SNETP
Sustainable Nuclear Energy Technology Platform

Deployment Strategy

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Cover illustration: Exterior view of the Civaux nuclear power plant ©EDF - Patrice Dhumes

In a context of electricity demand growth, there is a need for establishing a sustainable, secure and competitive energy system. In alignment with the EU's long-term vision and medium-term policy, the European electricity system must be largely decarbonised and nuclear energy has a major role to play as a low-carbon source of electricity generation, providing secure and affordable electricity for the final customers.

In the SNETP Strategic Research & Innovation Agenda (SRIA) released in 2013, industry, technical safety organisations, research organisations and academia have jointly expressed their vision of nuclear R&D programme development for its three pillars in support of the nuclear energy systems: Generation II (Gen II), Generation III (Gen III), Generation IV (Gen IV) and cogeneration.

This Deployment Strategy document complements the SRIA, and aims to prioritise the SNETP programme over the coming decades to make it fully aligned with the general context of electricity generation in Europe, which includes different energy sources, different national energy policies and societal challenges. Planning assumptions for the nuclear energy systems define the technical milestones to be reached.

The SNETP community has established a global and integrated vision of the R&D programme to be implemented for the next decades and to support the current and future nuclear systems, in consultation with other European technology platforms, and for the sake of consistency with the development of other, non-nuclear electricity sources.

The Deployment Strategy priorities and planning are the result of a challenging and difficult process of prioritisation and consensus-building among the SNETP members. This is expected to reinforce the visibility of nuclear fission R&D programmes to the relevant institutions at EU level, international fora and to the different EU Member States. This will help to identify the eligible financial instruments that are needed to support the R&D activities and research infrastructures.

I would like to express my gratitude to NUGENIA, ESNII and NC2I for their commitment in the preparation of this new version of the Deployment Strategy document.

Marylise Caron-Charles
Chair of the Deployment Strategy
2015 Task Force

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Foreword

Since the very beginning, around 2005-2006, of the idea of setting up technology platforms in support of the European Strategic Energy Technology Plan (SET-Plan), which aims at guaranteeing security of energy supply for the EU and allowing a drastic reduction of greenhouse gas emissions (20% by 2020 in comparison to 1990) through various technological breakthroughs, the EU has now defined its long-term vision and medium-term policy for establishing a sustainable, secure and competitive energy system.

In the framework of the SET-Plan, an integrated roadmap has been prepared, to strengthen links between low-carbon technology innovation, development and deployment and European Energy Policy.

Today, nuclear electricity constitutes nearly 27% of the EU's electricity generation with 131 nuclear power plants; as such it is still the largest low CO_2 emitting electricity source in the EU. Maintaining high levels of safety and competitiveness for the European fleet is a primary objective for the members of SNETP and this requires the support of a large R&D programme and associated research infrastructure. Nevertheless, the nuclear energy sector does not consider this situation as granted for ever and is aware of the evolving environment and the need to develop innovative technology for preparing the future. Among the challenges are: the improvement of long-term sustainability (safety, wastes, economics, public acceptance), the integration into an 'energy' grid with a significant content of variable renewable energy, the management of investment risks for power plant deployment, and of course the new safety constraints resulting from the Fukushima accident.

Therefore in order to position nuclear energy in the European Union SET-Plan Integrated Roadmap and Action Plan, SNETP has consolidated its strategic research and innovation agenda:

- To support the safe operation of present and newly built light water reactors, and allow the development of sustainable solutions for the management of radioactive wastes;
- To prepare the development and demonstration of advanced fast neutron Gen IV reactor technologies associated with a closed fuel cycle to enhance the sustainability of nuclear energy;
- To promote the use of nuclear energy beyond electricity generation namely in cogeneration of heat or hydrogen production or water desalination.

As a consequence of these structuring objectives, SNETP has worked out a new deployment strategy (DS 2015) for the fission R&D programme for the coming decades along with a global vision for the European nuclear energy strategy. A first master plan of technology development has been sketched in this report based on a clear vision of the role of nuclear energy in the future energy mix of the EU and clear planning and priorities for future technologies. This will help the preparation of SNETP members' R&D plans, the reinforcement of joint programming and the sharing of project outcomes with EU Member States, particularly for the construction and operation of large R&D and innovation infrastructures, and will help to identify the available financial instruments for nuclear fission research.

On behalf of the SNETP Governing Board, I would like to express my gratitude to all the persons who helped bring this second Deployment Strategy report into existence and to thank their employers who gave them the needed time to perform this work in due time.

Hamid AÏT ABDERRAHIM
SNETP Governing Board Chairman

Key messages

Since the release of the Deployment Strategy document in 2010, significant evolutions have occurred in the nuclear energy context:

- The European Union fixed targets until 2050 for energy policy, and the countries have implemented specific national legislation with different positions on nuclear energy policy.
- SNETP's structure has been endorsed for providing a collaborative R&D framework to its members, covering three main pillars for nuclear energy system development: light water reactors (LWR), fast neutron reactors (FNR) and cogeneration of heat and electricity.
- Progress has been made in refining the technical objectives and challenges to fulfil the support for nuclear product development and reinforcement of safety precautions following the Fukushima accident, and R&D topics have been defined in depth.

In such an evolving context, the purpose of the Deployment Strategy in 2015 (DS 2015) is to reinforce SNETP's global vision and alignment with nuclear energy challenges. This will be achieved through the following axis:

- The prioritisation of the R&D programmes is established along with a global vision in the general frame of SNETP and its position in the global energy context.
- A clear orientation of the R&D programmes is proposed, while ensuring consistency with the targeted technical objectives for each nuclear system, and this will generate the implementation of R&D projects of high technical value.
- Transversality should be sought for among the different systems and their related technology R&D, and cross-cutting issues have been identified, not only between the SNETP pillars but also with other European technology platforms.

To assess SNETP leadership in nuclear technology R&D, and to make its programme become a major contributor to the European R&D programme, the consistency and complementarity with HORIZON 2020 should be continuously ensured.

1. Today, nuclear electricity constitutes nearly 27% of the EU's electricity generation with 131 nuclear power plants. Maintaining high levels of safety and competitiveness for the European fleet is a major challenge. This requires the support of a large R&D programme and associated research infrastructure.

2. Development must be pursued for supporting LWR new build construction on time and to budget, while continuously improving safety and competitiveness of the next LWR generation, seeking innovation and facilitating an efficient integration within the energy mix.

3. The long-term sustainability of nuclear energy will be ensured by Gen IV fast neutron reactors and closing the fuel cycle, minimising the nuclear waste and offering a transmutation option as well. This will require a large R&D programme for supporting the construction of reactors (prototypes, research facilities, demonstrators) and related fuel cycle facilities.

4. Non-electric applications of nuclear energy could extend the low carbon contribution of nuclear fission to other energy systems by directly providing process heat. The demonstration of industrial feasibility requires the construction of a reactor prototype, high temperature gas-cooled as the best option, which would be coupled to an existing industrial steam distribution network.

5. The fuel cycle and waste management, including decommissioning and dismantling, are the foundation layers of nuclear system deployment, whatever their specific technology. Global optimisation of the fuel cycle should be achieved for long-term sustainability, and interaction should be reinforced with the technology platform dedicated to spent fuel management (IGD-TP).

6. Methodologies should be shared between LWR, fast neutron reactor and cogeneration development for assessing and reinforcing nuclear technologies. This will facilitate nuclear system licensing, construction, deployment and operations in a context where technology is continuously evolving, policy regulation is being modified, and safety requirements are more and more stringent.

7. Basic technology developments open routes for the identification of R&D project clusters for Gen II, III, IV and cogeneration applications. Technology bricks contribute to high-level objectives which should drive, as much as possible, common developments between the three SNETP pillars: performance and ageing of NPPs for long-term operation, high reliability components for structure and fuel, high reliability and optimised functionalities of systems. Closely linked to the R&D projects, research infrastructure including irradiation equipment, computational codes (including for severe accident), and knowledge transfer should be available, and could valuably build a bridge between the different nuclear system developments, and with other ETPs as well.

1. Elements of Context

1.1 Electricity demand evolution

The world's population is projected to increase to 9.2 billion by 2050 from the current 7 billion. The World Energy Council predicts that global demand, for electricity as well as energy as a whole, will increase by one third from 2010 to 2035 and double by 2050.

In their recent *World Energy Outlook 2014*[1], the International Energy Agency (IEA) predicts that the global energy demand will grow by 37% by 2040 in a central scenario. However, the rate of growth, which has been at 2% per year over the last two decades, is expected to fall to around 1% per year after 2025. Energy demand is forecast to be essentially flat in much of Europe, Japan, Korea and North America but to rise significantly in the rest of Asia, the Middle East and Latin America. With respect to electricity, some 7200 GW of new generating capacity will be needed worldwide to keep pace with the growing demand and to compensate for the approximate 40% of existing capacity due to retire by 2040.

Today, fossil fuels make up around 80% of the worldwide energy sources, shared between oil (32%), coal (27%) and natural gas (22%)[2]. In 2014, the IEA predicted that fossil fuels will still make up three-quarters of global energy supplies in 2040, with a roughly equal split between oil, coal and gas.

Fossil fuel substitution, with a view to limiting CO_2 emissions, will inevitably accelerate the continuously growing demand for electricity in spite of energy efficiency gains. Wider access to electricity will be coupled with higher expectations for supply security, meaning that electricity will increase in popularity as fossil fuel reserves diminish and become more contested.

In that context, nuclear energy has a major role to play as a low carbon source of electricity generation, providing secure and affordable electricity for the final customers. In the central scenario of the *World Energy Outlook 2014*, global nuclear power capacity increases by almost 60%, from 392 GW in 2013 to over 620 GW in 2040. Of this growth, China accounts for 45% and India, Korea and Russia collaboratively make up a further 30%; on the other hand, nuclear generation falls by 10% in the European Union. Over the same period, some 200 nuclear reactors (out of the 434 operational at the end of 2013) will reach the end of their operating lives and require replacement.

1.2 Breakdown per technology

Today, nuclear electricity constitutes nearly 27% of the EU's electricity generation with 131 nuclear power plants operating in a mix of liberalised and regulated electricity markets. The nuclear share of electricity varies from 73% in France to 3.9% in the Netherlands (Figure 1).

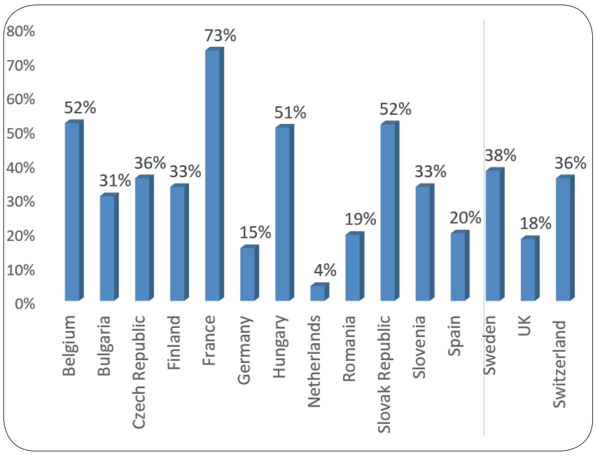


Figure 1. Share of nuclear in total 2013 electricity[3]

In December 2013, the European Commission's DG Energy published its latest update of the publication *Energy trends to 2050*[4] based on data from Professor Capros and colleagues at the Technical University of Athens. The Reference Scenario 2013 shows the following trends in percentage of EU electricity generation by fuel type.

1 - Source: http://www.worldenergyoutlook.org/publications/weo-2014/
2 - Source: IEA 2011
3 - Source: IAEA
4 - Source: http://ec.europa.eu/energy/observatory/trends_2030/doc/trends_to_2050_update_2013.pdf

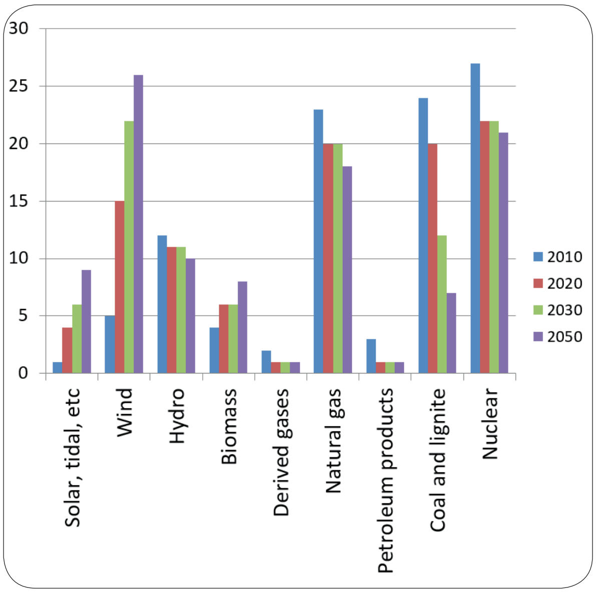


Figure 2. Energy trends to 2050 – EU electricity generation by fuel type

1.3 Energy policy for Europe

The European Union has defined its long-term vision and medium-term policy for establishing a sustainable, secure and competitive energy system:

- The 'Europe 2020 Strategy': 20% reduction of CO_2 emissions, a 20% share of energy from renewable energy sources and a 20% reduction in the use of primary energy by improving energy efficiency by 2020.

- The '2050 Energy Roadmap' adopted on 15 December 2011 envisages different low-carbon scenarios, in which the share of nuclear electricity would vary from below 15-20% depending on the assumptions made, and with reference to a 4800 TWh electrical capacity.

- As a result, the '2030 climate and energy goals for a competitive, secure and low-carbon EU economy' adopted on 22 January 2014 proposes a reduction in greenhouse gas (GHG) emissions by 40% below the 1990 level, an EU-wide binding target for renewable energy of at least 27% and a set of new indicators to ensure a competitive and secure energy system.

In the framework of the European Strategic Energy Technology Plan, an integrated roadmap has been prepared to strengthen links between low-carbon technology development and deployment, innovation and European Energy Policy.

1.4 The nuclear electricity market evolution

The combination of different elements, especially the Fukushima accident that occurred in Japan (March 2011), as well as the financial crisis (2008-2009) and subsequent reduction in large capital investment, has forced a context evolution regarding nuclear electricity generation. Public acceptance is another key factor in the decision-making process for country-specific policy regulation. In Europe, Germany, Belgium and Switzerland have scheduled nuclear phase out, respectively in 2022, 2025 and 2035. On the contrary, the United Kingdom has launched a large nuclear programme and will switch from their current mainly AGR nuclear fleet to LWR technology. Finland, Hungary and the Czech Republic envision a near- to mid-term increase of their nuclear capacity using LWRs too. In France, following a national energy debate organised in 2014, the new energy policy will limit nuclear generating capacity to 50% of France's total output by 2025 (currently 75% of electricity production) and maintain a constant installed capacity around 63.2 GWe as it is today.

Renewable resources will be increasingly deployed and jointly operated with nuclear reactors. The relative contribution of each should be determined via the most inclusive analysis considering whole system costs. For the time being renewables are facing intermittency issues and new technologies, such as for energy storage which still need to be developed. Their connection to the electrical grid will result in new requirements for nuclear energy which will have to accommodate high flexibility demands.

In addition to electricity generation, cogeneration of electricity and heat could open an additional market for nuclear energy of about the same order of magnitude as the electricity market.

1.5 Societal challenges

Environment

Unless there is a dramatic shift away from fossil fuels to low-carbon alternatives, the growth in energy demand will result in global warming becoming a complex and challenging problem for the world. The European electricity system must be largely decarbonised and both nuclear fission power and renewables have a beneficial role to play.

Public acceptance

The rationale behind nuclear energy acceptance is addressed, taking into account the differences in energy policies and public awareness that exist among the different European countries, through the evaluation of the cost and risk of nuclear energy versus its benefits. National policies change with time as a function of the future evolution of their economic and political situation. To build trust and constructive engagement, decarbonisation strategies including nuclear energy need to be made more transparent, inclusive and understood by a broader set of stakeholders. Along these lines, local information committees have been progressively established near each nuclear plant, giving way to the EUROCLI movement and to the application of the Aarhus Convention to nuclear activities. Furthermore, the European Group on Ethics in Science and New Technologies (EGE) proposed an integrated ethics approach for the research, production and use of energy in the EU by seeking equilibrium among four criteria – access rights, security of supply, safety and sustainability – in the light of social, environmental and economic concerns.

Competences, education and training

Competence building, education and training programmes should be developed to address market and societal needs and improve linkages between nuclear energy and its benefits to society and the economy.

European initiatives such as the European Human Resource Observatory in the Nuclear Sector (EHRO-N[5]), the ENEN[6] and the EU's Joint Research Centre databases support EU strategic actions. Mobility of the workforce is a central objective of the EU to foster growth and jobs, which implies a European approach to education and training.

Growth and jobs[7]

Regular operations of the nuclear plants are supporting a total of 900 000 jobs (estimated in 2012), including direct–indirect and induced jobs. This is considered as a base value, for the timeframe 2012–2050. Additional jobs will be created through lifetime extension, new build, decommissioning and waste management programmes.

Since the shutdown and retirement of nuclear plants would destroy the jobs associated with operation and maintenance, the net evolution of job numbers depends on the future role of nuclear power in Europe.

Taking the 'Delayed CCS' scenario from the EC's *Energy Roadmap 2050*, with a share of nuclear energy of around 20% within the EU energy mix, nuclear capacity is projected to be between 100 GW ('diversified' scenario) and 160 GWe ('reference' scenario). Depending on the size of the reactor, an average number of 100 units could be targeted for new constructions.

Under these assumptions, the following orders of magnitude have been calculated:

- Implementation of most LTO programmes between 2015–2035 leading to a total job creation of 50 000 jobs;
- Implementation of new build programmes spread between 2025–2045 or with a possible shift to 2030-2050[9] depending on the LTO programme, and leading to a total job creation of 250 000 jobs (for 100 units);
- Decommissioning and waste management activities will contribute to a total job creation of 20 000 jobs until 2030 and 30 000 jobs after 2030 (or after 2040)[10].

Around 350 000 additional jobs could be created on average over 2015–2050 in the EU by the nuclear industry, with a major part coming from new build construction. Several reactors would have to be built simultaneously to ensure that the required number of reactors is commissioned each year to reach the targets. In terms of created value, around €25 billion/year is expected from new build, €4.5 billion/year from LTO and €8 billion/year from decommissioning and waste management.

5 - Source: http://ehron.jrc.ec.europa.eu/

6 - Source: http://www.enen-assoc.org/

7 - Source: ENEF

8 - Source: ENEF

9 - Source: EHRO

10 - Source: EHRO

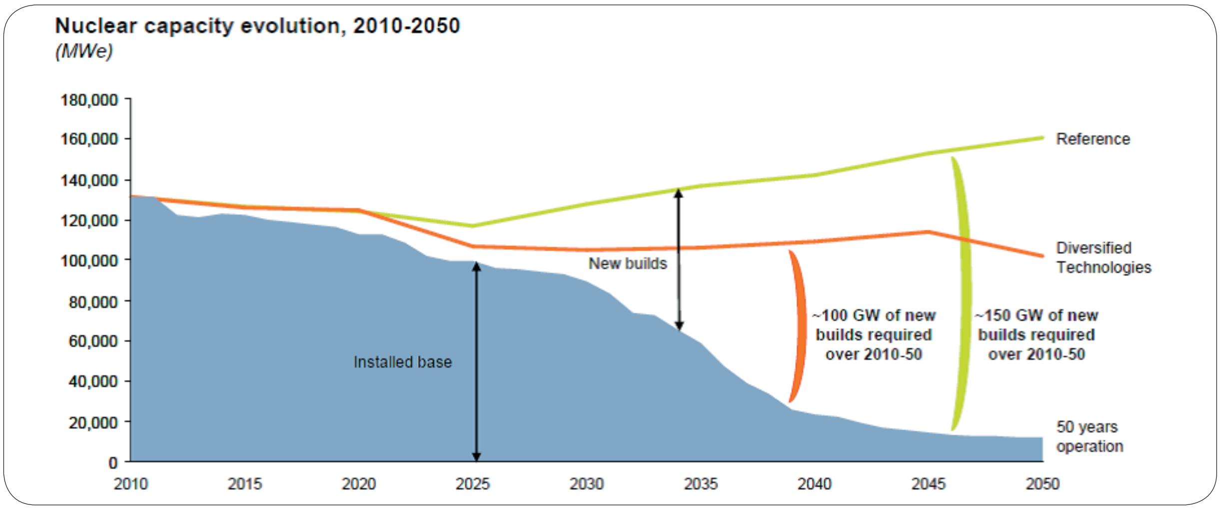


Figure 3. Nuclear capacity evolution according to different scenarios based on Energy roadmap 2050[8]

2. Challenges and planning assumptions for nuclear energy

2.1 Nuclear system technology drivers: safety & performance

Nuclear energy generation is recognised as a mature and reliable technology, under the permanent control of safety authorities, which can supply electricity at stable and competitive prices, generating low greenhouse gas emissions, and with established and secure supply chains for fuel, maintenance operations and new build.

Following the Fukushima accident, safety precautions have been reinforced and extended to so-called 'extreme events', and nuclear industry stakeholders have been committed to implement 'stress tests' performed at national level and complemented by a European peer review. For maintaining a leading role in electricity production, nuclear energy systems need to comply with both a safety and performance vision. This will comprise:

- Continuously updated safety: application of the 'hardened LWR core' concept and additional protection for emergency power and water supply;
- Application of the 2014 revised directive on nuclear safety with reinforced safety objectives, topical peer reviews, enhanced transparency and further means for achieving larger independence of the safety authorities;
- Maintained competitive economics: initial investment, operating cost, long-term operation;
- Increased sustainability: optimisation of resources use and minimisation of nuclear waste;
- Minimisation of environmental impact: waste management, fuel cycle and dismantling.

2.2 Technology evolution of reactors

Around 30% of the worldwide nuclear capacity is installed in European countries, mostly with LWR technology, which forms the Generation II. The European fleet is approximately 30 years old, and utilities are investing in plant lifetime extension beyond their original design lifetime of around 40 years. A 10-year extension can be validated on a case by case basis by the national regulators, but currently a 60-year lifetime has never been achieved in Europe.

According to national policy regulation and to the ageing of nuclear power plants, many reactors will be shut down and decommissioned in the next decades in Europe. In the countries that have selected nuclear energy for electricity generation, Gen II reactors will be replaced with Gen III technology. Compared to the installed Gen II, the third generation of new reactors is designed for improved performance and safety: efficient cost economics for electricity generation, longer term operation with a design life time of 60 years, reduced maintenance and improved safety margins even in extreme conditions. In Europe, two EPRs of the third generation are under construction and LWR technology has already proven maturity.

To keep a leadership position while seeking to continuously improve safety and performance, new and innovative technology features are continuously incorporated in the design and for operations. The expected evolution makes Gen III reactors a key player for electricity production throughout the 21st century.

Whereas most of the LWRs are sized for large generating capacity (1000 MWe-1700 MWe), there is a revival of interest in small and simpler units: the Small Modular Reactor (SMR) features a flexible and progressive means of nuclear capacity optimisation with limited infrastructure and reduced siting costs. They could be attractive for both existing nuclear countries and newcomers who are willing to use nuclear energy for either devolved electricity production (i.e. in remote districts) or process heat applications. The SMR concept based on light water cooling is ready for mid-term commercial deployment. Nevertheless, the small modular approach can apply to the fast neutron reactor and to different coolant technologies such as sodium or heavy metal.

The fourth generation (Gen IV) 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 minimisation and/or transmutation. Challenges related to safety and economic competitiveness are still key drivers to cope with, as well as increasing resistance against proliferation risks.

Sodium-cooled fast reactor development is part of several national programmes at different levels of advancement: the prototypes ASTRID (Advanced Sodium Technological Reactor for Industrial Demonstration) in France and PFBR (Prototype Fast Breeder Reactor) in India, and industrialisation proceeding in Russia (BN800). At the same time, the Accelerator Driven System (ADS) has been selected in Belgium and a large R&D programme supports the construction of the MYRRHA irradiation facility (Lead Bismuth coolant) foreseen for the development of different fast reactor technologies. The lead-cooled fast reactor is considered as a short-term alternative Gen IV technology, with the ALFRED demonstrator selected to be built in Romania and a large R&D programme ongoing in Europe in its support, along with the BREST300 reactor development in Russia. The gas-cooled fast reactor is the longer term alternative Gen IV technology, proceeding with the intermediate objective of building the small demonstration reactor ALLEGRO.

The industrial deployment of Gen IV reactors in Europe is not foreseen before 2050 and will likely be progressively introduced at a slow pace in order to take benefit from lessons learnt from prototype 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 for 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. In Europe, more than 1000 GWh of low temperature nuclear heat was being produced in 2006 in Bulgaria, Czech Republic, Hungary, Romania, Slovakia and Switzerland based on LWR technology. Depending on the targeted temperature range, different reactor technologies are envisioned, among which the high temperature gas-cooled reactor.

2.3 New build

Currently in 2015, around 60 light water reactors[11] are under construction worldwide among which, in Europe, two EPR 1600 MWe (Gen III) in Finland and France and one VVER 40 MWe (Gen II) in Slovakia with a restart of construction after 16 years of suspension. Other construction projects are foreseen, notably 11 new Gen III reactors expected in the UK.

Figure 4. Night view of the construction site of the EPR, Flamanville
(© EDF - Alexis Morin)

Investments in new build reactors have restarted after around one decade with no nuclear construction in Europe. As the construction of a plant involves a lot of sub-contracting, there is a need to re-assess procurement chains, qualified workers and skills, and project management capabilities. Another key challenge faced by nuclear construction lies in the continuous and increasingly reinforced regulatory control and approval, in line with national country practices and policy. All the most stringent are the regulatory constraints for the so-called First Of A Kind reactor (FOAK).

Many reasons can explain construction delay and subsequent cost overruns for new reactor construction, and all of the stakeholders are well aware this could result in public resistance for nuclear energy. All vendors are integrating lessons learnt from FOAK projects to improve their capability to deliver on time and to budget for upcoming projects.

2.4 Fuel cycle

Whatever the reactor technology is, 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[12]. 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

With the open fuel cycle, the spent fuel is not reused or recycled. Instead, all spent fuel is intended to be encapsulated and disposed of in a geological repository. In some European countries, encapsulation facilities and

11 - Source: AIEA / PRIS

12 - Source: IEA 2012

the related geological repositories are at an advanced design stage and the applications to build have been submitted.

Closing the fuel cycle

'Closing the fuel cycle' means that the spent fuel is not considered as waste but is treated in order to reuse the main fissile components, i.e. the plutonium and the uranium, by separating them from the unproductive and radioactive residues. Closing the fuel cycle involves different steps including:

- Fuel reprocessing for the separation of the uranium and the plutonium from the residual waste products
- Conditioning of the high-level waste products through vitrification followed by disposal in a deep geological repository
- Fabrication of recycled fuel in dedicated plants: mixed oxide fuel (MOX) formed from uranium and plutonium oxides with different Pu content depending on the reactor technology

The partially closed cycle with a single recycling of MOX fuel in thermal neutron light water reactors has been practised on an industrial scale for a few decades in several European countries (Belgium, Germany, France, Switzerland and UK).

Recurrent recycling of plutonium (i.e.multi-recycling) is feasible with the use of fast neutron reactors, as considered in ESNII.

A process complementary to the fully closed cycle is 'partitioning and transmutation' in which not only plutonium and uranium, but also the long lived residues (minor actinides) are extracted separately and transformed into shorter lived products and burned in fast neutron reactors.

Waste management

Whatever their fuel cycle option, countries have to manage their nuclear wastes. The quantity, level of radioactivity and lifetime will depend on the open, partially or fully closed fuel cycle. In all cases, responsible waste management is of the utmost importance, and opening a final repository is mandatory. This necessitates a sound final repository concept and design, and appropriate waste forms with related demonstrated performances to comply with the final repository waste specifications.

Waste minimisation techniques and appropriate waste forms should be developed further, leaving no orphan waste and accounting for the long-term behaviour of the waste form in its environment.

A nuclear programme is a very long-term commitment, which includes not only the operation of the nuclear power plants, but also the processing and/or disposal of the fuel.

Transmutation option for high-level waste

The transmutation of minor actinides in fast neutron reactors is an option for reducing the volume of ultimate high-level wastes. This could relax the conditions for geological disposal and could be more acceptable from a societal point of view. Transmutation could of course be envisaged at national level, but a multinational approach in synergy with countries wishing to continue with nuclear energy for electricity generation and aiming for the progressive introduction of fast reactors, therefore needing plutonium resources, is more reasonable. For the transmutation of high-level waste, dedicated burners such as Accelerator Driven Systems are also considered.

Sustainability

Fuel recycling offers a step towards sustainability since the reuse of fissile material allows the saving of natural resources, dependent on the number of recycling operations. In principle, multi-recycling in fast neutron reactors would result in a self-sustaining cycle. At the same time, waste products are concentrated, meaning a reduced volume needing to be stored in deep geological repository.

Cross-cutting issues

Once the Gen IV reactor 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. Initialisation of fast neutron reactor deployment relies on the plutonium produced in LWRs and requires reprocessing and recycling facilities to make this plutonium available for FNR fuel fabrication. In a fast transition scenario, the pace of FNR deployment can be limited by LWR reprocessing plutonium throughput, at least for the first core fuel loading. Dedicated FNR fuel has to be fabricated, i.e. MOX or other types of fuel enriched with plutonium. Then, new or modified reprocessing facilities will have to be brought on line for starting FNR fuel recycling.

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 FNR reprocessing, and with required plutonium throughput increasing step by step, as new FNRs are started and their fuels are being reprocessed.

The pace and extent of this transition to FNR 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.

2.5 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 characterisation, 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 simulation, augmented reality or advanced robotics will mature and offer new opportunities.

In addition, for new power plant or fuel cycle facilities, dismantling will be more and more considered at the design stage, and should comply with safety and efficiency criteria.

2.6 Energy mix

In a wide range of scenarios, nuclear energy is currently recognised as the least-cost option for base-load centralised generation[13]. Given the increased deployment of renewable energy sources, which are intermittent, stability of the overall electricity system will increasingly require load-following mode for the nuclear capacity. Potential changes to electricity production modes need to be investigated in depth. Implementation of load-following mode will impact nuclear reactor operations and lifetime management, since this will induce fast transient regimes from low to full power generation and vice-versa depending on the electrical grid demand, while at the same time needing to ensure efficient cost economics.

Figure 5. Energy mix

New technical requirements for both installed capacity and new build will arise and open routes to innovative technology development for nuclear reactors:

- Enhanced operability of the plant – instrumentation and control
- Impact of variable mode operation and ramp up or down rate on the ageing rate of the plant - materials and structural components
- Alternative options to cycling the reactor power in response to grid demand, such as with nuclear cogeneration configurations
- Fuel cycle management
- Fuel design
- Optimised core control
- Cost economics

13 - ENEF competitiveness SWOT report

3. Major progress since the last SNETP Deployment Strategy DS 2010

Numerous developments have occurred since the last Deployment Strategy document that was issued in 2010. The major outcomes are listed below, confirming the robust implementation of the Sustainable Nuclear Energy Technology Platform.

3.1 SNETP structure endorsement

An outstanding evolution within SNETP lies in its structure evolution since 2010. Today SNETP gathers more than 100 members from industry, technical safety organisations, research organisations and academia. Although SNETP's status remains as it was, a more formal structure has been endorsed for the three initial pillars:

- NUGENIA, a non-profit association founded under Belgian legislation, was launched in December 2011 and mandated by SNETP to cover research on Gen II and III light water reactors, for both the installed fleet and newly built reactors. Currently it counts more than 100 members from industry, TSOs, research organisations and academia. NUGENIA has adopted a three-tier management structure comprising a general assembly, an executive committee and eight technical areas.

- ESNII has been recognised as an industrial initiative under the SET-plan, with an endorsement of its scope by the Belgian EU Presidency in November 2010: Gen IV fast reactors, focusing on sodium-cooled, lead-cooled and gas-cooled fast reactors, as well as accelerator-driven systems. Currently 27 members form ESNII with around half from industry and half from research organisations. ESNII has adopted a two-tier management structure comprising a task force and an executive committee.

- NC2I has been activated as a task force since the beginning of 2010 with the scope: nuclear electricity and process heat cogeneration. NC2I has adopted a two-tier management structure comprising a task force and an executive committee. The Task Force has 12 members and an associated business group.

- Fukushima Task Force: Following the Fukushima accident in March 2011, SNETP mandated a special task force which released a technical report in January 2013. Thirteen topics were identified leading to R&D guidelines towards improved safety in extreme conditions. This has been integrated into the SNETP R&D programme especially within the NUGENIA roadmap.

Figure 6. Strategic Research and Innovation Agenda released in February 2013 by SNETP

3.2 Launching of the SNETP R&D programme

SNETP provides a sound structure for the implementation of its R&D programmes in support of the long-term operation of the current nuclear fleet, the deployment of the new generation of light water reactors, the preparation of the next generation of fast neutron reactors, and the development of non-electrical applications of nuclear energy. The common vision of more than 100 member organisations is formalised into R&D programmes which give orientations for launching collaborative R&D projects. A significant effort on documentation conveys all of the necessary information to its members, whereas governance processes are being implemented to facilitate collaboration, and ensure transparency.

Main events:

- Strategic Research and Innovation Agenda (SRIA) released in February 2013: key challenges of the R&D programmes along with a long-term vision

- NUGENIA+ (September 2013): coordination and support action granted by EU/FP7 and coordinated by VTT, for the purpose of reinforcing the governance and strengthening the synergy within the NUGENIA Association between its members and national and European authorities

- ESNII+ (September 2013): coordination and support action granted by EU/FP7 and coordinated by CEA, for establishing a preparatory phase in support of the development of a federating body for the overall portfolio management

- NC2I-R project (September 2013): coordination and support action granted by EU/FP7 and coordinated by NCBJ, for analysing the market potential of nuclear cogeneration and determining the optimum shape of the future nuclear cogeneration demonstration plant

- NUGENIA roadmap released in 2013, providing a detailed description of the technical objectives, challenges and priorities for each of the eight technical areas

3.3 A European framework for 2014-2020

The Horizon 2020 Research and Innovation Framework Programme is implemented from 2014 until 2020 to support all initiatives in research and innovation that fulfil the objectives of the 'European 2020, 2030, 2050 and beyond' energy challenges. Horizon 2020's priorities include "Excellent Science", "Industrial Leadership", and "Societal Challenges".

Figure 7. Horizon 2020 illustration and EC logo

The Euratom Horizon 2020 Framework Programme provides EU incentives or grants for nuclear fission, in line with the strategy implemented by the European Commission together with the EU Member States.

Horizon 2020's comprehensive objectives and integrated approach make available common implementation instruments across the Euratom and EU framework programmes, such as the European Energy Research Alliance (EERA) and its Joint Programme on Nuclear Materials, the European Institute of Innovation & Technology (EIT[14]) and its Knowledge and Innovation Communities (e.g. KIC InnoEnergy with a programme on the convergence of nuclear and renewable energies), the support for research infrastructures and activities, Marie Skłodowska-Curie Actions[15], the activities of the Joint Research Centre[16] (JRC) and so on.

Horizon 2020's Euratom work programmes promote joint programming in research, working together to tackle common challenges more effectively using Research and Innovation actions (RIA), Innovation Actions (IA), Coordination and Support Actions (CSA) and European Joint Programmes (EJP) designed to support coordinated national research and innovation programmes.

Furthermore, in addition to Horizon 2020 other EU funding sources can contribute to the objectives of the SNETP Deployment Strategy, such as, inter alia:

- Infrastructure-related financing, in particular via the European Regional Development Fund (ERDF)
- The European Fund for Strategic Investment (EFSI), cornerstone of President Juncker's €315 billion plan
- Other loan instruments such as InnovFin (for innovative projects) or the EURATOM Loans (for nuclear infrastructure)

14 - http://eit.europa.eu/

15- http://ec.europa.eu/programmes/horizon2020/en/h2020-section/marie-sklodowska-curie-actions

16 - https://ec.europa.eu/jrc/

4. Strategic vision for SNETP programme deployment

The SNETP structure has been endorsed to provide a collaborative R&D framework to its participants and to cover three main pillars for nuclear energy system development: light water reactors, fast neutron reactors and cogeneration of heat and electricity.

For each system, progress has been made in refining the technical objectives and challenges to support nuclear product development and to define R&D topics in depth. In such a context, SNETP programmes need to be deployed with a global vision:

- Prioritisation will be established, not only for each system, but also within the general frame of SNETP and its high-level objectives to meet nuclear energy challenges.
- A clear orientation of the R&D programmes needs to be proposed, while ensuring consistency with the targeted technical objectives for each nuclear system, and this will promote the implementation of high technical value R&D projects.
- Transversality should be sought for among the different systems and their related technology R&D, and cross-cutting issues need being identified, including with other European technology platforms.

4.1 NUGENIA

NUGENIA features an integrated framework for safe, reliable and competitive Gen II and III light water reactor technology development. The overall programme is described in the NUGENIA Roadmap document and the portfolio of R&D projects is managed and delivered by experts achieving excellence in nuclear fission research.

Figure 8. NUGENIA logo

Objectives

The NUGENIA research programme was established as a set of technical areas (TA) with their own fields of expertise, in order to cover all issues related to Gen II-III operations, while seeking improved safety and performance. The installed base as well as newly built reactors are considered within the European fleet, mostly using LWR technology.

As a complementary approach to TA specific challenges, cross-cutting challenges have been identified and are included in the high-level objectives of the NUGENIA programme:

- Improve safety in operation and by design:
  - To identify preventive and protective measures against all types of external or internal events and identify the way to efficiently and effectively implement them in current and future reactors.
- High reliability and optimised functionality of systems:
  - To ensure the safe operation of systems in Gen II and III NPPs through high reliability and optimised functionality by producing unified Europe-wide guidance for nuclear energy stakeholders.
- High reliability of components:
  - To ensure the safe operation of components in Gen II and III NPPs through high reliability by technological development of the fabrication processes for structural and fuel components resulting in improvements in maintenance and inspectability.
- Improve modelling of phenomena in NPPs:
  - To demonstrate the reliability and predictability of the advanced simulation codes based on the

interaction and coupling of different physical processes and providing them with opportune and extended validation for design needs and safety-assessment use, relying upon the existing data base from mock-up experiments and operation feedback.

- Increase public awareness:
  - To address the rationale behind nuclear energy acceptance/resistance and public opinion, taking into account the differences in energy policies and in the public awareness which exist among the different European countries.

- Efficient integration of NPPs into the energy mix:
  - To ensure flexible LWR operations with large load cycle for using mixed energy sources in the most efficient way. To cope with the unstable grid caused by renewable energy, which is intermittent, while waiting for energy storage capacity, advanced technology has to be developed for optimising LWR manoeuvrability and dealing with the resultant consequences on plant life time management (e.g. durability of materials, component ageing, fuel cycle, water chemistry, I&C, cost economics).

- Prepare the future to avoid technology obsolescence:
  - To accurately identify key components or systems where obsolescence needs to be avoided because of the impact on NPP safety and availability. Obsolescence mitigation procedures and recommendations need to be developed.

- Performance and ageing of NPPs for long-term operation:
  - To obtain enhanced understanding of the ageing degradation mechanisms and make available approaches and tools for effective monitoring and mitigation to guarantee that the ageing effects are properly managed and analysed (e.g. by time limited ageing analysis.

Scope

The high-level objectives clearly reinforce the consistency of NUGENIA's research programme by providing clear visibility of its ultimate goal: to secure the safe operation of nuclear power plants while maintaining their competitiveness and the contribution of nuclear energy in the mix towards the reduction of carbon emissions. To achieve that, research is needed in all of the steps from design to operation and decommissioning, and in all components and materials. This research should enable improvement of the understanding of their behaviour and the margins for safe operation, as well as improvements that might contribute to extending the safe operating margins.

As described within the NUGENIA Roadmap and reported in the Strategic Research & Innovation Agenda (SRIA 2013), the NUGENIA research programme is broken down into eight technical areas of expertise:

1. Plant Safety and Risk Assessment
2. Severe Accidents
3. Improved Reactor Operation
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. Harmonisation
8. In Service Inspection, Inspection Qualification and NDE Evaluation

SNETP should play a driving role in supporting NUGENIA because the latter can contribute significantly to enhancing safety and improving the economic exploitation of safe nuclear energy within the European countries, by gathering the forces of the main actors in the field (industry, research organisations, TSOs, universities, small & medium private companies) to define and conduct the most suitable programmes addressing current and future NPPs.

Research and innovation actions

TA1 Plant Safety and Risk Assessment

Assessment of nuclear power plant safety and risk is a vital task and even a necessary condition for plant licensing, startup and safe operation. The original approach using conservative deterministic analyses of the spectrum of transients and accidents up to the maximum design basis accident (DBA) documented in the safety analysis report (SAR) has been gradually extended by probabilistic risk assessment, human reliability analysis, assessment of external hazards, application of best-estimate methodology to safety analyses, analyses of extended design basis events etc.

The extension of plant safety and risk assessment is accompanied by the development of computational tools that are utilised for safety and risk assessment. Advanced computer codes used for DBA and extended design basis analyses are continuously developed. A shift from 1-dimensional to 3-D modelling, coupling of system thermal-hydraulic codes with core physics and/or computational fluid dynamics codes (CFD) are the tasks being solved at present. The methods and programmes utilised for probabilistic risk assessment have been developed for the extension of PSA to internal and external initiating events (fire PSA, seismic PSA, flooding PSA...), for the extension also to level 2 PSA analyses, which include fission product release assessment for core melt situations. These methods and programmes have been improved to integrate more complex plant risk analysis including detailed human reliability analysis (HRA), digital I&C system reliability analysis, accounting for common cause failures, considering long-term situations etc. The combining of deterministic and probabilistic methods is also a very promising direction for plant safety assessment.

The advanced methods and tools for plant safety and risk assessment enable the upgrading of reactor safety systems to handle new safety demands, effective replacement of obsolete components and support of LTO.

TA1 sub-areas of Research and Innovation actions

- Data, methods and tools for risk assessment
- Deterministic assessment of plant transients
- Impact of external loads and hazards on the safety functions
- Effect of electrical grid disturbances
- Effect of human errors and reliability evaluation
- Advanced safety assessment methodologies
- Design of reactor safety systems

TA2 Severe Accidents

The risk of severe accidents (SA) can be substantially decreased when state-of-the-art devices or systems for prevention and mitigation are installed. Lessons from the Fukushima accidents and recommendations related to accident management provisions from the recently completed ENSREG stress tests and other national activities are to lead to further enhancement of NPP safety.

The Severe Accident NETwork of excellence (SARNET) was integrated into TA2 in mid-2013, with an extension to environmental impact and emergency management. General objectives are defined and followed by specification of research and innovation challenges to further reinforce the NPP safety provisions.

Some predominant phenomena require a better understanding to improve the severe accident management guidelines (SAMGs), to design new prevention devices or new systems to mitigate SA consequences (or even terminate a SA), and support the emergency management, whenever needed.

Six main R&D objectives are addressed in TA2, the three first ones being directly linked to mitigation processes:

- Increase the efficiency of cooling a degraded core
- Preserve the containment integrity

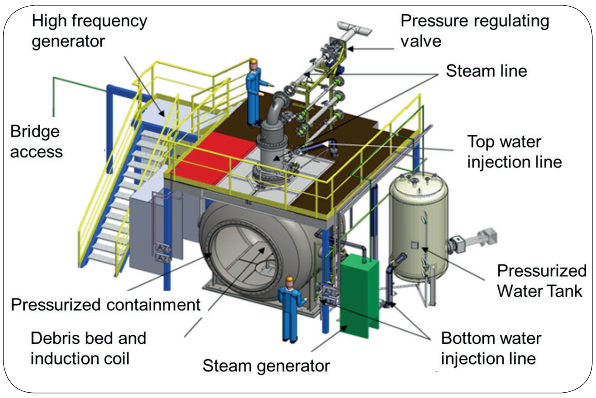


Figure 9. PEARL facility (IRSN) - large scale reflood tests on debris bed

- Reduce the source term (radioactivity released - from NPP to the environment)
- Reduce the uncertainty of the assessment of SA environmental impact
- Understand the evolution of complete SA scenarios
- Improve emergency preparedness and response

TA2 sub-areas of Research and Innovation actions

- In-vessel corium / debris coolability
- Ex-vessel corium interactions and coolability
- Containment behaviour, including hydrogen explosion risk
- Source term
- Severe accident linkage to environmental impact and emergency management
- Severe accident scenarios

TA3 Improved Reactor Operation

The TA3 is devoted to improving the technical and economic characteristics of reactor operations by various measures and to minimising the radiological impacts on plant workers, the environment and the public during normal reactor operations, including periods of shutdown, reshuffling, abnormal and emergency situations, but excluding severe accidents.

R&D topics on core physics and reactor operation are considered, such as reactor loading strategy, operation and control, management of the impact of the plants on the environment and man via effluents, chemical processes and radiation. It also includes R&D on human and organisational factors. In fact, safe and efficient operation of NPPs relies upon a suitable mix of human, organisational and technological aspects, among which human behaviour and organisation play a major role. Fields of endeavour have been identified within TA3, directly impacting safe, secure and economic reactor operations.

The scope of TA3 is defined with close interfaces with the other TAs while avoiding redundancy and seeking for complementarity, notably with safety issues, fuel thermo-mechanical behaviour, topics linked to system-structure and component integrity, in-service inspection and ageing management. Innovative technology solutions are considered too.

TA3 sub-areas of Research and Innovation actions

- Improvement of operation economics
- Human and organisational factors
- Integration of advanced digital technologies and solutions for cybersecurity
- Improvement of core management modelling tools and core monitoring and instrumentation
- Water chemistry and low level waste management
- Radiation protection

TA4 Integrity Assessment of Systems, Structures and Components

The objective of TA4 is to improve knowledge and methods in order to ensure high integrity and high performance in the case of internal and external loads, to increase safety and availability and control the lifetime of systems, structures and components (SSCs). While the assessment principles relating to SSCs are generally comparable in Europe, the actual methodologies and codes are different in the various European countries. With the longer term objective of European harmonisation in mind, it is necessary that the differences are fully understood and for the lessons learnt from Gen II nuclear power plants to be taken into account when developing and/or revising best practice guidance for the safe operation of SSCs with satisfactory, but not over-conservative safety margins.

In this technical area, all the material families included in NPP components are addressed: metallic components, civil works (concrete structures), polymers and cables, and instrumentation.

Issues such as the effects of load history, crack arrest, treatment of thermal and weld residual stresses and warm pre-stressing effects need to be considered. Modelling activities incorporate the knowledge from the mechanistic understanding into simulation tools, and into procedure assessments as well. The whole set contributes to the prediction of theoretical margins for the safe operation of NPPs taking into account structural features, real or postulated flaws, applied loads and resulting stresses (and strains), and relevant material characteristics including ageing effects.

Increased computing power over recent years, coupled with advanced modelling capabilities, and improved characterisation capabilities lead to the evaluation of the margin accuracy in greater detail, for example piping system loads and stresses resulting from pressurised thermal shock loading or fluid structure interaction.

For accurate plant life management it is essential to perform analyses for understanding and modelling the main ageing mechanisms concerning each SSC (potential or encountered). 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. The updating and/or development of new monitoring methods, diagnostics and monitoring simulation tools that will greatly increase ageing management efficiency has to be improved.

Prevention and mitigation measures require the development of efficient and applicable preventive measures and repair technologies.

Harmonisation documents summarising results and drawing conclusions from completed TA4 projects (in case such documents have not been issued for the project itself) have to be issued and the output/results of completed TA4 projects have to be prepared in such a way that they can be used as input for harmonisation in TA7, i.e. guidance documents, pre-codification projects.

TA4 sub-areas of Research and Innovation actions

- Integrity Assessment
  - Update of design curves, use of advanced tools and best practice procedures
- Description of loads
  - Advanced tools and methods for fluid to structure interaction modelling
- Materials performance and ageing
  - In-depth understanding of ageing mechanisms in environmental conditions
  - Development of testing procedures and advanced modelling tools using a multiscale approach to predict industrial component behaviour for long-term operation
  - Guidelines and rules for manufacturing conditions and material performance (e.g. cold work, metallurgical heterogeneities, heat treatment…)
- Ageing Monitoring, Prevention and Mitigation
  - Online monitoring tool development
- Equipment qualification
  - Development of unified EU technical obsolescence management methods and procedures
- Qualification
  - Development of specific and well controlled standard methods (e.g. tests on small specimens) to assess material behaviour under specific degradation mechanisms

Figure 10. X-ray control of a tank welding (Source: IRSN)

TA5 Fuel Development, Waste and Spent fuel Management and Decommissioning

Fuel behaviour currently is, and will continue to be, a major issue for the safe, secure and economic operation of nuclear power plants. An understanding of fuel behaviour is underpinned by fuel R&D, which must address new design and safety requirements, increase in uranium enrichment, actinide recycling, power up-rating, and increased cycle length and burn-up. It must also address differences in behaviour engendered by the incremental changes in the fuel design. Both spent nuclear fuel management and radioactive waste management have reached a relatively matured state, but still immense potential would be extracted through the optimisation of management steps and the introduction of more efficient and reliable technologies resulting in reduced cost and lower environmental impact.

Moreover, the number of nuclear facilities in decommissioning is to increase sharply; therefore development of remote dismantling techniques and dose minimisation approaches are needed along with reliable methods of reuse and recycle of bulk materials and release of other materials to the environment.

Figure 11. Hot cell for fuel characterisation (courtesy from NNL)

The rationale of TA5 is the improvement of reliable and economic operation of NPPs (specifically in-reactor and outside-of-reactor nuclear fuel management and radioactive waste management) and to maintain the sufficient level of safety defined by the regulatory bodies and reflecting the recommendations of the relevant international organisations, mainly through:

- Increasing fuel safety margins
- Reducing reactor operating costs (including fuel costs)
- Minimising the amount and/or radiotoxicity of spent fuel
- Recycling existing waste (uranium, plutonium and minor actinides from prior reprocessing operations)
- Increasing sustainability
- Improving proliferation resistance

TA5 sub-areas of Research and Innovation actions

- Fuel development for existing, advanced and innovative fuel designs
- Fuel behaviour mechanisms and computational codes, for normal and accidental situations
- Fuel treatment, transportation and interim storage (spent fuel management)
- Waste and spent fuel management
- Dismantling and decommissioning

TA6 Innovative LWR Design and Technology

Innovation will be the key driver of the TA6 programme for supporting the incorporation of innovative technology into light water reactors, with a view to achieving:

- Long-term operation by design
- Safety by design
- Innovative components for reduced maintenance
- Enhanced economics

The overall R&D project portfolio, in addressing the operations of current reactors and the development of new LWR concepts as well, will be established using a consistent approach between different sub-areas which will also interact with all of the other NUGENIA areas.

As commonly recognised, material performance holds the key to fundamental advances in energy production systems. Advanced and breakthrough technologies in material processing areas need to be developed for producing innovative materials, with multi functionalities (e.g. multi-layer, composite), and fine-tuned properties (e.g. surface engineering). The fabrication of nuclear components with enhanced resistance to more stringent environmental conditions and/or for new requirements (e.g. compact components for small modular reactors) will be investigated too, using for example new metallurgy processes.

New light water reactor models will be screened, in order to foster and provide guidance for the development of technology, especially for materials and component fabrication processes. Specific safety approaches should be integrated within the early stages of design operations and should be consistent with existing safety requirements or new ones under development.

Key success factors for innovative LWR reactor deployment will be investigated with consideration given to the deployment of next power generation capacities, including Gen IV systems potentially beyond 2050 for the sodium fast reactor, and the growing contribution of renewable energy sources. Different routes should be explored: scenario evaluation using a wide range of combinations of electricity sources, impact of renewable energy sources which are intermittent, on LWR flexible operation and subsequent requirements on plant life time management (e.g. availability, component ageing, cost economics).

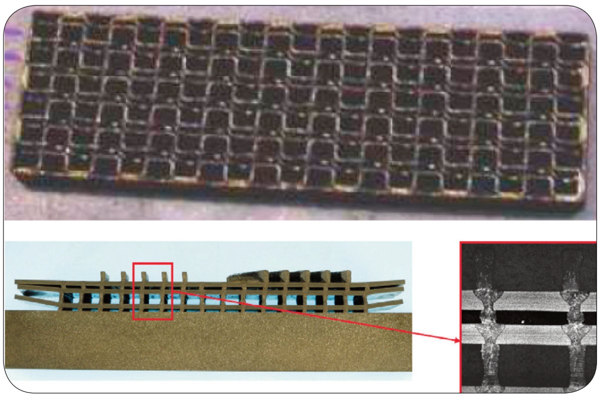


Figure 12. Example of innovation using powder metallurgy process for nuclear component

Knowing that new technology deployment at the industrial scale could be a long process, the following timelines will be considered:

- Proposing evolutionary technology for mid-term application

- Developing new LWR designs expected to be ready for commercial operation within 15-20 years
- Preparing breakthrough technology for the longer term future

TA6 sub-areas of Research and Innovation actions

- Innovative technology for reactor component design & construction
- Innovative LWR concepts such as: high conversion ratio LWR, small modular reactors
- Innovative LWR-specific safety approach
- Key success factors for innovative LWR deployment
- Public acceptance drivers for new builds

TA7 Harmonisation

Harmonisation in the civil nuclear domain is a cross-cutting topic aiming at settling best practices, codes and standards. It is aimed at reducing any substantial difference within a group of countries in nuclear safety requirements and objectives, safety assessment procedures and practices, as well as fabrication, verification and operation procedures for systems and components. It implies the search for a long-term convergence which guarantees respect of agreed general objectives and principles - and the shared way to achieve them. This requires an organised and structured ascending abstraction process relying upon shared best practices, which needs suitable data, the collection of which should be supported by pre-normative research[17].

17 - That is why TA7 will be managed as a transverse layer to all of the other TAs.

The objectives of harmonisation in Europe are meant to bring improvement in three different fields of endeavour:

- Improving the safety level of the nuclear installation through shared design approaches and licensing processes
- Supporting the deployment of nuclear energy within the European market and setting up the basis for an effective standardisation of reactor component assessment
- Benefiting public acceptance and cost reduction

Considering the goal to promote the safe and efficient operation of nuclear installations, and the participation of the main stakeholders, NUGENIA is to provide the scientific and technical basis for efficiently and effectively harmonising criteria, methodologies and practices in the nuclear fission field and propose guidelines for their implementation.

TA7 sub-areas of Research and Innovation actions

- Undertake pre-normative research for new design and operating conditions, but also for establishing operating limits, improving safety criteria and promoting best practices
- Develop improved methodologies and provide the technical basis for design and assessment of reliable NPPs
- Contribute to the establishment of shared codes and standards through oriented research
- Adopt a harmonisation strategy with smooth and efficient methods to enlarge progressively the field of consensus among stakeholders

TA8 In-service Inspection, Inspection qualification and Non-Destructive Examination

In-service inspection of nuclear power plants is a powerful tool for supporting safe and reliable long-term operations. The European Network for Inspection and Qualification (ENIQ) has been integrated into TA8. This is a utility-driven network aiming at establishing a harmonised European approach to reliable and effective in-service inspection (ISI) using non-destructive testing (NDT) techniques, and risk-informed ISI as well.

A comprehensive study on the performance of non-destructive testing techniques, such as computed and digital radiography will provide a consistent approach for the qualification and the production of technical justifications.

Risk informed ISI strategy for the control of specific degradation mechanisms needs to be consolidated and continuously updated, notably for the specific degradation mechanisms related to NPP long-term operation. For example, in the field of fatigue under environmental conditions, the number of locations to be examined is increasing with the ageing time. A robust strategy will result in optimised in-service inspection with reduced risk.

Lastly, for harmonising the practices used in the different countries while reinforcing their consistency, reliability, and assessing their qualification, collaboration and exchange of information provides a strong support. Continuous transfer of knowledge between experts can involve ISI personnel as well.

TA8 sub-areas of Research and Innovation actions

- Qualification, dealing with the qualification of in-service inspection systems
- Risk, focusing on risk-informed ISI (RI-ISI)
- Inspection Qualification Bodies providing a forum for information and experience exchange between independent qualification bodies

Figure 13. Installation inspection (©EDF - Pierre Merat)

In addition to these technical challenges, a formal procedure for the periodic review of all the documents released by ENIQ ensures their relevance, validity and applicability.

NUGENIA programme prioritisation

The NUGENIA research programme is planned for the next 20–25 years for supporting light water reactor technology during the current existing reactor operations, new build construction and the preparation of the next LWR generation as well. Prioritisation of the NUGENIA programme is proposed using a transverse approach between:

- NUGENIA high-level objectives and cross-cutting challenges between the eight TAs
- Technical objectives and challenges in the field of expertise of the 8 technical areas

A complementary way of supporting the prioritisation process among NUGENIA partners lies in evaluating research topics according to:

- National and individual needs
- Outcome of finished collaborative projects
- Links between national and NUGENIA challenges
- Prioritisation according to each TA process

Technical objectives, specific challenges and major milestones to be reached within the next 20 years have been listed in **Table 1**, with a view to highlighting the main orientations of the NUGENIA programme. This covers base technology and methods for structural components, fuel, operations (normal, abnormal and accidental) and systems, to be developed along with the aim of improved safety, performance, harmonisation 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, harmonisation, or for up-scaling innovative technology development to onsite application.

Funding resources: public/private

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

R&D project generation and partnerships are facilitated through the use of the NUGENIA Open Innovation Platform (NOIP). The process is well defined for posting project ideas in the appropriate technical areas and sharing input with other potential contributors, until project labelling by NUGENIA Executive Committee takes place. Different funding schemes are then proposed by NUGENIA.

Regarding the overall cost of R&D in support of Gen II-III, this has been evaluated to be around €400 million/year in a previous study[18]. 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.

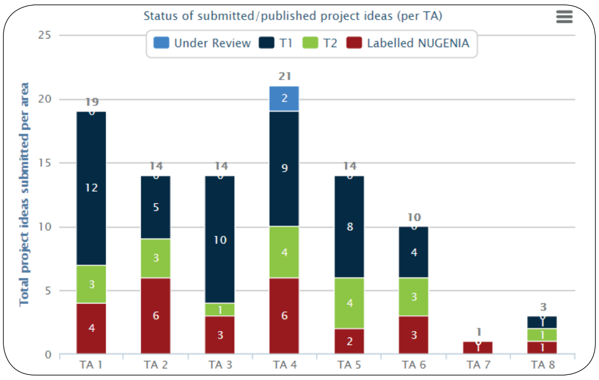


Figure 14. Number of current projects submitted (per TA) in the NUGENIA Open Innovation Platform (NOIP) - December 2015

18 - SNETP Deployment Strategy document released in 2010

High level objective	Technical objective	R&D topics	Expected major milestone (T0 + X y)
Improve safety in operation & by design	Minimise the impact of internal and external loads and hazards on the safety functions	Improve methodologies to assess impact on barriers, structures, systems and components considering single and multiple events,	T0 + 5 - 10y
	Eliminate accidental sequences that could yield very important consequences	Developing methods to better assess the probability of rare events and their consequences	T0 + 5 - 10 y
	Develop advanced safety assessment methodologies	- Integrating deterministic and probabilistic safety assessments in order to better quantify safety margins with best estimate methods - Dynamic PSA	T0 + 10 y
		Implementation of stress tests in Europe	T0 + 5 - 10 y
	New systems for mitigating consequences of severe accidents	- Identification of solution - Validation & qualification	T0 + 5 -10 y
High reliability & optimised functionality of systems	Operational excellence	Innovative asset management approaches, sharing of best practices	T0 + 5 - 10 y
	Reliability and security of digital systems	Maintaining the necessary cybersecurity level by continuous improvement	T0 + 5 - 10 y
	Reliability of NPPs as complex socio-technical systems	Development of system resiliency concept (interaction of safety, human organisation capabilities and I&C systems)	T0 + 5- 10 y
High reliability of fuel	Accident tolerant fuel	Identification of candidate materials for fuel, cladding and components	T0 +5 y
		Advanced material assembly in test reactor	T0+ 10 y
		Production of lead test assembly on accident tolerant fuel type	T0+ 20 y
High reliability of structural components	Increased resistance of materials under severe and/or more stringent conditions	- Advanced surface engineering technology - Advanced capabilities for in depth characterisation and long lifetime assessment - Advanced /innovative material including with multi functions	T0 + 5 – 10 y T0 + 5 – 10 y T0 + 10 – 15y
	Increase integrity of components	Develop improved methods for assessing integrity of systems, structures and components	T0 + 5 – 10 y
	Improved and advanced processes for fabrication, manufacturing and assembly	- As low as possible no. of defects in component fabrication, especially for large components - Improve numerical simulation of manufacturing and assembly process - Master finishing operations - Qualify powder metallurgy process for nuclear application	T0 + 5 – 10 y T0 + 5 – 10 y
	Equipment qualification & control	- Advanced NDE - Instrumented component from design & fabrication to installation - Advanced methods for on-site surveillance	T0 + 5-10 y continuous

Table 1: NUGENIA R&D programme prioritisation in support of installed reactor base and new LWR construction

High level objective	Technical objective	R&D topics	Expected major milestone (T0 + X y)
Improve modelling phenomena in NPPs	Fully validated codes for severe accidents	- Improved modelling of severe accident phenomenology and management - System code and CFD code validation - support existing tools and build new ones when necessary	Continuous T0 + 5 – 10y and continuous
	Develop predictive software platform based on multi-physics and multi-scale modelling	Advanced capabilities & methods in material behaviour – neutron physics – fluid dynamics- chemistry - Coupling between different phenomena - Provide accurate test results for validation and qualification	T0 + 5-10y and continuous evolution
Efficient integration of NPPs in the energy mix	Define NPPs' role in a country-specific generation mix	Assessment of functions for stabilisation of transmission grid	T0 + 5 y
	Identify consequences of more flexible operations on NPP management and cost	- Impacts of dynamic loading on material ageing - Improvement of core and fuel management - Impacts on performance characteristics and development of economic strategies	T0+ 5-10 y
	Implementation of flexible operations on existing plants – Flexibility by design for new build	Continuous plant modification : I&C – component management – fuel cycle Implement measures allowing the minimisation of grid instability risks	 T0 + 5 – 15 y T0 + 10 – 15 y
Performance and ageing of NPPS for long term operation	Demonstrate structural integrity of NPP components at regular intervals throughout lifetime	- Reliable design curves valid for environmental conditions - Plant data to underpin the safety case using structural integrity by surveillance programs - Advanced capabilities for load evaluation: fluid to structure interaction – Pressurised thermal shock… - Advanced capabilities and methods for accurately predicting material ageing with best estimate margins (chemistry – irradiation – thermal ageing – fatigue – crack initiation…)	T0+ 5-10 y T0+5-10y T0+ 5 – 10y
	Develop on-line /on-site monitoring & diagnostic - NDE	Support PLIM- PLEX in implementing structural health monitoring	T0 + 5-10y
		Instrumented components from design & fabrication to installation	T0 + 10 - 15y
		Crack detection beyond 60 years	T0+10 -15y
		Update in-core measurement - SPND	T0 + 5 - 10 y
Prepare the future to avoid technology obsolescence	Continuously update technology and practices Foster harmonisation	- Ensure technology transfer and dissemination - Incorporate innovative technology - Update codes & standards through pre normative research	continuous
Increase public awareness	Dissemination and transparency of the information, especially on safety	New information channels and use of social media to increase public awareness	T0 + 5 y continuous
		New participatory approaches in decision making	T0 + 5 – 10 y continuous

Table 1: NUGENIA R&D programme prioritisation in support of installed reactor base and new LWR construction

4.2 ESNII

Figure 15. ESNII logo

Objectives

Fast reactors will allow a large decrease in natural resource (uranium) comsumption, at least by a factor of 50. In this way, it is clear that the use of fast reactors with a closed fuel cycle approach will allow more sustainable implementation of nuclear energy. One of the major concerns of society with regard to 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. The main objective of ESNII is to maintain European leadership in fast spectrum reactor technologies that will excel in safety and will be able to achieve a more sustainable development of nuclear energy.

Scope

With regard to reactor technologies, four main projects are promoted within ESNII addressing the following major challenges:

- To design-license, construct and start commissioning the ASTRID (sodium-cooled) prototype and MYRRHA (lead-bismuth cooled) research facility between 2025–2030
- To perform the necessary R&D and design work for ALFRED (lead-cooled) to start construction before 2030
- To investigate and support the feasibility of ALLEGRO (gas-cooled)

The second strategic priority within ESNII lies in developing the different building blocks for the fuel cycle technologies:

- A fuel fabrication plant for fast reactor MOX driver fuel (pelletised)
- A reprocessing plant
- A dedicated fuel fabrication facility for transmutation fuel

The important technical choice of pelletised fast reactor MOX fuel should lead to the harmonisation 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 pelletised MOX and compacted MOX at the international level will be a useful exercise.

ASTRID will allow Europe to demonstrate its capability to master the mature sodium technology with improved safety characteristics as defined by WENRA. ASTRID shall be coupled to the grid with an electrical power of about 600 MWe. Its design integrates operational feedback of past and current reactors. It is seen as a full Generation IV integrated technology prototype. Its safety level shall be at least as good as current Generation III reactors, with strong improvements in core design and sodium-related issues. After a learning period, the reactor shall have a high load factor (e.g. more than 80%). The reactor could provide capability for demonstration of transmutation of minor actinides, at larger scale than previously done in Phénix. The investment costs of the prototype shall be kept to the lowest possible, with technical options compatible with later deployment on a commercial facility. An associated R&D programme will continue to accompany and support the development of of ASTRID 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.

With MYRRHA, Europe will again operate a flexible fast spectrum research facility in support of the technology development (in particular for material, components and fuel irradiation tests) of the three fast reactor technologies (SFR, LFR and GFR). Also, MYRRHA will offer a wide range of interesting irradiation conditions for fusion reactor material research. Since MYRRHA will be conceived as an 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. An associated R&D programme will accompany and support the development of MYRRHA.

The ALFRED project deals with the LFR technology development through the design, construction and operation of a small-scale, state-of-the-art LFR demonstrator (ALFRED). ALFRED is an essential step in order to reach the technology maturity level for the industrial implementation of the European lead-cooled fast reactor (ELFR) and to re-position Europe among the other countries that are currently investing in this technology. ELFR will fulfil the Generation IV goals and thanks to the characteristics of lead, it will be largely based on passive safety approaches for reaching high safety levels. ALFRED will largely benefit from the associated MYRRHA project R&D and design programme and early feedback from the commissioning of MYRRHA.

Whereas both the sodium-cooled fast reactor and the lead-cooled fast reactor have as their 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 constrained by mitigating corrosion of materials in contact with the liquid metal. Medium temperature heat applications are envisaged. A gas-cooled fast reactor has the unique advantage of possibly combining high temperature heat applications with electricity provided that suitable materials are found that are resistant to high temperatures, pressure and irradiation. As such, the

GFR can be viewed as being a sustainable high temperature fast reactor for process heat utilisation.

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. Each of these prototype construction projects, dedicated to the construction of large infrastructure, e.g. research facility, demonstrator, and prototype, is managed by a separate consortium comprising European partners coming from research organisations and industry.

- ASTRID: consortium led by CEA comprising 14 industrials partners[19], contributing in cash and/or in kind to the project. The significant, high-level Japanese contribution led by METI, JAEA and MHI is to be noted[20].
- MYRRHA: consortium in preparation by SCK-CEN and with notably, Japan and the European Union
- ALFRED: FALCON consortium formed with ICN, Ansaldo Nuclear, ENEA and CV-Rez
- ALLEGRO: GFR Centre of Excellence as a first step, with 5 partners (MTAEK, UJV, VUJE, CEA, NCBJ)

Research and innovation actions

ASTRID project

A lot of R&D is required in support of the Conceptual Design phase. The main areas for research and innovation actions are given below:

- Confirmation of CFV (core with low sodium void coefficient) core behaviour for prevention but also for mitigation of severe accidents
- Definition of complementary safety system(s) to enhance margins in addition to the natural behaviour of the core
- Complementing and improvement of material properties for core materials, assimilating the post irradiation expertise of experimental subassemblies irradiated in Phénix
- Pursuit of the development of innovative non-swelling cladding (manufactured with oxide dispersion strengthened steels), including irradiation tests
- Development of a core design enabling the most efficient use of depleted or reprocessed uranium, through in-situ plutonium production and consumption, and the recycle of minor actinides
- Pursuit of the validation of innovative technologies for minimising sodium leaks, improving

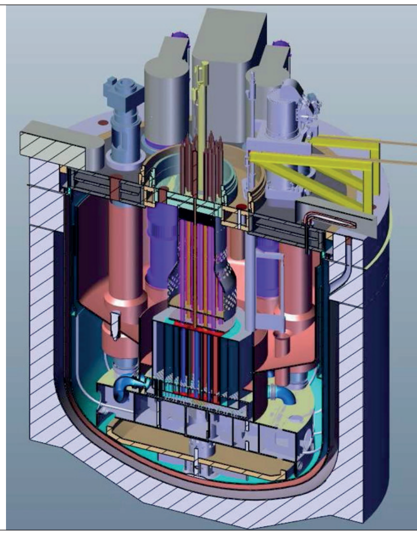


Figure 16. ASTRID

detection performance and reliability, and the development of mitigation options for limiting any chemical consequences at the site boundary

- Pursuit of the development of advanced sodium-water reaction detection and secondary loop designs enabling the containment of any sodium-water reaction accident without giving rise to consequences on the plant
- Pursuit of the development and the validation of an advanced instrumentation and control system for the core
- Pursuit of the development and the validation of mitigation provisions and simulation methods concerning hypothetical situations, such as core fusion (including the core catcher design), aircraft crash, very large earthquakes
- Pursuit of the primary circuit concept for increasing the performance of in-sodium telemetry or non-destructive examination techniques enabling efficient and practicable in-service inspection campaigns
- Pursuit of the development of robotics, under sodium-viewing and repair devices
- Pursuit of the development and the test of advanced cost-efficient steam generator concepts in order to improve the global thermal efficiency of the plant
- Pursuit of the development and the testing of a gas energy conversion system, that should permit the elimination of sodium-water reaction risk
- Pursuit of the development of efficient fuel and component handling systems that allow availability objectives to be reached by reducing fuel and component replacement durations
- Pursuit of structural materials R&D in support of the justification of lifetime of structures and components

19 - AREVA, EDF, ALSTOM, COMEX Nucléaire, TOSHIBA, BOUYGUES, ROLLS ROYCE, JACOBS France, AIRBUS, ALCEN/SEIV, VELAN, MHI/MFBR, Technetics Group France, ECM Technologies

20 - Signature of a collaboration agreement on ASTRID between CEA, METI and MEXT in May 2014, in the presence of Japanese Prime Minister and French President.

Another important R&D axis is to continue:

- The verification and the validation of codes that will be used during the Basic Design phase, with an important effort for severe accident codes

- The upgrading or the building of experimental facilities in support to the verification and the validation of codes and for the qualification of ASTRID options and systems, such as handling machines, control rod mechanisms, heat exchangers, subassemblies

MYRRHA

Along with the Belgian Federal Agency for Nuclear Control (FANC), a pre-licensing procedure has been agreed. This pre-licensing procedure contains a list of 'focus points' to be examined in more detail in view of the preparation of the Design Options and Provision File (DOPF) to be submitted by SCK•CEN to the FANC. Based on these interactions, the major areas for research and innovation actions for the MYRRHA research facility are:

- Lead-bismuth chemistry control and conditioning R&D programme
- Lead-bismuth component testing and thermo-hydraulics programme
- Lead-bismuth instrumentation programme
- Material qualification programme
- Fast reactor MOX driver fuel qualifcation programme
- Coupling technology of accelerator with subcritical core
- High intensity proton accelerator performance and reliability programme

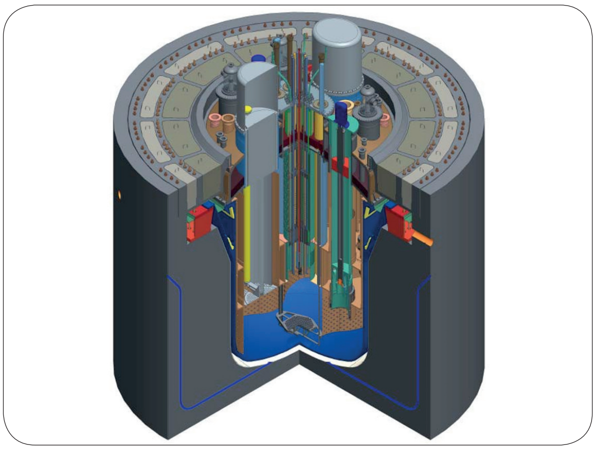


Figure 17. MYRRHA

ALFRED

A continued exchange of information is expected to take place between the ALFRED and MYRRHA projects, in order to exploit to the maximum possible extent the large synergies existing between the two projects.

The action plan for research and innovation actions will be focused on the following open issues:

- Scaled tests for the LFR Decay Heat Removal System (DHR) to demonstrate feasibility/reliability and validate the computational model

- Qualification of the innovative design adopted for the Steam Generator

- Conceptual design and related tests for Fuel Assembly (FA) spacer grids (prototype manufacturing, grid-to-rod fretting…)

- Self-protecting of structural materials through coolant chemistry control and corrosion inhibitors (controlled through purification systems for large pools) in thermal convective loops and/or dedicated coatings for cladding materials

- Computational Fluid Dynamic analysis of FA flow blockage and lead freezing

- Verification and validation of simulation and modelling tools suitable for LFR design

- Safety cases and design issues in support of site selection and pre-licensing activities

- Further investigations on core neutronics and fuel development

- Development of non-destructive examination techniques for in-service inspection in a lead environment

- Development of fuel and component handling systems

In order to meet the above listed R&D needs, the LFR demonstrator programme will rely as much as possible on the currently available European experimental facilities. Actions are however presently undertaken by the FALCON consortium to implement a first phase of activities dedicated to the development of lead technology using Structural Funds and government funds with the aim of constituting a pan-European Research Infrastructure able to provide technological breakthroughs.

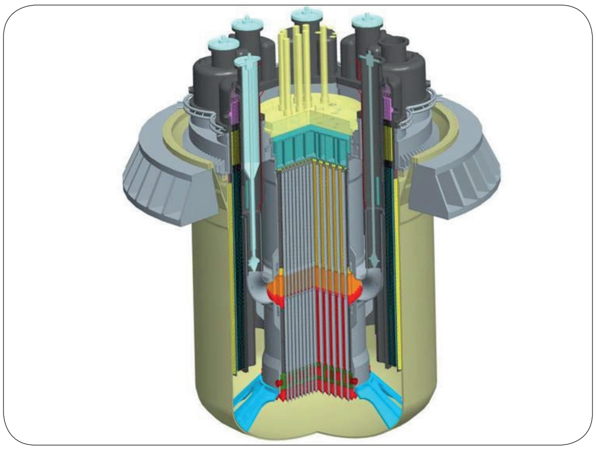


Figure 18. ALFRED

ALLEGRO

The main areas for research and innovation actions for the GFR are the following:

- Helium technology and component development
- Fuel development:
  - In this framework the development of the SiC-SiCf cladding and carbide pellets is foreseen.
  - Regarding the ALLEGRO first core MOX fuel, a careful qualification procedure shall be executed because of the novelty and also because of the lack of fuel behaviour data in a helium cooled fast spectrum reactor.
- Development & validation of analysis tools and qualification
- Site selection & site permit, licensing issues

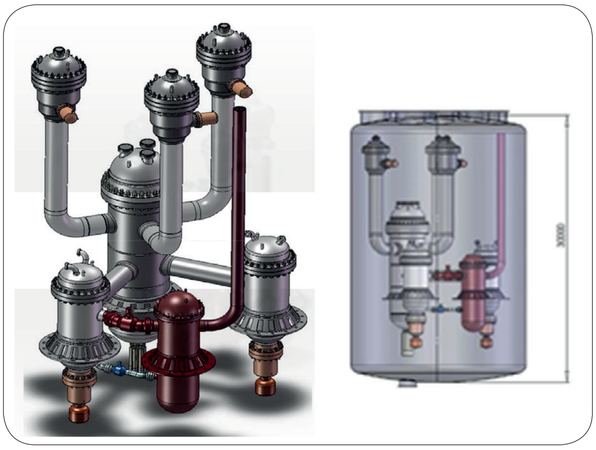


Fig 19. ALLEGRO

ESNII programme prioritisation

At the end of 2012, a prioritisation exercise was performed by ESNII. With respect to the 2010 evaluation of technologies, sodium is still considered to be the reference technology since it has more substantial technological and reactor operations feedback. The lead(-bismuth) fast reactor technology has significantly extended its technological base and can be considered as the shorter term complementary technology, whereas the gas fast reactor technology has to be considered as a longer term alternative option. The main goal of ESNII is to design, license, construct and commission between 2025 and 2030 the sodium fast reactor prototype reactor called ASTRID and the flexible fast spectrum research facility MYRRHA.

For the development of the lead-cooled fast reactor, maximum synergy of activities will be sought with the MYRRHA development to optimise resources and planning. For the LFR demonstrator ALFRED, the main focus should be on design activities typical for a critical power reactor connected to the grid, as well as on R&D activities on the lead coolant, addressing the specific characteristics that differ from lead bismuth. Design activities and support R&D shall be performed in the next few years, to the maximum extent compatible with available resources and taking full advantage of synergies and return-of-experience, where applicable, from the ongoing design of MYRRHA and related R&D programmes. These activities will allow the LFR consortium to start the licensing phase and then the construction of ALFRED, provided that adequate financial resources are available.

In addition to the closure of the nuclear fuel cycle in a sustainable manner, the gas fast reactor has the potential to deliver high temperature heat at ~800°C for process heat applications, production of hydrogen, synthetic fuels, etc. The helium-cooled fast reactor is an innovative nuclear system having attractive features: helium is transparent to neutrons and is chemically inert. Its viability is however essentially based on two main challenges. First, the development and qualification of an innovative fuel type that can withstand the irradiation, temperature and pressure conditions put forward for the GFR concept. Secondly, a high intrinsic safety level will need to be demonstrated for this GFR concept. This will imply dedicated design activities followed probably by out-of-pile demonstration experiments. These high priority R&D activities should be embedded into an overall R&D roadmap in support of the development of the gas fast reactor concept. For the development, guidance and implementation of this R&D effort, a GFR centre of excellence will be created. This centre could develop the technical capability to launch the ALLEGRO gas-cooled demonstrator.

Funding resources: public/private

The R&D projects in support of the prototypes' construction are mostly supported by national programmes and European Commission calls for proposals. Industry is currently committed through in-kind contribution as well as funding of R&D national laboratory programmes. Long-term R&D requested for the deployment of ESNII systems is expected to come from the EC and public-public partnerships, since the realisation of such prototypes and demonstrators aims at implementing, in a pre-commercial and operational environment, the last stage of an R&D programme, for future technology deployment.

In 2010, the French finance law put into place a multi-annual budget for the ASTRID programme and an agreement was signed between CEA and the French Government awarding €650 million to CEA to conduct the ASTRID R&D and design studies, including the development of associated R&D facilities.

The Belgian Federal Government decided on 5 March 2010 to give its strong support and commitment to the MYRRHA project, involving a financial contribution of the Belgian Federal State at a level of 40% of the total project investment cost of €960 million. A budget of €60 million has already been allocated by the Belgian Federal Government for the first phase of works (covering the period 2010-2014 for the Front End Engineering Design phase).

ASTRID and MYRRHA may take different forms since both have clearly different objectives: ASTRID is a prototype for electricity production and MYRRHA is a research facility. The ALFRED demonstrator and ALLEGRO might benefit from EU Structural Funds. 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.

	T0 + 10 y	T0 + 20 y	T0 + 30 y
ASTRID	Basic design – license and start construction	Commissioning and operations – integration of feedback experience	Basic design , license and start construction of FOAK SFR
MYRRHA	Basic design – license and start construction	Commissioning and integration of feedback experience from operations	
ALFRED	Conceptual design – start basic design and licensing	Complete basic design – construction and commissioning	Basic design , license and start construction of FOAK LFR
ALLEGRO	Viability of GFR concept	Conceptual- basic design and licensing	Start construction and commissioning
Fast reactor MOX fuel cycle facility	Basic design- license and start construction of FR MOX fabrication	Conceptual design – licensing of a reprocessing/ recycling facility	Start construction and commissioning of advanced recycling facility
			Extend capacity of FR MOX fuel fabrication for FOAK FR
Transmutation	Fabrication of one Am bearing segment of fuel pin per year	Conceptual – basic design and licensing of a pilot plant of capacity one full Am (or MA) fuel assembly per year	Start construction and commissioning of pilot plant for Am / MA fuel fabrication

Table 2: ESNII R&D programme prioritisation in support to the construction of research facility – demonstrator and prototype.

4.3 NC2I

Objectives

Cogeneration technologies could extend the low carbon contribution from nuclear fission to the non-electrical energy system by directly providing heat for different applications like process heat, sea water desalination, synthetic fuels or hydrogen production, district heating, or intermediate heat storage to stabilise the electricity grid.

The district heating market has the capacity to grow, since centralised production of heat reduces CO_2 emissions and fuel consumption, when compared to individual sources of heat.

The EU currently generates 11.2% of its electricity using cogeneration. In Latvia and Denmark, cogeneration makes up around 45% of total electricity generation. Today, cogeneration installations are dedicated to individual buildings, industrial factories 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 cogeneration 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, which is further discussed in this section.

NC2I
Nuclear Cogeneration Industrial Initiative

Figure 20. NC2I

To understand the challenges and opportunities of nuclear cogeneration, it is important to evaluate the potential of different reactor types: LWR, liquid metal-cooled reactor, very high temperature gas-cooled reactors.

The EUROPAIRS project (2009–2011) identified 3 different classes based on the temperature required and the technology used:

- Steam class: steam (150–600°C) is used as transport and heating medium. Examples are: distillation units in refineries, plastics and fertiliser production, district heating, drying processes, power generation in steam turbines, desalination by multi-stage flash distillation.
- Chemical class: heat, mainly supplied by combustion or electrical heating, is the driver of chemical reactions and is consumed as reaction enthalpy at constant temperature. (600-900°C). Examples are: production of oil and coal derivatives, methane reforming, biomass processing.
- Mineral class: heat is used to melt solids or to drive reactions between solids (above 1000°C).

The main criterion is the temperature at which the energy is consumed. However, another important parameter is the amount of heat consumed by each process.

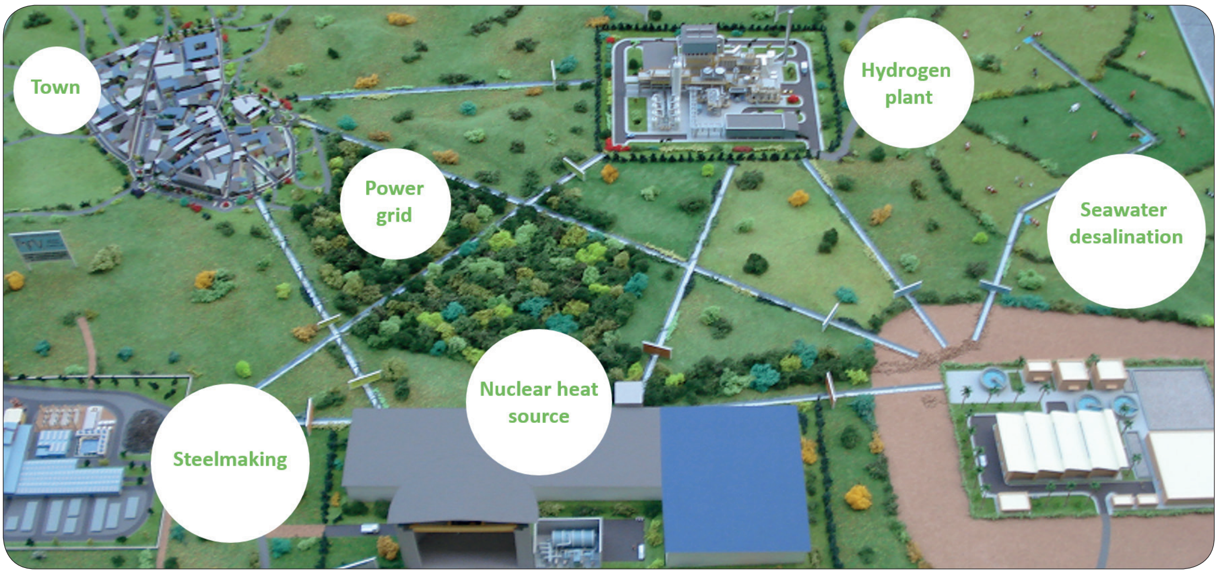
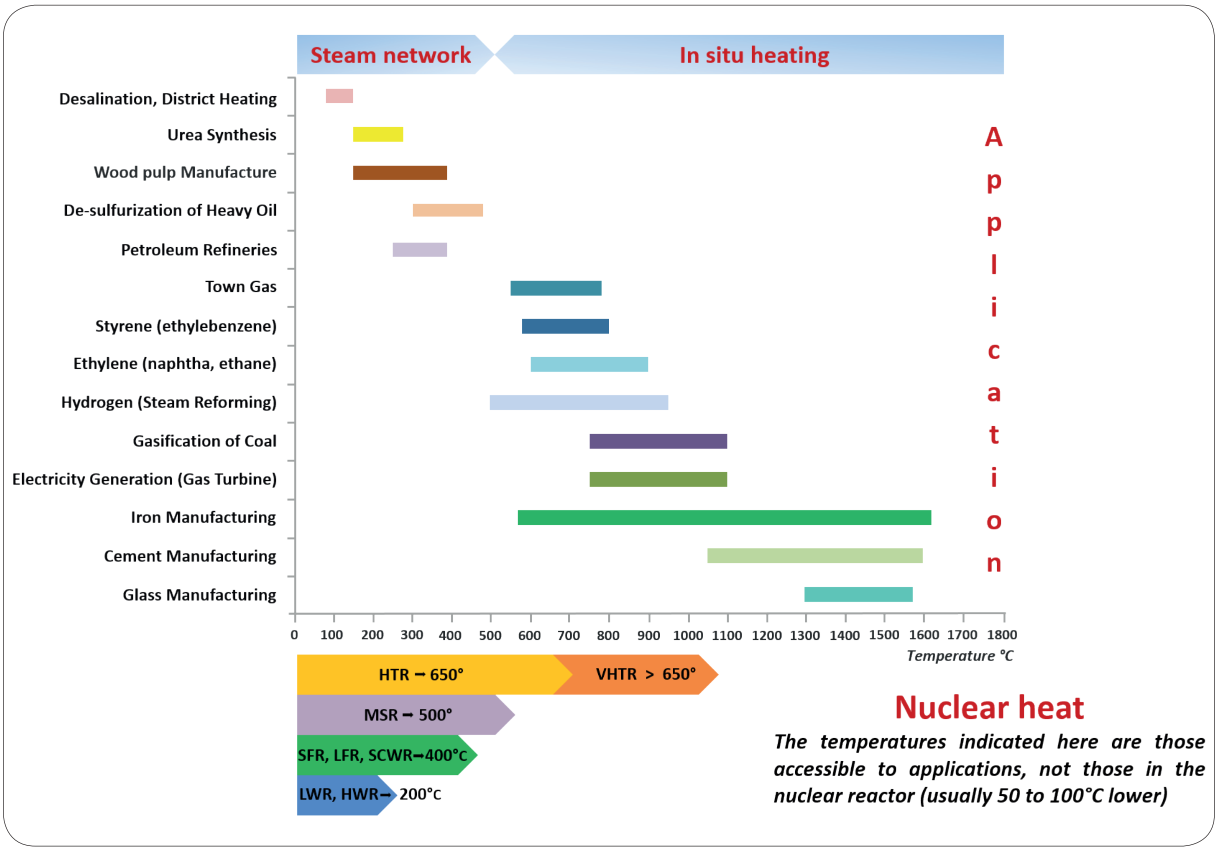


Figure 21. The nuclear cogeneration concept: providing heat and power to industrial applications



21 - Michelangelo Network: MICANET-02/06-D-4.12.0, Karl Verfondern, W. von Lensa, "Synthesis of information on non-electricity applications of nuclear energy: Data collection on available non-nuclear processes and coupling with nuclear reactors"

Figure 22. Temperature range of different applications in the heat market VS temperature range of the heat supplied by different types of nuclear systems[21]

For short-term implementation, the steam class is the most promising area for the nuclear technology, since available and conventional infrastructures could be adapted to cogeneration.

Existing nuclear technology, LWR for the lower temperature range, and HTGR for the whole range, can be used to supply industrial processes already, without excessive R&D effort. Therefore it can also be called a plug-in market, where reactors can directly replace existing fossil-fuelled steam boilers.

It is worth noting that the supply of existing steam networks represents a market of the same magnitude as the electricity market.

The temperature utilised in the plug-in market varies between 100°C and 550°C. Industrial cogeneration is limited today to 550°C for material related reasons while the flow temperatures in the district heating systems are typically in the range from under 100°C up to 170°C.

The NC2I strategy is to introduce nuclear cogeneration into the market as soon as possible, which introduces two important constraints:

- Using as much as possible proven technologies, minimising R&D efforts and technological risks.
- Looking for international partnerships that can accelerate the development and share the risks. The GEMINI initiative was launched in 2014, and NC2I has signed an agreement with the NGNP Industry Alliance in the US, to cooperate on the demonstration of HTGR technology.

Scope

In Europe, individual industrial processes require less than a few hundred MWth, so the best answer for nuclear electricity cogeneration is a reactor of small to medium power. HTGRs fit here well, with power ranges up to 600 MWth, very good safety parameters, and the ability to provide heat at temperatures utilised 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 MWth.

The action toward a broad implementation of nuclear cogeneration should therefore concentrate on developing and building demonstrator(s), which would serve as a 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.

Research and innovation actions

For a fast and successful deployment of nuclear cogeneration in Europe, HTR demonstrator plant construction is selected, using mature and proven technology, and for an outlet temperature of about 750°C. As a next step, VHTR will be designed for other process heat applications requesting higher outlet temperature. There are several categories of specific technical challenges still remaining for HTGR, which can be divided according to the expected outlet temperature: high or very high.

Short-term HTGR cogeneration demonstration project

Within the next decade the top priority will be to perform an industrial-scale demonstration of cogeneration with an HTGR coupled with an industrial steam network feeding process steam to industrial processes.

The reference scenario in the frame of the GEMINI initiative (www.gemini-initiative.com) is to converge as much as possible between Europe and the US on the design of the demonstration nuclear system, only keeping differences if unavoidable for satisfying different customers (e.g. difference in power) or regulatory requirements and to have two demonstrations, one in the US and one in Europe. An alternative scenario would be to have a single demonstration plant, either on US or European territory.

Figure 23. GEMINI meeting in Piketon, Ohio, with the NC2I Task Force and the NGNP Industry Alliance

The demonstration is more focused on the feasibility of licensing and of coupling with industrial processes than on the HTGR technology itself, which is already backed by the construction and operation of a significant number of test reactors and industrial prototypes.

The design of the demonstration plant will, as usual, include 3 phases, conceptual, basic and detailed design, each with parallel phases of licensing. As already mentioned, to minimise risks and accelerate the development, the project will as much as possible rely on existing industrial designs, like the HTR Module, MHTGR, ANTARES, etc. In addition to the conventional criteria for site selection, the local industrial infrastructure should be examined carefully in order to minimise costs and maximise benefit. Though HTGR technology is a mature nuclear technology, design will nevertheless have to be fed by well-focused R&D, which is described in the following section.

Support R&D required for the short-term 'plug-in' demonstration plant

Most of the technology is available from past HTGR programmes. Nevertheless, as some parts of the technology used three decades ago are becoming outdated and as licensing requirements are becoming more demanding, the existing knowledge should be complemented in the following fields:

- **Computer codes:** validation of modern tools (reactor physics, CFD, structural mechanics, fuel performance) for HTGR applications
- **Graphite internals:** development of design methods taking into account the uncertainties of the deformation of the internals during operation, oxidation data in normal and accident conditions, dust formation and transport
- **Fuel:** development of a reliable industrial process for TRISO particle fuel manufacturing and qualification
- **Component qualification:** construction of facilities, in particular a large helium loop for the steam generator qualification
- **Innovation:** use of composite materials for the control rod cladding, improvement in reactor instrumentation, use of magnetic bearings for the primary circulator, innovative non-destructive methods for controlling the quality of the manufactured fuel
- **Codes and standards and design rules:** extension of the existing tools to cover HTGR specific features
- **Safety approach:** specific approach especially for the modular HTGR

Long-term R&D

VHTR R&D

With the aim of reaching higher operating temperatures in order to access new market segments, in particular hydrogen production through high temperature water splitting, the architecture of the whole system will change:

- For the secondary circuit: design of gas-gas heat exchangers (Intermediate Heat eXchangers orIHX). To keep a reasonable size, the technology of compact plate heat exchangers will be favoured, and will require qualification for industrial application.

- For electricity generation, at temperatures above ~ 800°C: development of gas turbines for high temperature process heat applications.

- For the components: selection, characterisation and qualification of advanced materials such as Ni base alloys, Oxide Dispersed Steel (ODS), ceramics, SiC-SiC composites, etc.

- For the fuel: development of advanced VHTR fuel (e.g. the substitution of the SiC coating layer by a ZrC layer), design optimisation, development of a manufacturing process and qualification.

- Heat transport: development of new types of heat networks, likely with a different heat carrier from steam, or if steam is still kept, with the use of different materials.

Fuel cycle and waste management

The R&D needs will depend on the strategic options selected concerning the use of different fissile resources, the closing of the fuel cycle, the requirements for high-level waste volume minimisation, the choice of recycling the irradiated graphite or sending it to disposal. Depending on the selected strategic options, different combinations of R&D programmes will be necessary, among the following ones:

- For reprocessing uranium HTGR fuel, either a new aqueous reprocessing head-end process for full separation of particle kernels from carbonaceous materials surrounding them or a fully innovative pyro-metallurgical process will have to be developed;
- For reprocessing Th-U233 fuel, an aqueous process similar to PUREX, THOREX, or a pyro-metallurgical process will be needed;
- In case of direct disposal of HTGR fuel without reprocessing, the long-term behaviour of HTGR fuel in a deep geological repository will have to be investigated;
- Depending on graphite management options, decontamination/C14 separation techniques will have to be developed and possibilities of recycling graphite should be explored.

NC2I programme prioritisation

Prioritisation of the NC2I R&D programme 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 MWth 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 programme 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 startup, tests and subsequent operation

For the fast-track demonstration, the HTGR 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 the VHTR field; likewise the AVR or the 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: public/private

The major obstacles to the implementation of nuclear cogeneration are the costs of the design and construction of the prototype. The key for establishing the landscape of the HTGR'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 centres – 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 to develop the prototype and predicting potential obstacles, and in the second step, the prototype will be licensed and built. In each step, the consortium may consist of different members. Lastly, it is worth noting that the NGNP-NC2I collaboration could accelerate the construction of an HTR in both the USA and Europe.

	T0 + 5 y.	T0 + 10 y.	T0 + 20 y.
Demonstration plant	• Basic design of the demonstrator operating at 700-750°C core outlet temperature with steam cycle. • Site selection • Economic analysis of the demonstrator • Plan for financing demonstration project • Organisation of consortium for project management	Licensing, starting of construction	
		Review of possible very high t° applications & decision to launch VHTR development	VHTR design
			Very high t° heat network designed
		Assessment of supercritical CO_2 power conversion system	Supercritical CO_2 power conversion system qualified
Commercial plant	Economics and cost reduction strategies		Commercial deployment
Design computer codes	Codes qualified	Source term modelling developed & qualified	Code qualification extended to VHTR
Components	Reactor components designed	Feasibility of critical VHTR components (IHX, ducts…) assessed	VHTR components designed
	Feasibility of proposed innovations validated	Components qualified including innovative ones	
	Component test facility construction		
	Selection of supply chain	Components manufactured	
Materials	Design methods for graphite internals	VHTR materials selected	VHTR materials qualified
Fuel	Fuel for demonstration plant qualified (in the frame of GEMINI)	Fuel for demonstration plant procured	VHTR fuel qualified
		VHTR fuel design options	
Fuel cycle and waste management		Feasibility of possible technologies assessed	Technologies qualified
		Selection of the strategy	
		R&D programme for required technologies	
Industrial processes		Extension of application domain for HTGR cogeneration: - Polygeneration - Preheating	Very high T° processes optimised for interfacing with heat network
			Hydrogen production technologies developed & qualified
		Identification of alternative processes to very high t° processes with t° < 700°C	Alternative processes for t° < 700°C developed
Codes & standards	Graphite codification Code cases for metallic materials		Codes & standards for VHTR materials
Safety approach	Modular HTGR safety approach accepted	Demonstrate safety margins of modular HTGR and coupling with industrial processes	

Table 3. NC2I R&D programme prioritisation in support of the demonstrator plant construction and for cogeneration development

4.4 Analysis and recommendations

Each SNETP pillar is promoting its own R&D projects, carried out by different teams and with different funding schemes. As expected, plant operations and lifetime management are mostly supported by industry, whereas R&D projects linked to new reactor technologies are supported by public/public partnership. Nevertheless, in all cases, research, development and innovation are needed to ensure progress in performance and safety. This common goal brings together research organisations, academia, technical safety organisations, utilities and vendors, and forms the nuclear R&D community.

NUGENIA is hosting a myriad of R&D projects for short, mid and long-term applications, which all align with one or more of the high-level objectives and challenges identified in the specific Technical Areas. Short-term projects mainly focus on operations–related research, and are often funded by in-kind contribution. Mid and long-term projects are generated for different reasons, such as from gaps identified in short-term projects, new regulatory demands, the harmonisation process or innovative technology development. An EC contribution is requested in those cases.

ESNII has a clear objective to promote the construction of research facilities, demonstrators and prototypes of fast reactors. Basic technology development is requested too, provided that it underpins design, licensing, construction and commissioning of these infrastructures. Most of the projects are part of national programmes and are submitted for EC funding.

NC2I promotes a double objective, namely i) cogeneration of electricity and process heat, and ii) an HTR prototype construction to be coupled to steam production. Basic technology development is mandatory to support component design and construction. Most of the projects are submitted for EC funding, while waiting for more visible support from industry.

The whole set of these R&D projects is aligned with the objectives of the Horizon 2020 nuclear fission programme, and eligible for H2020 calls for proposals. For optimising R&D in terms of time and cost while reinforcing the global vision on nuclear system technology, collaboration between the different pillars should be fostered. This could be achieved through the identification of common trunks, such as in basic technology, methods, computation or research infrastructure. At the same time, support from H2020 will help maintain the nuclear R&D community in its capacity to push forward new and/or innovative technology development.

5. Integrated vision and global deployment for SNETP programme

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 Gen II and III operations, Gen III new build and other potential new systems: SMR using LWR technology, Gen 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).

Project clusters for the cross-cutting issues should be identified at different levels, between the different pillars of SNETP as well as between SNETP and other European Technology Platforms or alliances. The organisation of clustering workshops on a regular basis is valuable for achieving that goal. A first meeting was held in July 2014 between SNETP, EERA, IG-DTP and MELODI.

Transverse issues and clustering

For optimising R&D project implementation, while reinforcing synergies between the nuclear systems and with other ETPs, a preliminary analysis is proposed and should be refined and continuously updated by the SNETP pillars.

Basic technology developments open routes for the identification of common trunks for Gen II, III, IV and cogeneration application, notably in areas such as:

- Material behaviour for structural components and fuel
- Structural integrity of systems and components
- Manufacturing & assembly technology
- Instrumentation & control, online/onsite monitoring and diagnosis
- I&C - digital system - cyber-security

The interface with EERA/JPNM should be reinforced for the development of new and innovative materials which could fit NUGENIA, ESNII and NC2I requirements for structural and fuel components. Progress should be made in modelling and numerical simulation as well.

These technology bricks contribute to high-level objectives which should drive as much as possible common developments between the three SNETP pillars:

- Performance and ageing of NPPs for long-term operation
- High reliability components for structure and fuel
- High reliability and optimised functionalities of systems

Closely linked to the R&D projects, research infrastructures including irradiation equipment and computational codes, including for severe accidents, could valuably make the bridge between Gen II, III and IV related developments. An inventory of the existing European capabilities is being established in the frame of NUGENIA for LWR application and this should be considered as a basis for identifying the complementarity with other areas.

Fuel cycle and waste management is an essential layer of nuclear system deployment whatever the specific technology.

- NUGENIA-ESNII global optimisation for long-term sustainability should be achieved throughfuel cycle related issues, i.e. MOX fuel fabrication and recycling.

- Advanced fuel cycle scenarios should be evaluate using a regional approach based on the energy policies and strategies of the different countries, for a quantitative assessment of the fissile material (U, Pu) inventory, with a view to estimating optimised ways for operating both Gen II-III LWR and SFR-LFR-GFR-ADS Gen IV systems and their related fuel processing and fabrication (i.e. recycling) facilities.

The interface between IGD-TP and NUGENIA, ESNII and NC2I should be reinforced for optimising spent fuel management and establishing ultimate nuclear waste specifications. Likewise, NC2I could benefit from IGD-TP for the management of graphite waste, as a key issue.

Methods should be shared among the SNETP pillars for facilitating nuclear system construction, deployment and operations, in an evolving context where technology is continuously improving, while policy regulation is being modified and safety requirements are becoming more and more stringent. This is all the more important since different nuclear reactor technologies may coexist before the end of this century.

- Harmonisation could be envisioned using different approaches. In NUGENIA, harmonisation is promoted as a cross-cutting objective to be shared by designers, operators, R&D organisations and TSOs for the purpose of enhancing competitiveness, improving safety and possibly benefitting public acceptance. Technical fields have been identified in pre-normative research and the establishment of shared codes and standards, with a special goal of converging on one EU code. In ESNII and NC2I, harmonisation is integrated within prototype design and construction activities through the material selection for structural components and fuel, and licensing of new prototypes.

- Enhanced safety in the major driver for any development in any nuclear system. Methods should be shared to the maximum possible extent for Gen II, III, IV and cogeneration in order to reach high safety levels in operation and by design.

- Flexibility issues should be addressed for all nuclear system generations, for accommodating new energy mix requirements, such as operating mode, availability, fuel management and cost economics. The interface with the 'Smart Grid' Industrial Initiative could provide valuable input data. In the same way, market sizing of nuclear power generation requirements needs to be evaluated for new build: small, medium or large size reactor.

- The small modular concept can be considered independently of the nuclear reactor technology and all SNETP pillars are considering similar ranges of nuclear reactor sizes including small size. Reducing the size of a reactor implies new approaches which could be shared, notably for the common characteristics, safety approaches, compact component and modular construction techniques.

SNETP tentative roadmap with an integrated vision

To give a global vision to the SNETP programme, 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 Gen II, III, IV and cogeneration as previously identified have been set out in these layers for reinforcing the synergies between the SNETP pillars:

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

The SNETP Deployment Strategy is displayed in simple terms in **Table 4**, which seeks to illustrate the consistent connection between the industrial nuclear panorama, the technology R&D programme (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 prioritising 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.

Five 4th generation prototypes are being studied, with different maturity levels, as well as an HTR cogeneration demonstration plant. Start of construction milestones are expected as follows[22], provided that appropriate financing is secured:

- **ASTRID and MYRRHA 2020–2025**
- **HTR cogeneration demonstrator: ≤ 2025**
- **ALFRED: 2025–2030**
- **ALLEGRO: beyond 2035**

Commissioning of new prototypes should be supported by harmonisation 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.

ASTRID and respectively ALFRED construction and operations will provide sound experience to prepare the industrial deployment of SFR and LFR[23] technology from around 2050, and subsequently, adequate fuel cycle facilities.

Methodologies dealing with safety and licensing assessment could strengthen interfaces between the different nuclear systems, for the construction of prototypes as well as for new build. For LWR new build, a harmonised licensing process should be ready before the expected peak around 2035–2040. These methodologies will contribute to assist with the suitable integration of different energy sources in the European mix.

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

22- Prototype construction starting dates can move and will result in a translation of the planning when additing the construction period evaluated at 5 years.

23 - Of small to medium capacity

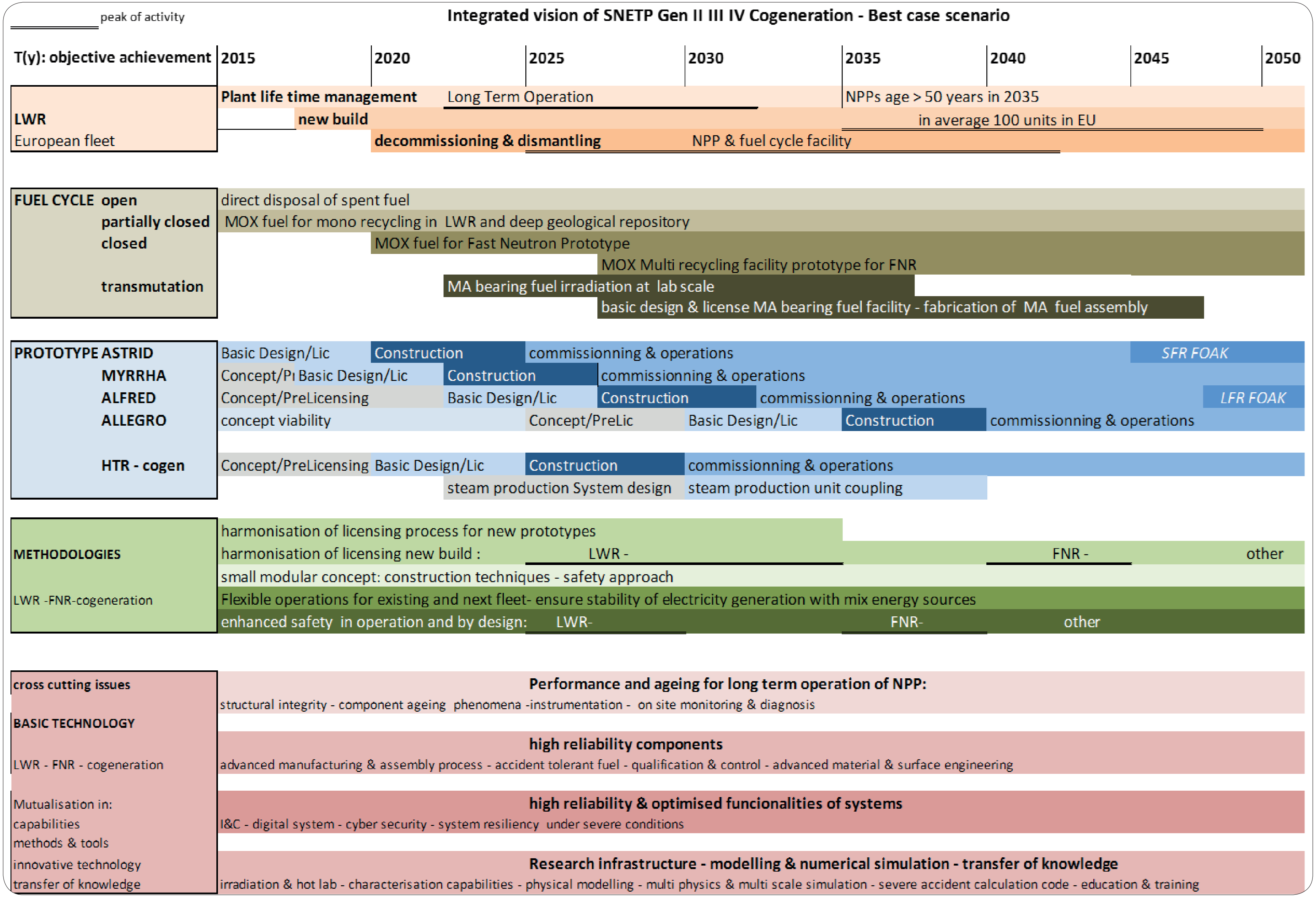


Table 4. Integrated vision of SNETP Gen II, III, IV and cogeneration - Best case scenario

Glossary of acronyms & contributors

Glossary of acronyms

AVR Allgemind Versuch Reactor

DBA Design Basis Accident

EERA European Energy Research Association

EIT European Institute of Technology

ENEN European Nuclear Education Network
www.enen-assoc.org

ENIQ European Network for Inspection and Qualification
www.bindt.org/What-is-NDT/Index-of-acronyms/ENIQ/

ESNII European Sustainable Nuclear Industrial Initiative
www.esnii.eu

ETP European Technology Platform

FOAK First Of A Kind

GFR Gas (cooled) Fast Reactor

GHG Greenhouse Gas

HTGR High Temperature Gas-cooled Reactor

HTR High Temperature Reactor

HTTR High Temperature Test Reactor

IGD-TP Implementing Geological Disposal of Radioactive waste Technology Platform

JRC Joint Research Centre (EC)
https://ec.europa.eu/jrc/

LFR Lead (cooled) Fast Reactor

LTO Long Term Operation

LWR Light Water Reactor

NC2I Nuclear Cogeneration Industrial Initiative
www.nc2i.eu

NDE Non-Destructive Examination

NDT Non-Destructive Testing

NOIP NUGENIA Open Innovation Platform

NUGENIA Nuclear Generation II and III Association
www.nugenia.org

SA Severe Accident

SNETP Sustainable Nuclear Energy Technology Platform
www.snetp.eu

SAR Safety Analysis Report

SFR Sodium (Ccoled) Fast Reactor

SMR Small Modular Reactor

SRIA Strategic Research and Innovation Agenda

Contributors

Core team for DS 2015

TSO: Edouard Scott de Martinville (IRSN)
NUGENIA: Steve Napier (NNL)
ESNII: Peter Baeten (SCK CEN)
NC2I: Tomasz Jackowski and Kajetan Rozycki (NCBJ)
FORATOM: Richard Ivens
DG-RTD: Roger Garbil
LGI: Vincent Chauvet
DS2015 Cordinator: Marylise Caron-Charles (AREVA)

Reviewers:

NUGENIA
ESNII
NC2I
SNETP Executive Committee
SNETP Secretariat

Editors: DS Working Group and SNETP Secretariat I Design: LGI Consulting www.lgi-consulting.com

9 782919 313082

WWW.SNETP.eu