ESNII VISION PAPER

2022 Edition

ESNII Vision Report No. 1

08/04/2022

Author(s): Marc Schyns (SCK CEN), Roberto Adinolfi (Ansaldo), Noel Camarcat (PSL), Jiri Duspiva (UJV) Michele Frignani (Ansaldo), Jean-Claude Garnier (CEA), Jean-Marie Hamy (Framatome), Eric Breuil (ORANO), Elsa Merle (CNRS), Ralph Hania (NRG)

SNETP Association

c/o EDF

Avenue des Arts 53B, 1000 Brussels, Belgium

Email: secretariat@snetp.eu

Website: www.snetp.eu

This document was prepared by the ESNII Task Force established within the Sustainable Nuclear Energy Technology Platform.

Brussels: The SNETP Association

ISBN 978-2-919313-27-3

Index

Executive Summary

The Sustainable Nuclear Energy Technology Platform (SNETP) was established in 2007 as a Research & Development & Innovation (R&D&I) platform to support and promote the safe, reliable and efficient operation of civil nuclear systems. The European Sustainable Nuclear Industrial Initiative (ESNII) has been launched in 2010 under the umbrella of SNETP and is one of its 3 pillars.

The ESNII initiative has been able to gather European teams around technologies and demonstration projects to pursue R&D on Generation IV systems using technologies based on fast neutron spectrum and closed fuel cycles allowing competitive and sustainable energy production, better use of the uranium resources as well as waste minimization. The main strategy is to promote the advances in R&D&I of these technologies, strengthening synergies and utilizing common technical solutions to maximize effectiveness of the whole process.

In particular, sustainable industrial initiatives supported by the following technologies and projects are promoted within ESNII:

- Lead-cooled Fast Reactor (LFR) and the ALFRED project,
- Gas-cooled Fast Reactor (GFR) and the ALLEGRO project,
- Sodium-cooled Fast Reactor (SFR).

The MYRRHA project, an Accelerator Driven System to demonstrate transmutation of high-level waste, was judged having the highest potential in support to these ESNII technologies.

In addition, ESNII intends to encourage the R&D developments on Molten Salt Reactor (MSR) technology, as a potential further path towards the goal of sustainable energy production, better use of uranium resources and waste minimization.

The present document describes the ESNII mission, vision, deployment strategy and intended actions.

1. ESNII Mission

The European Sustainable Nuclear Industrial Initiative (ESNII)[1] has been launched in 2010 under the umbrella of the Sustainable Nuclear Energy Technology Platform (SNETP)[2]. ESNII is established as one of the three pillars of SNETP.

Its mission stems from the energy needs assessment of the European economy and focuses on Generation IV systems with closed fuel cycles in line with the objectives and timing of the integrated Strategic Energy Technology Plan issued by the European Commission (SET-Plan)[3].

Other organizations worldwide pursue comparable objectives. The Generation IV International Forum (GIF)[4] was founded in 2001 and gathers research teams all around the world on comparable R&D subjects. Since it is a worldwide organization, it can gather more resources and study more systems than the ESNII technologies and projects. However, and for understandable reasons, GIF is not committed to demonstrator projects like ESNII and limits its scope to technologies. ESNII representatives and in particular its industrial members participate to a GIF subgroup: the Senior Industrial Advisory Panel (SIAP). They endeavour to explain the benefits of the ESNII approach. The International Atomic Energy Agency (IAEA)[5] performs long term technology evaluation exercises in its INPRO[6] section. ESNII and SNETP representatives are interacting with INPRO to present the European Generation IV approach and in particular its MOX fuel R&D strategy.

The use of fast reactors in a closed U-Pu fuel cycle (recycling of spent fuel) can allow a large increase in efficiency with regard to natural resources consumption, by a factor of at least 50, leading in the long term to a more sustainable implementation of nuclear energy.

One of the societal concerns regarding nuclear energy is the high-level nuclear waste. Fast spectrum reactors with closed fuel cycles can allow a significant reduction in radiotoxicity and volume of high-level nuclear waste. Apart from the deployment of fast reactors, advanced reprocessing and remote fuel manufacturing techniques are needed to recycle the minor actinides in order to meet this goal.

ESNII aims to develop safe and performing fast neutrons spectrum reactor technologies with closed fuel cycle Generation IV energy systems - allowing competitive and sustainable energy production, better use of the uranium resources and waste minimization.

2. ESNII strategy

The ESNII initiative has been able to gather European teams around technologies and demonstration projects to pursue R&D on Generation IV systems using technologies based on fast neutron spectrum and closed fuel cycles. The main strategy is to promote the advances in R&D of these technologies, utilizing

---

[1] ESNII: https://snetp.eu/esnii/

[2] SNETP: - www.snetp.eu

[3] SET-Plan: - https://setis.ec.europa.eu/actions-towards-implementing-integrated-set-plan

[4] GIF: https://www.gen-4.org/gif/jcms/c_9260/public

[5] IAEA: https://www.iaea.org

[6] INPRO: https://www.iaea.org/services/key-programmes/international-project-on-innovative-nuclear-reactors-and-fuel-cycles-inpro

synergies and common technical solutions to maximize effectiveness of the whole process. One good example is the nuclear fuel – fast reactors require the use of appropriate fuels, among which Mixed Oxide fuel (MOX) is the most mature in the European framework. The important technical choice of pelletized fast reactor MOX fuel should lead to the harmonization of fast reactor fuel R&D in Europe.

In particular, sustainable industrial initiatives supported by the following technologies and projects are promoted within ESNII:

1. The Lead-cooled Fast Reactor (LFR) and the **ALFRED** (Advanced Lead-cooled Fast Reactor European Demonstrator)[7] project, an Industrial Initiative with the goal of building a European demonstrator of the LFR technology in Europe, having SMR-oriented features;
2. The Gas-cooled Fast Reactor (GFR) and the **ALLEGRO** project (GFR demonstrator)[8], an initiative with the goal of building an experimental facility to demonstrate the technological viability of the GFR concept;
3. The Sodium-cooled Fast Reactor (SFR)[9]: it is the most internationally mature technology with operating reactors in the Russian Federation, at the industrial scale, and in India and China at the research scale. The challenges prior to an industrial deployment in western Europe are to improve the economics and to consolidate the safety demonstrations. Major issues are addressed in the French R&D program in connection with European skills.

In 2019, ESNII analysed the status of the ESNII projects and system maturity based on the prioritization criteria of Technology Readiness Level (TRL) and the advancement or impetus of European projects. **MYRRHA** (Multi-purpose hYbrid Research Reactor for High-tech Applications)[10], a lead-bismuth Accelerator Driven System to demonstrate transmutation of high-level waste, was judged as the most advanced R&D project in the European context having the highest potential to reach full maturity in support to the ESNII technologies, thanks to the increased technology readiness level in liquid lead-bismuth technology, pre-licensing activities and the continued strong support of the Belgian Government. As leading European R&D project on fast neutron technology as of today, MYRRHA will generate useful information for the various Sustainable Industrial Initiatives.

In 2021, ESNII analysed the MSR technology based on fast neutron spectrum (see the Molten Salt Fast Reactor MSFR concept studied at CNRS and in the successive European programs EVOL, SAMOFAR and SAMOSAFER), already selected by the GIF in 2008[11], and concluded it can be currently considered as an emerging initiative of high potential in terms of sustainability. Therefore, ESNII included MSR among the technologies of interest requiring investments in basic R&D to prove feasibility and to support the definition of a reference concept and associated demonstration roadmap.

---

[7] ALFRED: http://www.alfred-reactor.eu/

[8] ALLEGRO: https://www.gen-4.org/gif/upload/docs/application/pdf/2019-03/geniv_template-_dr._ladislav_belovsky_final_3-20-19.pdf

[9] SFR: https://www.gen-4.org/gif/jcms/c_42152/sodium-cooled-fast-reactor-sfr

[10] MYRRHA: https://myrrha.be/

[11] GIF: https://www.gen-4.org/gif/jcms/c_42150/molten-salt-reactor-msr

3. State of art of the various ESNII projects and technologies

3.1. Lead Fast Reactor

International cooperation is considered an asset for the deployment of the ALFRED project. The structure of the FALCON consortium (namely, Fostering ALFRED Construction)[12] is envisioned to welcome any organization sharing the vision of its members, or willing to join forces on specific topics. Leveraging the catalysing objective of the project, a number of expressions of interest have been received from Europe and globally. Cooperation agreements have been signed with international institutions and industries by FALCON, or its key members.

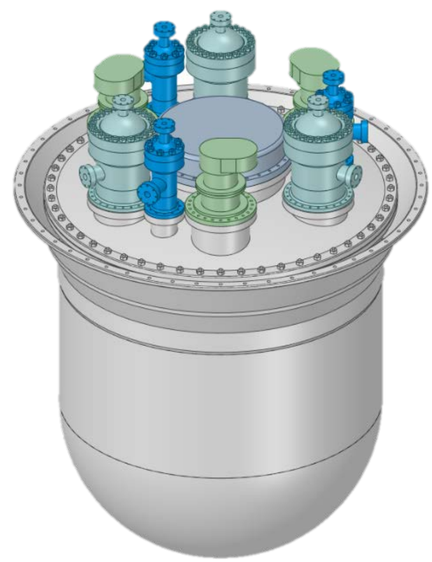

Figure 1 - ALFRED system arrangement.

The means of financial support, required for the execution of the project, are being secured on the basis of the governmental commitment of Romania. A regular, dedicated budget of about 4.5 M€/year ensures the smooth execution of the activities[13]. Extraordinary investments are required to cover special actions planned in the roadmap. The Romanian Government is aimed to ensure the pre-conditions for securing structural funds: a first dedicated financing worth 20 M€ has been secured in 2019 for the realization in Romania of relevant experimental facilities[14]. Necessary steps for access to European Regional Development Funds are underway: these funds will be complemented by the 20% cost share committed by the Romanian Government.

Presently, ALFRED is included as a key element of innovation in the Governmental Programme, in the National Energy Strategy and in the National Plan for Research, Development and Innovation. Finally, thanks to the inclusion of ALFRED both in the Smart Specialization Strategy of the South-Muntenia region[15] (where the selected site for the demonstrator is located) and in the National Roadmap for Major Research Infrastructures[16], actions are being organized for appointing ALFRED as a major project of strategic relevance within the Programme for Operational Competitiveness.

---

[12] FALCON: http://www.alfred-reactor.eu/index.php/falcon-2/

[13] PRO ALFRED: https://www.raten.ro/?page_id=2618&lang=en

[14] POC ALFRED Stage 1: https://www.raten.ro/?page_id=2893&lang=en

[15] South Muntenia Smart Specialization Strategy: https://www.adrmuntenia.ro/index.php/download_file/article/60/regioengprint.pdf (page 39)

[16] Romanian National Roadmap: https://www.research.gov.ro/uploads/sistemul-de-cercetare/infrastructuri-de-cercetare/cric/romania-national-roadmap_2017.pdf

3.2. Gas Fast Reactor

Development of the GFR demonstrator ALLEGRO has been carried out under the governance of the V4G4 Centre of Excellence consortium, which consists of four full members – one from each V4 countries, Czech Republic, Hungary, Poland and Slovakia, two associated members (one from Czech Republic, one from France) and an ever-increasing number of "collaborating organizations" from the above-mentioned countries. The structure of the V4G4 CoE[17] is prepared to welcome new members that would share the common vision and would actively participate in the consortium's R&D tasks.

Recent developments in the ALLEGRO design show that, from the point of view of nuclear safety, the technology as a whole is viable[18]. However, there are still a lot of technological challenges that need to be tackled and resolved before the technology can be considered as mature and ready for construction of the prototype. The list of challenges comprises mainly issues connected to fuel and core materials, fuel handling, I&C and reduction of uncertainties in safety analyses.

In terms of allocated resources, the R&D programme of ALLEGRO relies on two main sources – in-kind contributions from members of the V4G4 CoE, and specific R&D projects co-sponsored by national governments or the European Commission. In total, there are six ongoing national R&D projects and one international (H2020) ongoing project dedicated to GFR, with a total budget of 14.0 M€, that corresponds to a secured average yearly budget of 2.8 M€/year for the next 5 years (2021-2025).

3.3. Sodium Fast Reactor

The SFR is a reference Generation IV nuclear technology since the reactor feasibility as well as the closure of the MOX fuel cycle have been demonstrated already in the 70's and 80's. The heritage is significant, especially in Europe. The basic technologies are known and also the ways of progress.

Compared with the first achievements, the reactor concept has to evolve. First, it must meet the best standards of nuclear safety and security. In Europe, safety-oriented innovations have been identified in the ASTRID program (2010-2019)[19], in compliance with the WENRA requirements. These developments should be pushed forward by dedicated studies and experimental programs in the next decade.

The cost of SFRs compared to PWRs slows down their industrial deployment. In the current context of abundant uranium, no project of construction exists in Europe. Projects for new construction exist in Russia (industrial reactor), China, India and the USA (demonstration or research reactors) offering other opportunities for bilateral collaborations.

Beyond ASTRID, France remains the solid leader of SFR development in Europe. The time that separates us from fast reactors industrial deployment should be used to go on developing the technology. Reducing the investment costs should be considered at the same level of importance as the improvement of safety/security in the specifications of the Generation IV SFR. Some ideas have been explored already in

[17] https://www.nucnet.org/news/central-europe-s-v4-nations-establish-generation-iv-centre-of-excellence
[18] Vácha, P. et al.: Progress in the ALLEGRO Project - Neutronics and Thermal-Hydraulics, Proceedings of ICAPP 2019 conference, 2019.
[19] ASTRID: http://www.cea.fr/Pages/domaines-recherche/energies/energie-nucleaire/reacteurs-nucleaires-futur.aspx

the ESFR-SMART [20]project. Further exploratory studies (sketch studies) are supported by both the French Government and the French nuclear industry. Specific realisations will be proposed for European collaboration complementing France-Japan bilateral collaboration on SFR (extension agreement signed on 3 December 2019).

3.4. Accelerator Driven System

With MYRRHA, Europe will again operate a flexible fast spectrum research facility in support of the material development of fast reactor technologies or fusion as complement to other facilities and programs. 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 of the accelerator up to 100 MeV and its target stations, the design of the extension to 600 MeV and the design of the lead-bismuth cooled reactor[21], 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.

[20] ESFR-SMART: https://esfr-smart.eu/

[21] Lead-bismuth cooled reactor: https://myrrha.be/myrrha-project/myrrha-reactor/

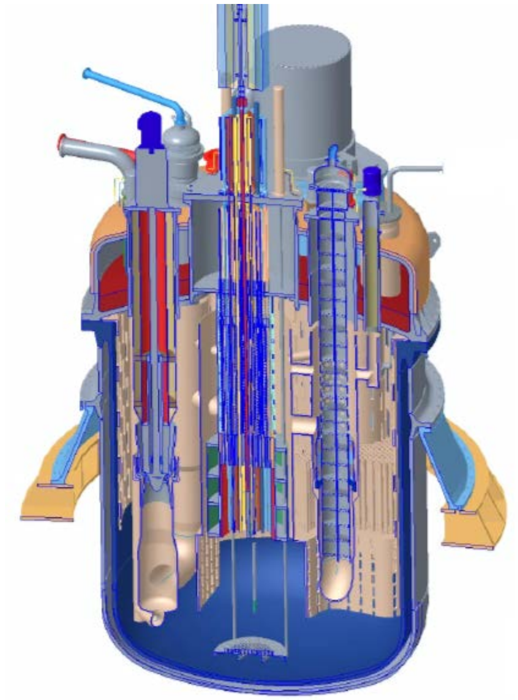

Figure 2: MYRRHA Research Reactor Facility – Primary System design

3.5. Molten Salt Reactor

Despite its low maturity, the MSR is considered by many actors as a promising system. Conceptual studies are performed by several startup companies in France (NAAREA), Denmark (Seaborg and Copenhagen Atomics) and The Netherlands (Thorizon). R&D organizations such as CNRS, CEA in France, NRG and TU Delft in The Netherlands, CV Rez in the Czech Republic and JRC are performing activities to increase basic knowledge (salt chemistry and properties …) and to explore the key feasibility issues (reactor physics, materials …).

In particular, the **Thorizon** concept emphasizes practical feasibility and shortest-term implementation. In collaboration with Orano, Thorizon aims to establish a first epi-thermal waste burning system in 10-15 years. The technology basis is generic and enables potential future developments towards a closed Thorium/Plutonium cycle, a fast spectrum version, and size flexibility (smaller or larger systems), depending on (future) market needs. MSR, in particular fast spectrum variants, have potentially strong assets: the primary system is compact, the salt thermal dilatation causes a strong negative reactivity feedback providing inherent safety and last, the incorporation of minor actinides like americium and curium in the liquid fuel appears as much more easily manageable than it is in a conventional solid fuel. Therefore, the MSR could take a specific role in a closed fuel cycle strategy. Concerning fuel cycle issues, it is important for some European countries to develop Molten Salt technologies compatible with the PUREX reprocessing plants. This would minimize the challenges of developing a completely new system of reactors and associated fuel cycle technologies and infrastructure.

In the meantime, the fast neutron MSR raises new scientific and technological questions regarding feasibility:

- the salt medium is highly corrosive: a challenge is to protect structural materials by different means including use of special alloys and/or implementation of proper salt redox control and to justify a lifetime of major reactor components compatible with the requirement of an industrial facility;
- reactor physics: beside the strong coupling of neutronics and thermal hydraulics, a large fraction of the delayed neutrons is generated outside of the core zone. Therefore, experimental activities and model validation studies are necessary to investigate the impact in terms of time and space power evolution in case of perturbation;
- the reactor is highly atypical: the MSR is a nuclear reactor with a powerful heat source, and at the same time a nuclear facility containing radioactive materials in solid, liquid and gaseous forms (like a fuel reprocessing plant). This complexity should be analyzed in term of risk minimization and proliferation resistance.

4. Strategic deployment

A strategic deployment calendar of the European Generation IV projects and technologies is outlined in Figure 1 hereunder. Of particular importance are the construction phases for the various demonstrators in fact reflecting the TRLs of the corresponding projects. Construction of MYRRHA, the most advanced European project using lead-bismuth technology is scheduled in 3 phases between 2023 and 2033. Next comes the ALFRED pure lead demonstrator taking benefit of the feedback from MYRRHA, whose construction phase is scheduled between 2030 and 2035. Last comes ALLEGRO, the Gas Fast Reactor demonstrator whose construction takes place beyond 2035, since it is a longer-term technology than lead and lead-bismuth fast reactors. It is worth mentioning that the construction phase of a High Temperature Reactor (HTR) cogeneration demonstrator takes place in Europe in the same time frame as MYRRHA. Because of the French Government's decision in 2019 to terminate the ASTRID project, a construction phase no longer appears for a sodium demonstrator in Europe. It is pushed much further back, in the later part of the 21st century and does not appear in Figure 1. Engineering studies and R&D may continue both for large scale sodium fast reactors and for smaller scale ones.

Molten Salt Reactor (MSR) technology is gaining increasing attention and momentum. Multiple research centres and academia are devoting efforts to feasibility studies and conceptualization of reactor designs. Large efforts are still devoted towards a more thorough understanding of the benefits and challenges related to molten salts as coolant. Therefore, a timeframe for nuclear experimental reactors based on MSR technology is being considered between 2030-2035.

With respect to reactor technology, the following main R&D priorities have been identified:

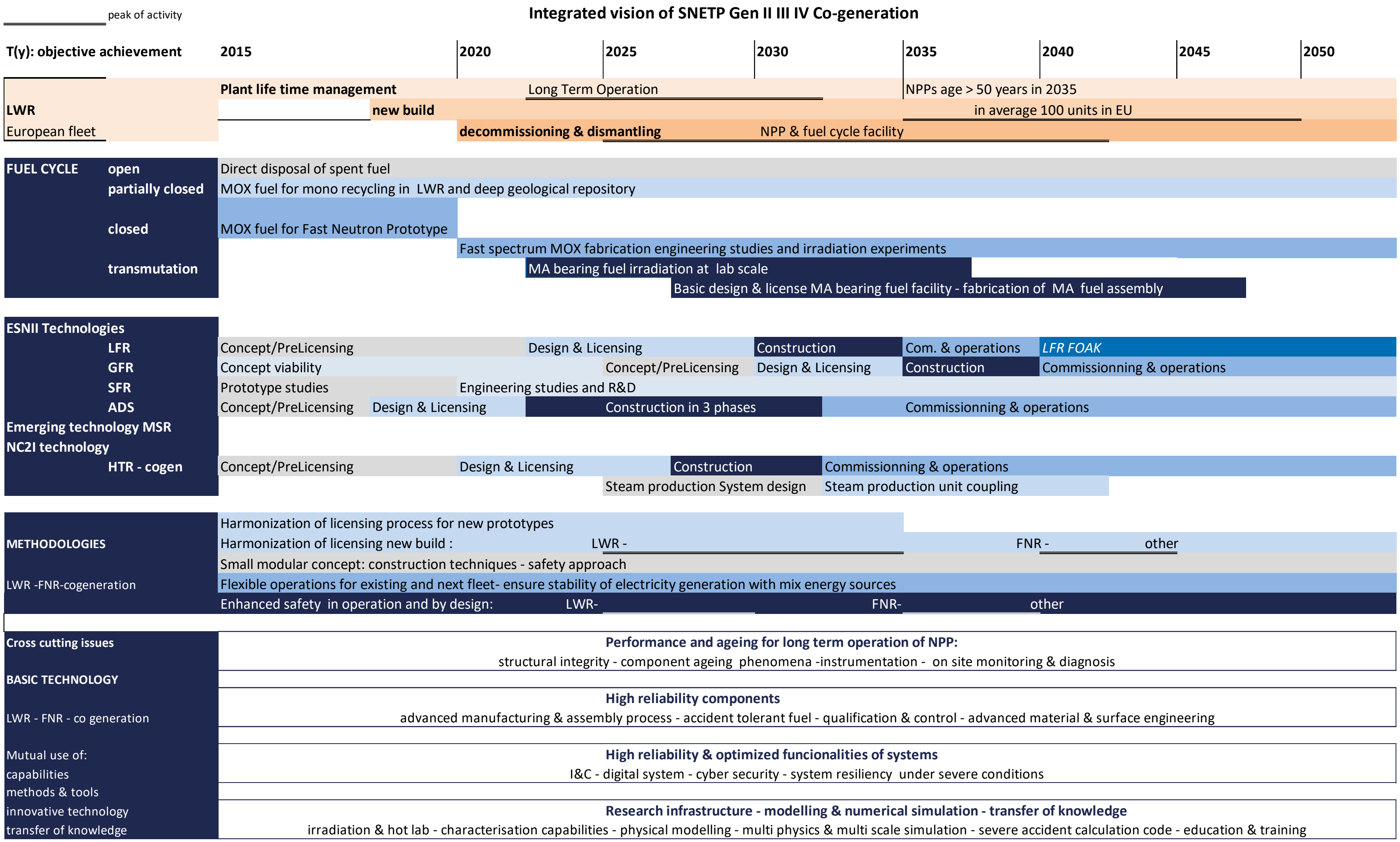

Figure 3: ESNII within the SNETP deployment strategy

4.1. Fuel development and qualification

A variety of fuels for fast neutron reactors are under study worldwide, under the auspices of the Generation IV International Forum (GIF). The USA plan to use metallic fuels consisting of alloys of plutonium, uranium and zirconium. India has a small power (5 MWe) experimental reactor running on carbide plutonium-uranium fuel and is building a large scale (500 MWe) fast prototype using mixed plutonium and uranium oxides (MOX). It has announced plans to revert it in later phases to metallic fuels to increase the conversion rates. Russia is operating its commercial fast reactors BN 600 and BN 800 on enriched uranium oxide and has started an ambitious program to convert BN 800 to MOX fuel. It has pursued R&D programs on 2 types of MOX fuels: pelletized (as in the west) and vibropacked obtaining fuels of lower densities than the pelletized MOX ones. Russian institutes have also announced a very ambitious R&D program on mixed plutonium and uranium nitrides fuels in the framework of the Proryv project[22]. China operates a small research reactor on MOX fuel and may follow the Russian road map in its development program.

Europe has chosen to concentrate its R&D effort on MOX fuel for its leading demonstrators. It can use the considerable experience of the European industry (CEA and Orano) in fast reactor MOX fuel including the latest developments for the conceptual design of the ASTRID MOX workshop[23]. Switching to other fuels such as nitrides or carbides for MYRRHA or ALFRED would delay their calendar by more than 15 years and require costly R&D programs. With the help of the European Commission – via the Euratom Programme – which has funded the ESNII+[24], ESFR_SMART, INSPYRE[25] and PUMMA[26] projects, ESNII has been able to renew competencies in European R&D teams for measurements of physical and chemical MOX properties in the parameter regimes of the future demonstrators. This is of great importance for the future MOX fuel designs.

The general ESNII R&D objectives are to increase the knowledge of UO_2-PuO_2 fuels at high burn up and at high PuO_2 content, above 26%, which will be needed for plutonium multi-recycling in fast spectrum research reactors and demonstrators. This R&D is closely related to the cladding behaviour at high burnup, described in the materials development section.

In the context of plutonium multi-recycling in molten salt reactors, liquid chloride fuel is studied with the aim of collecting thermophysical data for optimized compositions, minimizing corrosion of construction materials, and informing models for heat transfer and fission product behavior.

---

[22] PRORYV : https://www.tvel.ru/en/activities/proryv-project/

[23] AFC project: in French Atelier de Fabrication des Coeurs

[24] ESNII+: https://cordis.europa.eu/project/id/605172;

[25] INSPYRE: http://www.eera-jpnm.eu/inspyre/

[26] PUMMA: http://www.nuclearenergy.polimi.it/pumma/;

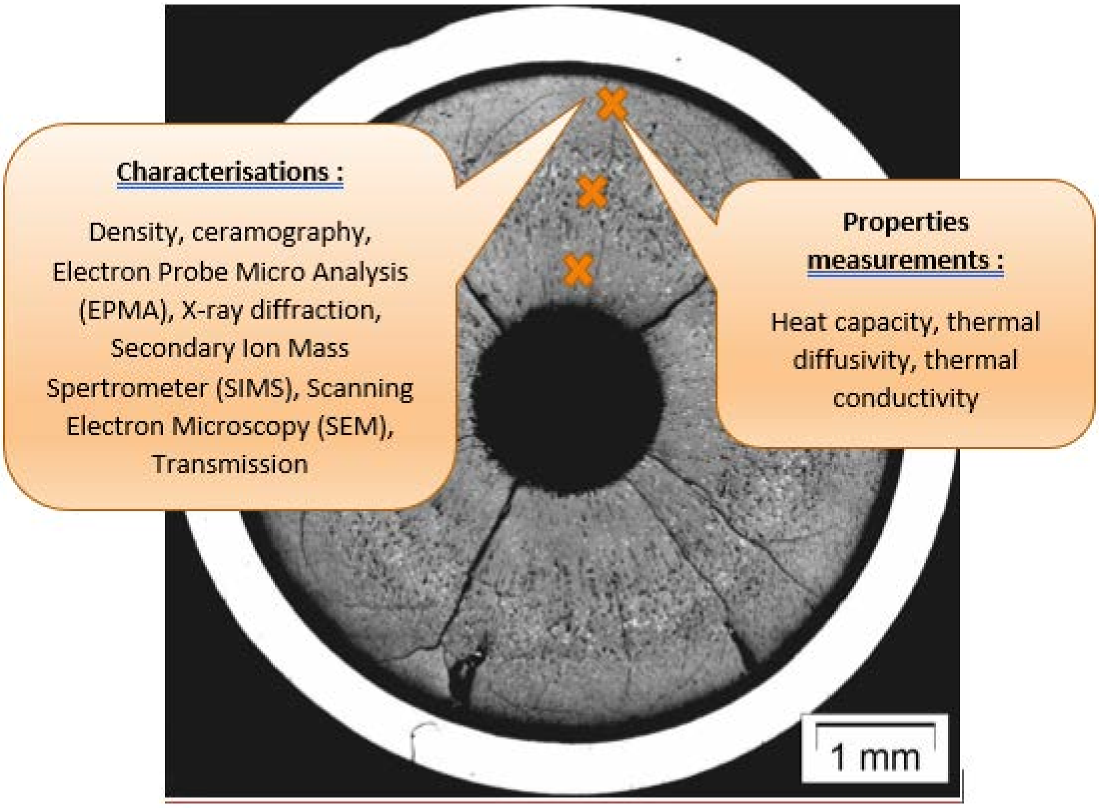

Figure 4: Irradiation of MOX fuel NESTOR in Phenix, characterisations and properties measurements at JRC Karlsruhe and LECA-Cadarache (Source: ESNII+ European project, deliverable D732)

4.2. Materials development and qualification

The availability of materials resistant to neutron damage, to high temperatures and to the aggressiveness of non-moderating coolants, is a condition to deploy fast reactors. Other conditions are to prepare the industrial capabilities (manufacturing and welding technics …) and to develop a suitable construction code (ESNII and AFCEN[27] collaboration is in place).

Austenitic steel 316L(N) is the reference structural material for SFR and LFR. A qualification program of today's industrial production was initiated for ASTRID. The completion of this long-lasting program is relevant for all future projects. Particular attention should be paid to the knowledge deepening on thermal ageing phenomena, creep and creep-fatigue damages (component lifetime justification). Also, solutions of coatings for prevention of corrosion induced by lead and lead-bismuth coolant should be qualified.

Regarding fuel claddings, the 15-15Ti-AIM1 material grade qualification will be completed in the next decade. The qualification of alumina-forming austenitic steels may be necessary for LFR, to solve compatibility issues. Looking further, ferritic Oxide Dispersion Strengthened (ODS) steels and possibly alumina forming ODS steels could permit significantly higher fuel performances for SFR and LFR respectively. The development of these steels, initiated in a series of former and ongoing EU projects, must be continued with new fabrications, characterization and irradiation tests.

[27] AFCEN: https://www.afcen.com/en/

For GFR, steels are not suitable for some of the components of the primary circuit. One such area calling for very high temperature resistant materials is the core itself – 15-15Ti steel cladding cannot withstand the target GFR core outlet temperatures (over 850°C), so a SiC-SiCf composites were selected as the reference cladding for GFR. Recent development of Accident Tolerant Fuels (ATF) boosts the development in this area. For critical parts of the reactor (active parts of heat exchangers, core support plate), refractory metallic alloys such as nickel-based alloys or innovative high-entropy alloys (HEA) is needed to be qualified. Here, synergy with the VHTR technology R&D, and experience from HTR development and operation in the past can be utilized.

Getting new materials or new manufacturing processes qualified can be a long and tortuous process and the long lead times involved produce an effective and consequent barrier to market entry of new or optimised materials and processes at an industrial scale. It is therefore a key priority to reduce the time from development to deployment of advanced material solutions.

4.3. Improved understanding of coolant behaviour, thermal-hydraulics and chemistry control

The purpose is to develop and validate accurate methods to model the coolant behaviour using various modelling approaches ranging from system thermal-hydraulics codes to Computational Fluid Dynamics and multi-scale codes.

Thermal hydraulics is recognized as one of the key topics in the design and safety analysis of fast reactors. Thermal-hydraulic challenges[28] that appear in liquid-metal-cooled fast reactors with a focus on pool-type reactors, can be divided in three main categories: core thermal-hydraulics, pool thermal-hydraulics, and system thermal-hydraulics. For each of these main categories, a division is made between normal reactor operation, off-normal conditions and severe accidents. The seven basic phenomena that are at the basis of the challenges mentioned above are turbulent heat transfer, thermal fluctuations, mechanical fluctuations, mass transfer, bubble transport, particle transport, and solidification. The safety demonstration of fast reactors relies in large part on the numerical simulation of various transients of interest. In order to qualify these simulations, the numerical tools used must be checked for correctness (*verification*). Their capability to correctly predict the physics of each transient must be assessed against an exhaustive experimental database (*validation*). Also, the uncertainties associated with the outputs of the calculation must be quantified (*uncertainty quantification*).

The coolant chemistry control R&D programme for liquid-metal-cooled fast reactors includes mainly three topics. The first is the control of the coolant itself. This includes the mastering of the coolant condition as well as the management of impurities. Specific sensors and control methods as well as filter systems have to be developed for these purposes and tested in dedicated pilot-scale loops. The second topic encompasses the measurement of the transport of radioactive elements from the coolant, in both normal operation, transient and accident conditions. Phase change mass transfer as well as aerosols have to be considered. Also, capture systems for volatile radioactive elements need to be developed. The results of these studies are used as input for safety analyses. The third topic focuses on component cleaning and decontamination. This is a relevant information for the reactor maintenance programme and the decommissioning plan.

[28] Roelofs F. edit., 'Thermal Hydraulics Aspects of Liquid Metal Cooled Nuclear Reactors', ISBN 978-0-08-101980-1, Woodhead Publishing, Elsevier (2019).

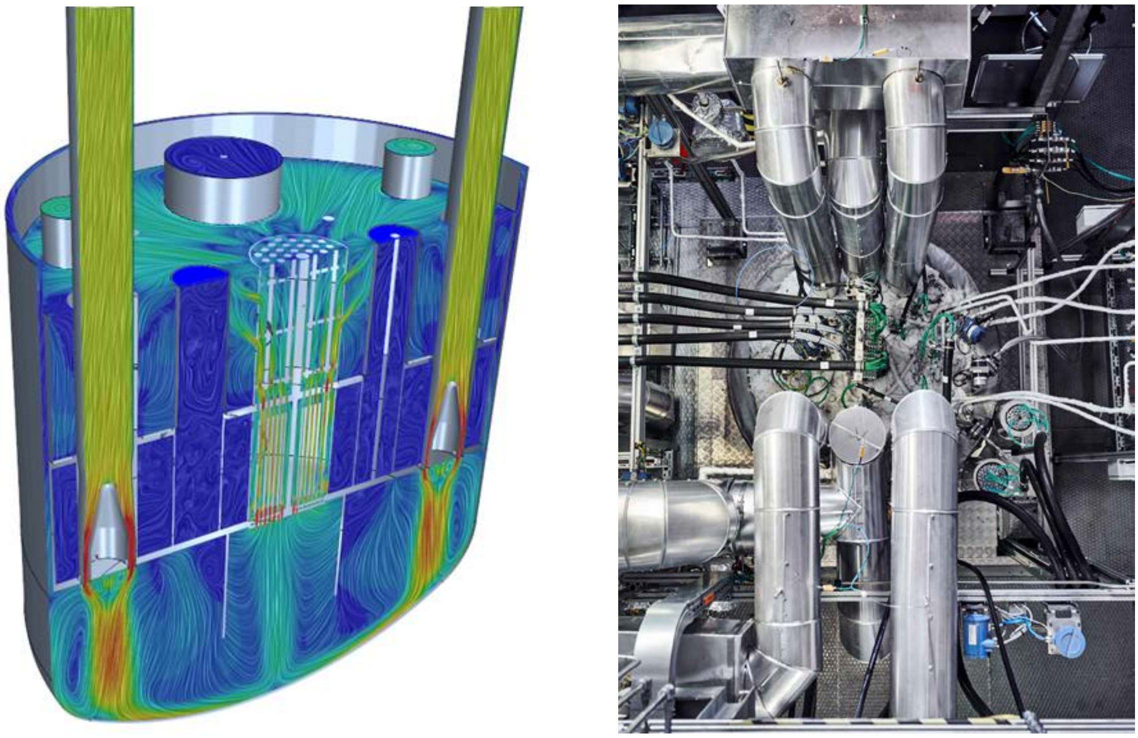

Figure 5: ESCAPE facility – a scaled thermal hydraulic model of MYRRHA using LBE ; Left: vertical cut, right: top view

Although there are no secondary phases in the gaseous coolant of GFR, better understanding of its thermal-hydraulics behavior is a key element in design of a fully passive safety concept for GFRs. It is especially important in situations like station blackout, where core cooling is switched from the main cooling system to the dedicated decay heat removal system working on natural convection principle. This process is extremely important in severe accident prevention in GFRs and experimental validation of various system and CFD calculations on this topic is needed. V4G4 CoE operates two facilities where such a kind of experiments will be performed – the STU helium loop in Trnava, Slovakia, and the S-ALLEGRO integral facility in Pilsen, Czech Republic.

Figure 7: STU-helium loop in Trnava

Figure 6 - Close-up of a helical coil steam generator for liquid metals.

4.4. Component design and testing

ESNII technologies require the development of innovative components for a competitive and safe operation, throughout the life cycle of the plant. A comprehensive range of solutions is being engineered, including core-related components, heat transfer solutions, pumping systems, confinement and containment components. Nuclear design codes offer a comprehensive set of design rules to ensure an adequate level of safety, but some of the innovative features being introduced are not fully covered and require dedicated testing and qualifications.

Most innovative components are safety-related, either performing one or more safety functions or having a potential impact on the safety of the reactor. Nuclear design codes (in particular, RCC-MR(x) and ASME) offer a comprehensive set of design rules to ensure an adequate level of safety in materials selection, design, manufacturing, inspection and repair, as a solid basis for the licensing of the plant. However, specific features of innovative reactor technologies, either due to primary coolant properties or to the aim of increasing competitiveness, are not always fully covered by existing design codes and require dedicated testing and qualifications.

Advanced reactor projects and their synergies with small- or medium-sized units, are attracting increasing interest towards innovative manufacturing techniques, including workshop-prefabricated structures and components, assembled in modules at the plant location, aiming at lowering final costs through full standardization and series production. Advanced manufacturing techniques (e.g., additive manufacturing, thermal bonding), largely introduced in the conventional field, are gaining increasing attention among nuclear designers to ease the prototyping process, reduce costs and increase performances of main components.

Figure 8 - Prototypical pump impeller for lead coolant.

Early involvement of a qualified supply chain for the development and testing of prototypical components will allow for optimized solutions for future deployment phases. Prototyping of scaled-down components allows for preliminary assessment and validation of design principles and performances, through dedicated testing and qualification in relevant environment. Collection of experimental data during testing operations following strict standards and procedures will provide feedback to designers and manufacturers for a continuous improvement. Moreover, data sets will also produce the necessary basis for improvement of design codes and will ensure the safety of innovative components, subject to the scrutiny of safety authorities and technical safety organizations throughout the licensing process.

4.5. Development of appropriate instrumentation and system control

The specific instrumentation needed for the safe and reliable operation of the ESNII reactors will be achieved through a continuous monitoring essentially based on the follow-up of the operating parameters like temperature, flow rate, etc., as well as the indications reflecting the state of the structures and components like leaks, mechanical deformations, etc. The instrumentation has also to be able to provide, mostly in a diversified manner, the necessary measurements in order to detect or possibly forecast the identified panel of incidents and potential hazards resulting from the safety studies. Periodic inspection programmes must validate the hypothesis and project values concerning the damaging mechanisms considered during the design studies. A specific category of instrumentation is therefore needed for the inspection of structures and components as well as for the assistance in possible repair, cleaning, cutting etc. Adaptations and development of instrumentation techniques are necessary mainly in order to operate at high temperature (as high as 800 °C for operational conditions and higher for accidental situations) and in a radiation environment. In the frame of EU projects like ESNII+ and ADRIANA[29], it has been highlighted that even if basic instrumentation is available and advanced techniques are under development in European countries, qualification of the systems is often an open issue.

4.6. Safety assessment and code validation

The overall success of the ESNII program depends on, among other factors, the ability to develop, demonstrate, and deploy advanced reactor designs that exhibit excellent safety characteristics. Safety assessment must be based on appropriate methodologies (i.e., accepted by the safety authorities) and a deep knowledge of the physical phenomena and behaviour of materials.

[29] ADRIANA: https://cordis.europa.eu/project/id/249687;

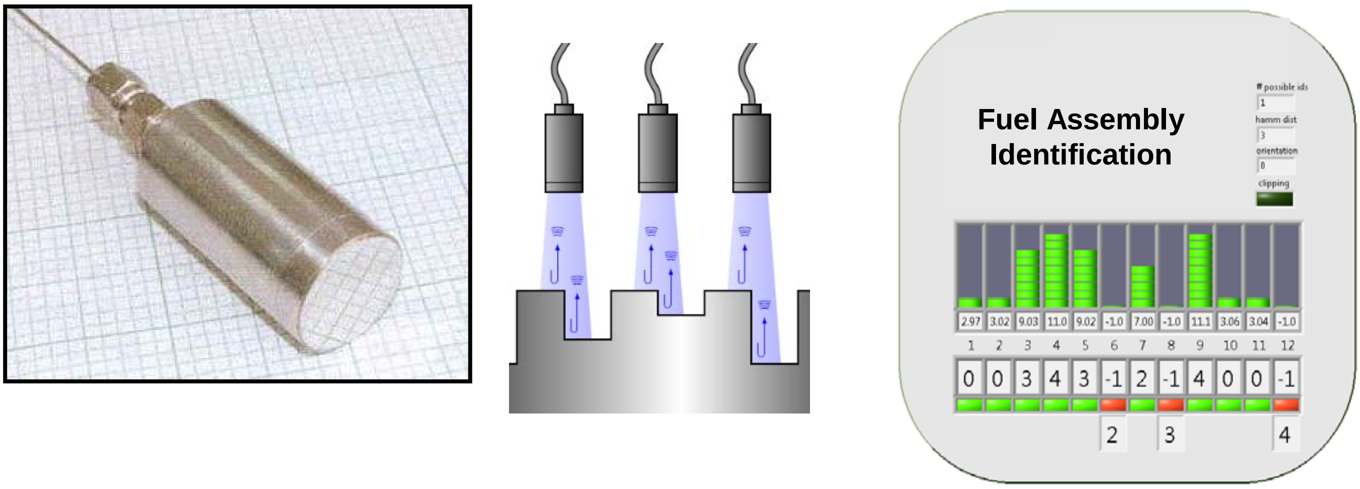

Figure 9: Fuel Assembly identification under liquid metal

Code validation is a part of the overall safety assessment. In 2017, The French safety authority issued a generic guideline document (Guide 28[30]) applicable to all domains of reactor physics. For each physics, there are several simulation tools among European players. This is an asset as it allows, *inter alia*, to perform benchmark exercises. In addition, dedicated experimental programs are sometimes necessary in support of the code validation. These costly realizations could be pooled between European partners and possibly with non-European players, with the help of the Euratom program.

4.7. Fuel handling technology and fuel-coolant interaction

Fuel handling systems are key for the operability of reactors and to reach a competitive availability factor that is one of the differential factors when considering the various nuclear reactor technologies. The Generation IV systems supported by ESNII seek to master the specificities of these systems, strongly different if compared to Generation III concepts. The key aspects managed through the various development roadmaps encompass in particular the severe environment conditions implied by: high temperature of the nuclear process and the cooled down states, cooling fluid characteristics (liquid metal, helium or other), specific decay heat to remove per fuel subassembly due to the fuel composition and the fast neutron irradiation. ESNII systems motivate R&D efforts and technological development requiring experimental facilities covering the main topics of interest as: the tribology of mechanical systems and their whole reliability under specific environment, remote operation and robotics applications with the whole enhancement of the safety and reliability of these systems. Stakes dealing with the spent fuel decontamination processes (i.e., cooling fluid residues elimination) and storage are specifically addressed, taking into account the fuel cycle next steps requirements. Innovation is driven by the simplification of the handling systems, their reliability and performances (automation) with the objective to contribute to the industrial relevance of the Generation IV concepts considered. European R&D initiatives are one of the key factors to sustain experimental tools and competencies on such topics taking benefit from multilateral collaborations. Demonstrators design

---

[30] ASN Guide No. 28. Published on 25/07/2017; https://www.asn.fr/Professionnels/Installations-nucleaires/Centrales-nucleaires/Guides-de-l-ASN-dans-le-domaine-des-installations-nucleaires/Guide-de-l-ASN-n-28-Qualification-des-outils-de-calcul-scientifique-utilises-dans-la-demonstration-de-surete-nucleaire;

progress will drive the momentum implying additional needs for risk reduction and qualification of the selected fuel handling technologies.

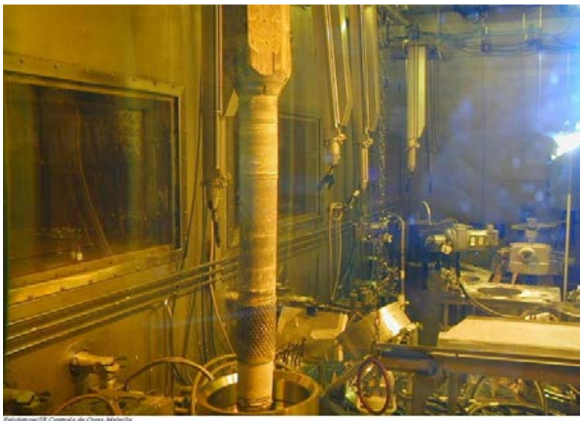

Figure 10: Example of liquid metal elimination on spent fuel at Superphenix plant – left: before cleaning of sodium, right: after cleaning)

4.8. MSR

In accordance with the issues presented in § 3.5 the main topics (strategic options and research areas) to be investigated to confirm the potential assets and the technological feasibility of MSRs are listed hereafter:

1. Study of a chloride MSR Conceptual Design,
2. Development of synthesis routes of chloride fuel salts for use at industrial scale,
3. Selection and qualification of optimized fuel salt composition with respect to its thermo-physical and reactor-physical properties,
4. Qualification of codes for burn-up calculations and of codes coupling neutronics and thermo-hydraulics in liquid circulating fuel reactors,
5. Pyro-chemical processes to recycle Plutonium and minor actinides,
6. Fission product (FP) behaviour and management (removal of FPs, extraction and purification of the valuable FPs such as radioisotopes, platinoids…, disposal of waste FPs, fission gas treatment),
7. Upgrading of existing experimental facilities and commissioning of new experimental platforms, in active and non-active environments, to perform tests on salts, materials, corrosion, instrumentation, control…,
8. Qualification of metallic and ceramic reactor materials for performance under MSR-relevant conditions (temperature, molten salt environment and radiation),
9. MSR safety assessment, in particular in relation to corrosion monitoring and mitigation methods and control of accident situations,
10. MSR maintenance by remote operations,
11. Assessment of the chloride MSRs in the LWR spent fuel multi recycling scenarios,
12. Feasibility of waste transmutation in fast chloride MSRs and assessment of their ability to reduce the inventory of HLW wastes.

These topics are currently addressed by ongoing or coming frameworks and projects in Europe :

ISAC (**I**nnovative **S**ystem fo**r** **A**ctinides **C**onversion). In the **French context** (closed fuel cycle, Pu multi-recycling, transmutation), the focus is on chloride fast MSR technology for actinides conversion (reducing ultimate wastes). The feasibility of the concept will be studied by the French nuclear team (Orano, Framatome, EDF, CEA and CNRS) in the framework of the ISAC national project. The characteristics of the target reactor called **ARAMIS** (**A**dvanced **R**eactor for **A**ctinides **M**anagement **I**n **S**alt) which is considered by this project are:

- Power of around 300 **MWth**
- Americium conversion around **50 kg/TWh**
- Salt NaCl-($MgCl_2$)-$PuCl_3$-$AmCl_3$

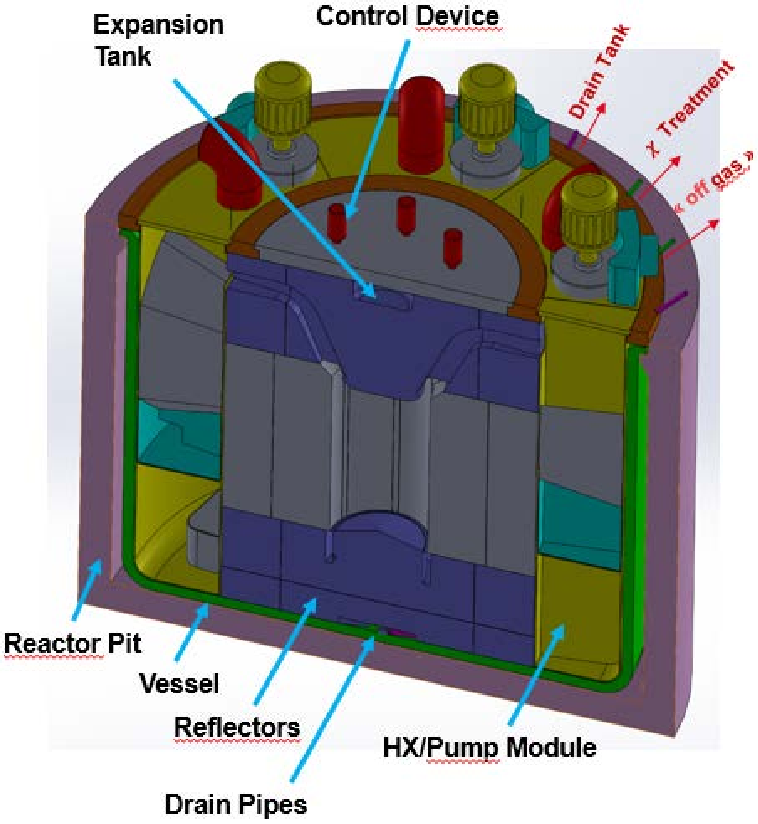

Figure 11: ISAC target reactor

ISAC deals with the topics 1-12

SAMOSAFER (**S**evere **A**ccident **MO**deling and **S**afety **A**ssessment for **F**luid-fuel **E**nergy **R**eactor). The EU-funded **SAMOSAFER** project uses advanced numerical and experimental techniques to prove the safety of MSRs. The project, which represents the first step towards large-scale validation and demonstration of the technology, aims to ensure that MSRs can comply with all expected safety requirements.

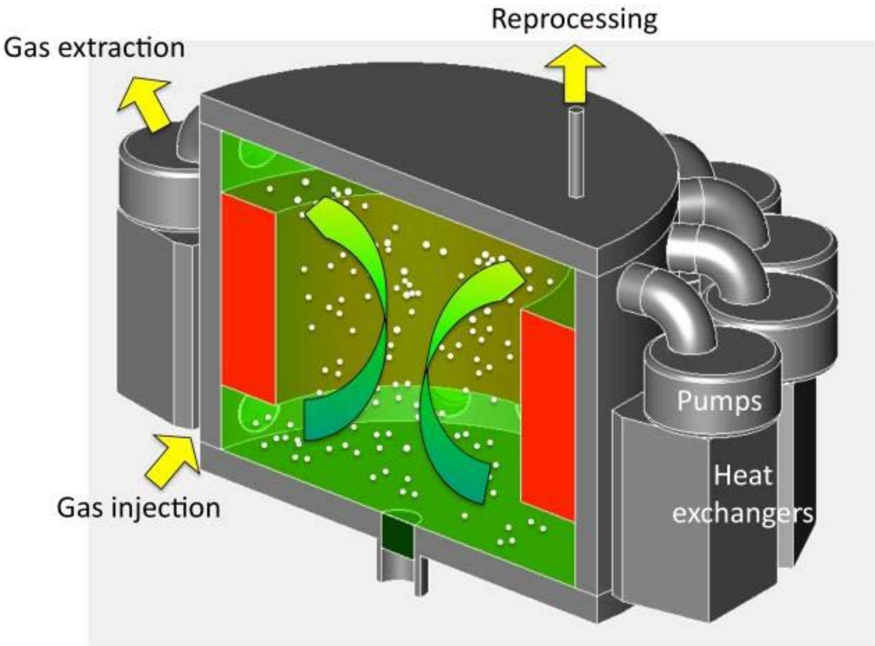

Figure 12: Severe Accident Modeling and Safety Assessment for Fluid-fuel Energy Reactors

SAMOSAFER deals with the topics 3,4 and 9

MIMOSA (**M**ult**I**-recycling strategies of LWR spent nuclear fuel focusing on **MO**lten **SA**lt technology) is a 4-year Horizon Europe project launched in 2022 managed by Orano. **MIMOSA** focuses on multi-recycling scenarios in Europe including chloride fast MSR to manage actinides (plutonium and, depending on the country, minor actinides). The project is not only developing a comprehensive vision of the European energy system including MSR, comparing it with other options of advanced technologies, but also assesses performance and key feasibility aspects of MSR.

MIMOSA deals with the topics 2-9, 11

NRG molten salt capsule irradiation program. Since 2015 NRG conducts an irradiation program in the HFR Petten to investigate fission product behavior, in-pile salt corrosion, effects of radiolysis in salts at low temperature, and mechanical performance of structural materials at MSR-relevant temperatures, in collaboration with JRC, TU Delft and CV Rez. The program aims to provide a basis for the qualification of MSR construction materials as well as validation of models for corrosion and fission product migration.

The NRG program deals with the topics 3, 6-8

Figure 13: (left) LiF-ThF4-UF4-PuF3 salt synthesized at JRC Karlsruhe for the SALIENT-03 irradiation experiment (source: JRC Karlsruhe), and (right) LiF-BeF2-UF4 salt prepared by CV Rez for the SAGA gamma irradiation.

4.9. Robust decay heat removal systems

One of the main principles issues of the safety of Generation IV technologies is the robust decay heat removal (DHR) system. DHR systems are applied in all cases of loss of heat removal from the primary system via standard heat exchangers. Due to strengthened requests on the safety of Generation IV reactors, the DHR system has to fulfil the following design and performance criteria.

From the performance point of view, the DHR system must be able to remove decay power from the fuel, through the coolant, to the ultimate heat sink efficiently in all relevant transients and accidents. It must also, under no circumstance, aggravate the accident beyond its own failure and thus unavailability. For example, it must prevent any ingress of significant amount of moderating or corrosive substances into the primary circuit.

Concerning the design criteria, the DHR system has to ensure its increased reliability, which makes passive solutions[31] preferable, possibly based on technological components of high readiness. The increased reliability also means among others that operators know the status of the system at any point in time of its stand-by or operation, reliance on operators' intervention is reduced, and the number of moving or heavily-loaded (thermally or mechanically) parts is reduced as much as possible. Such design criteria are met in case of passive solutions based on already proven technologies; however, this does not reduce the need for extensive testing and qualification of these solutions before use in a nuclear installation even if it does not need any actively controlled and powered devices and its functionality is based on physical principles only.

The realization is preferred using already proved technologies, it means to eliminate any super-exotic materials or processing. The preferred solutions should be based on technologies at technology readiness level 6 and higher.

[31] The definition of the "passive system" term in accordance with the IAEA-TECDOC-626 "Safety related terms for advanced nuclear plants" https://www-pub.iaea.org/MTCD/publications/PDF/te_626_web.pdf

4.10. Development of out-of-pile and in-pile mock-ups and demonstrators

Among the available research infrastructures, there are few examples, either operational or under construction, able to offer full environmental representativeness of ESNII technologies, through dedicated test channels or experimental loops and integral facilities. A technology implementation plan for the development, testing, and qualification of prototypic elements to support design and licensing of an innovative solution requires a progression from non-nuclear out-of-pile testing through nuclear in-pile testing (where needed), and from lab- to full-scale. Demonstrators provide the capability for the qualification of innovative technologies at high neutron fluxes and temperatures in fully prototypical conditions.

Figure 14 - Test section of the CIRCE facility.

Figure 15 - The TAPIRO fast-spectrum calibration pile.

ESNII demonstrators of relevant size are an essential step in the deployment strategy of the technologies. Beyond offering further qualification capabilities in a representative environment, demonstrators will offer additional capabilities in terms of verification and validation of computational tools and nuclear data, allowing a reduction of related uncertainties. In terms of engineered safety features, additional design provisions to mitigate very unlikely events or sequences of events might be needed if insufficient evidences are provided to exclude such conditions.

Figure 16: The S-ALLEGRO integral facility (GFR mock-up)

4.11. Digitalisation, Modelling and Simulation

The continuous progress in digital technology creates more and more powerful tools like advanced simulation, virtual imaging, augmented reality and artificial intelligence, that are able to increase safety and efficiency of activities in the nuclear domain like design, operation and maintenance.

For modelling and simulations, the general trend includes developments and validation of multi-scale, multi-physics and multi-phase analysis tools as well as uncertainty quantification methodologies. Increasing development and use of artificial intelligence through for example machine learning techniques will speed up progress in the above fields.

This recent technological progress enables applications like the development of digital twins of nuclear reactors that are able to simulate situations close to reality during their lifecycle, from design to decommissioning.

4.12. Harmonization of safety standards

In relation with Technical Support Organisations (TSO's), the Risk and Safety Working Group of the Generation IV International Forum has produced technology-neutral guideline reports and recommendations[32]. It contributes to the harmonization of methods and standards, which is of primary importance for the future of nuclear industry. Applying these methodologies to ESNII technologies and projects is useful in preparation of the licensing process, to get a consensus among the different actors. The licensing process itself is then performed on a national basis.

Experience of safety authorities and technical safety organizations is typically related to light- or heavy-water reactors. Difficulties exist in engaging early dialogues with safety authorities oriented to obtain a pre-licensing review statement. Uncertainties on the licensing process have an impact on the cost estimate of a FOAK. Therefore, demonstrators will offer opportunities to improve design, safety, licensing and financial aspects for future commercial reactors. By implementing prototypical solutions, the time-to-market of ESNII technologies will likely be shortened attracting increasing industrial interest.

[32] https://www.gen-4.org/gif/jcms/c_40424/risk-safety-working-group-rswg

5. ESNII Actions

In order to realise its goals, ESNII firmly aims, in synergy with other SNETP pillars:

- To share a common technological roadmap and to develop synergies among national and EU-funded programs, based on sustainable industrial initiatives.
- To promote and support the research and demonstration programmes needed to implement this roadmap, when the hereunder condition will be fulfilled for construction decision:
    - Availability of the necessary R&D results for design options selection,
    - Relevance for future utilities' needs,
    - Positive feedback from licensing authorities.
- To consolidate the technology roadmap and to promote the construction of the research and testing facilities that are necessary for the demonstration programmes leveraging on the synergies with other research initiatives included in ESFRI (*European Strategy Forum on Research Infrastructures*[33]) and taking into account the ERA (*European Research Area*[34]) vision.
- To establish the common basis of an R&D, industrial and financial partnership, facilitating the constitution of consortia and private-public partnerships for the best exploitation of the developed technologies and projects.
- To provide indications on the design, safety and operational criteria under which the assessment of the identified technological options as well as various complementary and emerging technologies shall be made to establish a sound and timely process for the evaluation of the technologies, the associated projects and their potential.

[33] ESFRI: https://www.esfri.eu/

[34] ERA: https://ec.europa.eu/info/research-and-innovation/strategy/era

6. Abbreviations

ADS	Accelerator Driven Systems
ADRIANA	ADvanced Reactor Initiative And Network Arrangement
AFCEN	Association française pour les règles de conception, de construction et de surveillance en exploitation des matériels des chaudières électro-nucléaires
ALFRED	Advanced Lead-cooled Fast Reactor European Demonstrator
ASTRID	Advanced Sodium Technological Reactor for Industrial Demonstration
ATF	Accident Tolerant Fuels
BN600	is a sodium-cooled fast breeder reactor built at the **B**eloyarsk **N**uclear Power Station, Russia. (600MW)
BN800	is a sodium-cooled fast breeder reactor built at the **B**eloyarsk **N**uclear Power Station, Russia. (800MW)
DHR	Decay Heat Removal
ERA	European Research Area
ESFR-SMART	European Sodium Fast Reactor Safety Measures Assessment and Research Tools
ESFRI	European Strategy Forum on Research Infrastructures
ESNII	European Sustainable Nuclear Industrial Initiative
ETIP	European Technology and Innovation Platform (by the European Commission)
FALCON	Fostering ALFRED CONstruction
GFR	Gas-cooled Fast Reactor
GIF	Generation IV International Forum
HTR	High Temperature Reactor
IAEA	International Atomic Energy Agency
INPA	international non-profit association (under the Belgian law pursuing networking and scientific goals).
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
INSPYRE	INvestigations Supporting MOX fuel licensing in ESNII PrototYpe REactors
LFR	Lead-cooled Fast Reactor
MINERVA	MYRRHA Isotopes productioN coupling the linEar acceleRator to the Versatile proton target fAcility
MOX	Mixed OXides
MSR	Molten Salt Reactor
MYRRHA	Multi-Purpose hYbrid Research Reactor for High-tech Applications
ODS	Oxide Dispersion-Strengthened
PUMMA	PlUtonium Management for More Agility
PUREX	Plutonium, Uranium, Reduction, EXtraction
PWR	Pressurized Water Reactor
R&D&I	Research and Development and Innovation
RF	Russian Federation

SET-Plan	Strategic Energy Technology Plan (issued by the European Commission)
SFR	Sodium-cooled Fast Reactor
SIAP	Senior Industrial Advisory Panel (GIF subgroup)
SMR	Small Modular Reactor
SNETP	Sustainable Nuclear Energy Technology Platform
TRL	Technology Readiness Level
TSO	Technical Support Organization
V4G4 CoE	V4G4 Centre of Excellence
WENRA	Western European Nuclear Regulators' Association

ESNII
European Sustainable
Nuclear Industrial Initiative

ABOUT ESNII

The **European Sustainable Nuclear Industrial Initiative (ESNII)** addresses the need for demonstration of Generation IV Fast Neutron Reactor technologies, together with supporting research infrastructures, fuel facilities and R&D work.

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

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

secretariat@snetp.eu   www.snetp.eu   SNETP   SNE_TP

9 782919 313273