first generation). This will be, assuming that every nuclear power plant is with us for a century or more, repeated also in the future. Between those waves, the demand for the new personnel is generally very limited.

In general, the (high) educational systems need sustainable and stable conditions and might need very specific support for the times with low demand to avoid university departments being shut down on the grounds of too low demand when professors retire. Such support may be necessary, among others, because of rather long times involved in the development of new faculty (e.g., up to 20 years).

6.3.3 R&D Topics

The bottom-up approaches to revive the nuclear education and training practiced during the last two decades were on the whole satisfactory to maintain the education systems and generate warnings to the decision makers. They were unfortunately not satisfactory to attract many new talents and did not lead to substantial innovations to nuclear (power) technologies. The proclaimed closures of operating plants in many countries may contribute to further dwindling of nuclear education. Top-down (strategic) approaches are needed to maintain and further develop the nuclear education and training. This includes for example the policy studies to review current and planned future activities and development and implementation of nuclear education, training and knowledge management strategies consistent with the long-term visions/plans for development and implementation of nuclear technologies. ENEN is, as a part of the ENEN+ project, working on a European strategic agenda for nuclear education, training and knowledge management. This document will be offered as the basis for discussion to all nuclear stakeholders and will hopefully serve as the basis for a joint action of all nuclear stakeholders.

Conclusion

Nuclear knowledge has been one of the major achievements of mankind. It has made many significant contributions to science and technologies beyond nuclear power. Examples include diagnostics through imaging and a variety of therapies in medicine, sterilization in food processing, and diagnostics in industry, forensics, archaeology and geology, among others. We believe that the time has come for all nuclear stakeholders to establish and follow a common strategic goal: preserve, maintain and further develop this valuable knowledge for present and future generations.

6.4 Global outreach of European SRIA

According to the IAEA PRIS database, there are 447 nuclear power reactors in operation and 52 nuclear power reactors under construction. The 126 nuclear power reactors in operation in the EU represent roughly 28 percent of the global fleet whereas the 6 nuclear power reactors under construction in the EU represent less than 12 percent of the global number of nuclear power reactors under construction. These facts indicate that the centre of gravity for the operation of nuclear and most importantly for the new projects and, thus, the future of nuclear is outside of the EU and Europe.

Yet, EU with its nuclear industry, operating utilities, R&D institutions, regulatory bodies, academia, civil societies and European associations such as SNE-TP with its three pillars NUGENIA, ESNII and NC2I or ETSON could contribute significantly to the safe and sustainable use of nuclear energy globally. As the future European market is unclear and can be shrinking as well as growing, this outreach is crucial for the future European nuclear R&D.

This document has identified the main R&D topics with respect to reactor technology in the areas of operation and construction, in-service inspection, qualification and non-destructive examination, advanced reactors and the next generation and small modular reactors. As regards the enabling conditions the main R&D topics have been identified in the areas of safety of nuclear power plants, development of fuel, the fuel cycle and spent fuel management, dismantling and decommissioning, and social, environmental and economic aspects.

With respect to cross-cutting technologies, the main R&D topics have been identified in the areas of digitalisation, modelling and simulation, and materials and with respect to non-technological cross-cutting aspects, the main R&D topics have been identified in the areas of research infrastructures, harmonisation, and education, training and knowledge management. Being an SNE-TP document, the viewpoint is European and based on the needs of the SNE-TP member organisations. However, all of these R&D topics are relevant globally. Depending on the scale and phase of the nuclear program the importance of the individual subjects may vary.

The strength of the SNE-TP SRIA is the wide palette of on-going and planned R&D activities from the ‘cradle to the grave’, the strong and versatile R&D infrastructure including also new research facilities, and the strong education and training components. This palette offers possibilities for cooperation with the R&D of established nuclear countries for peaceful use of nuclear energy. In these cases the best outcome is benefitting from the strengths of the partner. As regards embarking nuclear countries, the experience gained by the SNE-TP members, the availability of existing R&D infrastructure and programmes as well as availability of versatile education and training is a strong asset. Embarking countries may need advice and assistance in developing their own R&D framework and infrastructure.

Quite often the established small/medium nuclear countries as well as the embarking nuclear countries have strong ties to the country of origin of the reactor technology employed or planned to be employed. In these cases the role of the SNE-TP research could be for instance as offering confirmatory R&D, a second opinion or complementary education and training.

The first step of the outreach can be a cooperation agreement of SNE-TP and/or its pillars with an international organisation or with some national R&D program. To some extent SNE-TP or its individual pillars have already taken this step. The next step is implementation of the cooperation. Largely, this step still awaits its realisation. The following steps consist of deepening the cooperation in a case-by-case basis.

The final step and the offspring beyond the scope of the SNE-TP is competitive contract work done by the European organisations for the clients from outside Europe. Considering the level of public governmental or EU funding for nuclear R&D this kind of activity is a must for the survival of the R&D organisations in many small EU countries. The material and immaterial R&D carried out according to SNE-TP research agenda and in cooperation with partners from other continents can act as the starting point of such an activity that finally increases the prosperity of these European organisations. This further enables these organisations to maintain their high level of competence and thereby contributes to the continued safe and sustainable use of nuclear energy in the future also in Europe.

7 Conclusions and Way Forward

Independent reputed international energy outlooks clearly indicate that the world and Europe in particular will need to include nuclear fission energy in its energy mix when it wants to fulfil its low-carbon energy generation ambitions and minimise the probable effect on climate change. SNE-TP is fully aligned with this conclusion. At the same time, SNE-TP as an organization has made an important step towards a legal association. The maturity of the organization and its pillars has allowed to update the Strategic Research and Innovation Agenda. This agenda shows that in the long-term vision of SNE-TP is still valid, while at the same time small changes in priorities can be identified reflecting the changing landscape and progress in research and innovation methods, tools, and knowledge.

While safety will always remain a first principle in nuclear research, this update of the Strategic Research and Innovation Agenda emphasizes that research towards affordability, reliability and financial risk mitigation is a boundary condition for long-term operation and future deployment of nuclear systems. After all, without long-term operation and new nuclear deployment in Europe, we will not be able to meet the environmental goals set in international agreements. This also shows the need for proper communication channels on nuclear to inform the public at large about the benefits of nuclear energy. Together with organizations like Foratom, the OECD/NEA, and the IAEA, SNE-TP will continuously ensure that factual information will be provided to the public.

The current Strategic Research and Innovation Agenda 2020 has been aligned well with the Strategic Energy Technology (SET) Key Action 10 Implementation Plan (EC, 2019), including the visions of the three SNE-TP pillars, NUGENIA, ESNII, and NC2I.

The future for development and deployment of nuclear technology in Europe is bright if we manage to:

- Operate our assets in a reliable, affordable and safe way,
- Collaborate (in Europe and internationally),
- Connect scientists and reactor designers (to ensure we are working on the right challenges),
- Link experimental teams with numerical modellers (to ensure mutual knowledge exchange improving both sides of the scientific spectrum),
- Educate continuously a new European nuclear workforce,
- Communicate in an effective way the benefits of nuclear energy to the European citizens.

Obviously, future deployment of nuclear systems and nuclear research infrastructure in Europe will also strongly depend on the financial conditions and long-term political support of member states. Funding mechanisms put forward by the European Commission, e.g. through Horizon Europe, but also national initiatives will play an important role in which SNE-TP may act as a catalyser to encourage collaboration and maximise integration of research, development, and innovation efforts. Funding will remain a major challenge. A significant increase in funding levels will allow to cover properly all the needs identified within this Strategic Research and Innovation Agenda. This development will also depend on the deployment of renewables to which the nuclear industry will have to adapt.

8 Glossary

ADS	Accelerator Driven System
ALARA	As Low As Reasonably Achievable
ALFRED	Advanced Lead Fast Reactor European Demonstrator
ALLEGRO	GFR Demonstrator
ALLIANCE	European Radioecology Alliance Association
AMP	Ageing Management Plan
ASTRID	Advanced Sodium Technological Reactor for Industrial Demonstration
ATF	Accident Tolerant Fuel or Advanced Technology Fuel
CANDU	Canadian Deuterium Uranium reactor
CO_2	Carbon-dioxide
CONCERT	European Joint Programme for the Integration of Radiation Protection Research
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
ENEF	European Nuclear Energy Forum
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
EURADOS	EUropean RAdiation DOSimetry
EURAMED	EURopean Alliance for MEDical radiation protection research
GEMINI	Collaboration between NC2I and NGNP
GFR	Gas Fast Reactor
GIF	Generation IV International Forum
HTR	High Temperature Reactor
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
LFR	Lead Fast Reactor
LLW	Low Level radioactive Waste
LMFR	Liquid Metal Fast Reactor
LTO	Long-term Operation
LW-SMR	Light Water – Small Modular Reactor
LWR	Light Water Reactor
MCCI	Molten Core Concrete Interaction
MELODI	Multidisciplinary European LOw Dose Initiative
MINERVA	Phase 1 of the MYRRHA project

MIT	Massachusetts Institute of Technology
MOX	Mixed Oxide
MSR	Molten Salt Reactor
MYRRHA	Multi-purpose hYbrid Research Reactor for High-tech Applications
NC2I	Nuclear Cogeneration Industrial Initiative
NDE	Non-Destructive Examination
NDT	Non-Destructive Testing
NEA	Nuclear Energy Agency
NERIS	European Nuclear and Radiological Emergency Management and Rehabilitation Strategies
NGNP	Next Generation Nuclear Plant
NI2050	Nuclear Innovation 2050
NPP	Nuclear Power Plant
NUGENIA	NUclear GENeration II & III Association
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
SFR	Sodium Fast Reactor
SMFR	Small Modular Fast Reactor
SMR	Small Modular Reactor
SNE-TP	Sustainable Nuclear Energy - Technology Platform
SSC	Structures, Systems, and Components
TA	Technical Area (of NUGENIA)
WANO	World Association of Nuclear Operators
WENRA	Western European Nuclear Regulators Association
WNA	World Nuclear Association

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