SNETP
Sustainable Nuclear Energy
Technology Platform

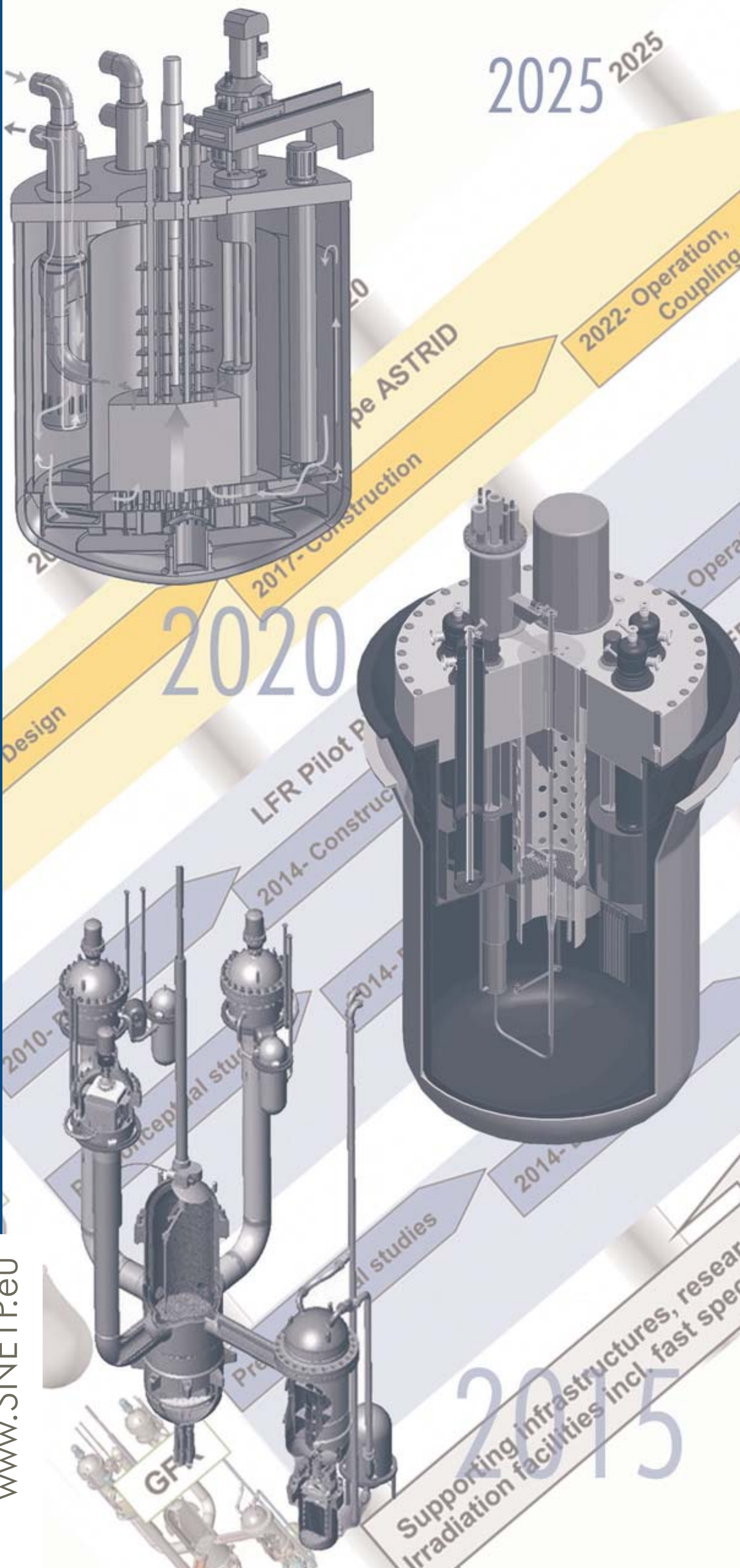
ESNII
The European Sustainable Nuclear Industrial Initiative

October 2010

A contribution to the EU Low Carbon Energy Policy:

Demonstration Programme for Fast Neutron Reactors

Concept Paper



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1. Introduction.

Nuclear will remain an important part of the EU energy mix for base-load electricity generation.

Today more than 2 billion people worldwide have no access to electricity. Current forecasts show that the world population will increase up to 9 billion people by 2050. All these people have an inalienable right to have better conditions of life, which primarily includes energy supply.

At the same time, the threats to the Earth's climate have never been so strong; sustainable development to address the future needs of humankind requires non CO2 emitting sources of energy. In that regard, nuclear energy has a lot of advantages – it is clean and competitive – and even if nuclear energy is not the whole solution, it is part of the solution for the coming years and decades. Therefore, strong and concerted action is required to develop appropriate technologies from the short term to the long term.

Today, nuclear energy represents about 16% of electricity production in the world and about 30% in the European Union. More than 30 countries have already expressed to the IAEA their interest in getting support for the definition and realization of a nuclear programme. The main nuclear reactor technology available today is the Light Water Reactor which has the cumulated record of more than a thousand years of excellent safety and operation. For those countries already equipped with Generation II nuclear reactors, the main issue is to manage plant ageing and power upgrades properly in order to obtain the best economic value from their fleet while keeping the highest standards of safety. New reactors (Generation III) are being built, decided upon, or planned in countries which are extending their nuclear fleet and in countries that are "new comers" to nuclear energy: this requires top level expertise both in industry and in R&D organisations.

> Nuclear will remain an important part of the EU energy mix for base-load electricity generation.

The competitiveness of nuclear fission technologies, together with the questions raised on the management of spent fuel and radioactive waste, are the key short and medium term issues addressed by the 2020 objectives for nuclear energy in the Strategic Energy Technology Plan of the European Union (SET Plan). But demand for electricity is likely to increase significantly in the near future , as current fossil fuel applications are replaced by processes using electricity, for example in the transport sector. The present known resources of uranium represent about 100 years of consumption with the existing reactor fleet. However, depending on the growth rate of nuclear energy worldwide, the question of uranium resources will be raised; therefore, it is reasonable to anticipate, as foreseen by the SET Plan, the development of **fast neutron reactors with closed fuel cycle**. These technologies have the potential to multiply by a factor of 50 to 100 the energy output from a given amount of uranium (with a full use of U238), while improving the management of high level radioactive waste through the transmutation of minor actinides. They are therefore potentially able to provide energy for the next thousand years with the already known uranium resources[1].

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[1] - 2010 Eurelectric Power Choices Study: http://www.eurelectric.org/powerchoices2050

2. Vision by 2050:

Fast neutron reactors with closed fuel cycles in the frame of ESNII

2.1 State of the art

In parallel to similar efforts made in the United States, Russia and Japan, European laboratories and industries supported an active development of Sodium cooled Fast Reactors (SFR) from the 1960s to 1998. No less than seven experimental demonstration and prototype reactors were built and operated over this period: Rapsodie, Phenix and Superphenix in France, DFR and PFR in United Kingdom, and KNK-II and SNR-300 (which was never put in service) in Germany. In addition, France, Germany and the UK jointly developed the European Fast Reactor project which was intended to be a commercial sodium-cooled fast reactor project. Thus there is significant historic experience in these countries.

However, the industrial development of SFR stopped in Europe when political decisions were taken in Germany, the UK and finally France to abandon SFR development; this culminated in the decision to cease operations at Superphenix in February 1998. As noted, the cessation of SFR technology development was not as a result of concerns regarding technical feasibility. Whilst there were initial issues to be addressed with early systems (reliability and global competiveness), no technical showstoppers were identified.

SFR technology development had stopped earlier in the United States with the Non Proliferation Act promulgated in 1978. Russia proceeded with the development of SFR in spite of budget constraints and is expected to put BN-800 (800 MWe) in service in 2013, with commercial power production starting in 2014. Japan's efforts since 1995 were mainly devoted to putting MONJU back into service. India and China, which both plan for nuclear power to supply part of the energy needed for their rapid economic growth, have aggressive agendas to develop light (and heavy) water reactors and SFR with respective plans to start a prototype fast reactor (PFBR, 500 MWe) and an experimental reactor (CEFR, 65 MWth) already in 2010.

All these reactors were targeted to make progress with regard to the previous ones but today's International and European standards require the design of a new generation of reactors. These are the so-called Generation IV, or GEN IV, systems. Important R&D on six major reactor concepts is currently being coordinated at the international level through initiatives such as the "Generation IV International Forum" GIF[1]. **Europe, through SNETP[2], has defined its own strategy and priorities** for the fast neutron reactors that are the most likely to meet Europe's energy needs in the long term in terms of security of supply, safety, sustainability and economic competitiveness (see the figure below):

- the Sodium Fast Reactor (SFR) as a first track aligned with Europe's prior experience, and
- two alternative fast neutron reactor technologies to be explored on a longer timescale: the Lead cooled Fast Reactor (LFR) and the Gas cooled Fast Reactor (GFR).

Europe, through SNETP, has defined its own strategy and priorities for the fast neutron reactors that are the most likely to meet Europe's long term energy needs.

Indeed, the previous work in Europe on SFR technology gives this option a strong starting position. However, significant R&D is still required because of today's more stringent constraints on capital cost, environmental impact, safety, safeguards, proliferation resistance, operational performance, etc.

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[1] - GIF: http://www.gen-4.org/

[2] - SNETP: Sustainable Nuclear Energy Technology Platform: www.snetp.eu

As an alternative to sodium, lead does not react with water or air, has a very low vapour pressure, good heat transfer characteristics and is cheap. It has a very high boiling point and high gamma shielding capability. Finally its density is close to that of MOX fuel, which reduces the risks of re-criticality in case of core melt. Significant progress is still necessary to confirm the industrial potential of this technology, in particular because of the corrosive character of lead, and of its high melting point requiring the temperature to be maintained above 350 °C. Furthermore, lead like sodium is opaque, so that in-service inspection remains to be properly addressed.

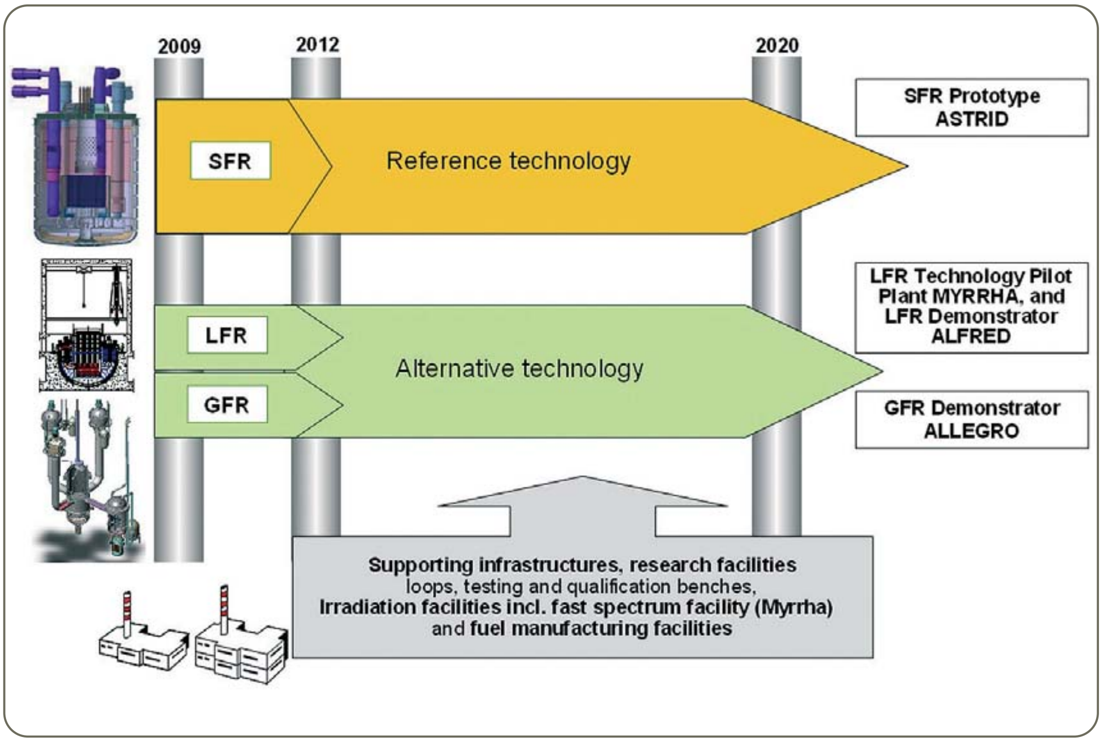
As another alternative, the gas fast reactor offers enhanced safety using a totally inert coolant, with low risk of core disruptive accidents (no core voiding effect), simplified inspection and repair due to the non activated and transparent gas coolant, and potentially high temperature heat delivery for industrial processes. Significant progress is also necessary to confirm the industrial potential of this technology, in particular because of small thermal inertia of the core, which requires a specific safety approach; innovative fuels with refractory cladding should also be developed to address the issues relating to the high power density and high temperatures in the core.

Even though only SFR led to a prototype so far, all types of fast reactor have a comparable potential for making efficient use of uranium and minimising the production of high level radioactive waste. They may also all contribute to non-electric applications adapted to their respective range of operating temperature.

Technology breakthroughs and innovations are still needed for all Generation IV reactor types. Innovative design and technology features are needed to achieve safety and security standards anticipated at the time of their deployment, to minimise waste, and enhance non-proliferation, as well as to improve economic competitiveness especially by having a high availability factor. In particular, one of the challenges for fast neutron reactors will be to demonstrate that they are as safe as other existing reactors at the time of their deployment (by 2040-2050). For that, it will be very important to pursue both cooperation with the GIF and to initiate discussion with relevant European safety authorities.

R&D topics for all three fast neutron reactor concepts (Sodium, Lead and Gas fast reactors) are described in the next chapters, with their challenges and milestones. They include:

- primary system design simplification;
- innovative heat exchangers and power conversion systems;
- advanced instrumentation, in-service inspection systems;



ESNII roadmap

- enhanced safety, partitioning and transmutation;
- innovative fuels (incl. minor actinide-bearing) and core performance;
- improved materials.

In particular, a specific focus is the development of structural materials and innovative fuels which are needed to sustain high fast neutron fluxes and high temperatures, as well as to comply with innovative reactor coolants. It is important to emphasise that the development and qualification of new fuels require a significant R&D effort in terms of resources and time and they will constitute also a major pathway for future innovation in fast neutron reactors beyond demonstration and prototype phases.

In addition to R&D, **Demonstration** projects are planned in the frame of the European Industrial Initiative for sustainable fission ESNII. These demonstration projects include the SFR prototype ASTRID (Advanced Sodium Technological Reactor for Industrial Demonstration), with a start of operation foreseen in France by 2020, and the construction of a demonstration reactor based on one of the alternative technologies, to be sited in another EU Member State.

All these facilities will be open to European and international cooperation, through consortia dedicated either to building the facility or to running R&D projects, in particular those for material and fuel development and qualification.

For the alternative technologies – LFR and GFR – an assessment process will start in 2012 to prepare for decisions on design and construction. The assessment may request international peer reviews. It will be based on various criteria, including:

- the results of the R&D performed during the 2010-12 period and the relevance to the GEN IV requirements;
- the potential international cooperations which could reinforce competencies for system development;
- the ability to establish consortia or partnerships of organizations aiming to invest in the projects and in particular to offer a site to host them.

Finally, supporting research infrastructures, irradiation facilities, experimental loops and fuel fabrication facilities will also need to be constructed. Accelerator Driven Systems (ADS) are also envisaged as dedicated facilities for transmuting large amounts of minor actinides from high level nuclear waste in a concentrated approach. The development of ADS technology has considerable synergy with the R&D required for fast reactors and in particular the Lead Fast Reactor. Mainly for economic reasons, the ADS is not considered in ESNII as a potential energy production system, but as a fast neutron irradiation and testing tool which can support the development of fast neutron systems.

2.2 Technology objectives and cross-cutting actions

The technology roadmap and the accurate definition of the technical objectives have been assisted both by the national programmes on fast neutron reactors and by the Euratom Framework Programmes.

2.2.1 Demonstration and prototype facilities

The ESNII initiative, as described above, will demonstrate that fast neutron reactors:

- are able to exploit the full energy potential of uranium by extracting up to 50-100 times more energy than current technology from the same quantity of natural uranium;
- have the ability to "burn" (i.e. eradicate though nuclear transmutation) the minor actinides produced in the fuel during reactor operation and in so doing significantly reduce quantities, heat production and hazardous lifetime of the ultimate waste for deep geological disposal, while keeping as low as reasonably achievable the radiation protection risks in the surface facilities;
- can attain safety levels at least equivalent to the highest levels attainable with Generation II and III reactors;
- reinforce proliferation resistance and fully satisfy expected future international standards;
- can attain levelised electricity and heat production costs on a par with other low carbon energy systems.

This is covered by the components ESNII-1, ESNII-2 and ESNII-3 of the initiative.

2.2.2 Support Infrastructures

The infrastructures needed to support the design and/or operation of prototype and demonstrator fast neutron reactors, in particular:

- irradiation facilities and associated devices for testing materials and fuels;
- facilities for the development of materials and components, code validation and qualification, and design and validation of safety systems;
- fuel fabrication workshops for the SFR prototype and alternative demonstrator reactor, dedicated to uranium-plutonium driver and minor actinide bearing fuels.

This is covered by the component ESNII-4 of the initiative.

2.2.3 R&D

Each component of the Initiative (ESNII-1, ESNII-2, ESNII-3 see below) has identified its specific R&D needs in support of the design of the corresponding reactors. This R&D will also benefit current reactors of Generations II and III in terms of maintaining safety and radiation protection, increasing performance and competitiveness, improving lifetime management, and implementing solutions for waste management.

Both basic and applied research is essential to support the activities foreseen in the actions above, in particular, the development of simulation and testing tools and associated methodologies to support the design and operational assessment of the reactors and support facilities. This will draw heavily on current R&D programmes, but efforts in all domains need to be intensified and focused on the ESNII objectives. Much of this research will be linked to nearer-term R&D activities of relevance for current nuclear technology, e.g. design and operational safety and radiation protection, waste management, component ageing and lifetime management, materials science and multiscale modelling of material behaviour (structural materials, fuels, cladding), code development and qualification, severe accident management, etc.

Selection of materials for demonstrators and prototypes is another critical issue. Because the development of new structural materials is a very long process, the construction of technology demonstrators or prototypes envisaged to be operational around 2020 will make use of already available and qualified materials. In the longer term, 2030 and beyond, new materials able to resist higher temperatures will be used so as to increase thermal efficiencies. A specific joint programme on “advanced nuclear materials for innovative nuclear reactors” is currently under definition under the umbrella of the European Energy Research Alliance[3] established within the SET-Plan.

This programme on fast neutron systems also needs to be supported by research on advanced fuel cycle technologies for recycling minor actinides in fast reactors or dedicated burners.

2.3 Global impact of the ESNII

A huge potential increase in the sustainability of nuclear energy will be achieved through demonstrating the technical, industrial and economic viability of Generation IV fast neutron reactors, thereby ensuring that nuclear energy can remain a long-term contributor to a low carbon economy.

ESNII will play a key role by involving European Industry and maintaining and developing European leadership in nuclear technologies worldwide, and will make possible the further commercial deployment by the European industry of these technologies by 2040 and beyond. This is the prime goal for industry, which in the meantime will seek to maintain at least a 30% share of EU electricity from currently available reactors for the benefit of the European economy (the industrial needs for nuclear energy could be enhanced with an expansion towards cogeneration of process heat for industrial applications when such markets develop)[4].

2.3.1 Key Performance Indicators

The major challenge for the new low-carbon technologies is to reach the market by deploying the production capacities while bringing their levelised cost to competitive amounts, taking also into account the required adaptation of the electricity grid. Nuclear power production, as a proven low carbon technology already provides large capacities at competitive cost; Generation II and III light water reactors are very safe,

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[3] - EERA: see http://www.eera-set.eu/

[4] - 2010 Eurelectric Power Choices Study: http://www.eurelectric.org/powerchoices2050

reliable and offer large availability factors. The major objective for research, development and demonstration programmes in this initiative, at the horizon 2020 is to bring the Generation IV fast neutron technologies to the same levels of safety, reliability, availability and costs.

This will ensure that nuclear fission technologies will stay available in the low carbon energy mix, in a sustainable way, for the very long term, when the reduction in Uranium resources availability would start to affect the cost effectiveness of light water reactors. Therefore this initiative is not about quantitative deployment by 2020 of Generation IV fast neutron reactors, but about proving their sustainable "availability" for the low carbon energy mix at a time when this deployment might become necessary in the longer term.

Therefore, two categories of key performance indicators may be considered to monitor ESNII:

- overarching indicators that may be used for all low carbon technologies, but keeping in mind the specificity described above, and
- specific indicators relating to nuclear technology.

The overarching indicators are classically:

- the levelised cost of electricity production,
- the capacity and the availability factors.

The specific indicators for ESNII are described in the dedicated chapter 4.

3. ESNII-1: SFR –
the Sodium cooled Fast Reactor

■ 3.1 Objectives

Design, construction and operation of an innovative prototype sodium fast reactor ASTRID coupled to the grid.

Investigating innovative paths leading to significant progress on Sodium Fast Reactor technology in the main areas needing improvement:

- Robustness of safety demonstration, in particular by prevention and mitigation of severe accidents including those linked to sodium;
- Economic competitiveness;
- Meeting operators' needs: ease of maintenance, in-service inspection, occupational safety, limited sensitivity to human factors;
- Capability to reduce the long-term burden of radioactive waste for geological disposal by recycling and transmutation of actinides extracted from spent nuclear fuel.
- Implementing these innovative paths through the development, licensing, construction and operation in France of the pre-industrial scale prototype fast reactor ASTRID, coupled to the grid, with an electrical power of the order of 600 MWe;
- Demonstrating the improvements in operability and the potential economic competitiveness of SFR technologies by return of experience from the operation of the prototype;
- Demonstrating the capability for recycling of actinides through representative irradiations on the prototype.

■ 3.2 Work Programme

ESNII-1.1 Innovation

Investigating innovative paths allowing significant progress in domains such as safety, economy, in-service inspection and actinide incineration requires close collaboration between R&D organisations, industry, utilities and safety experts.

Past R&D, engineering and construction experience, together with operating and licensing experience of past European SFRs (DFR, KNKII, Rapsodie, PEC, PFR, Phenix, SNR300, Superphenix) represents a huge asset for Europe, which was 10 years ago the undisputed leader in this domain, with the European Fast Reactor (EFR) project.

On the basis of this asset, the work programme includes investigations and developments on the following main technical tracks:

Core and fuel

Develop an innovative core design that allows drastic reduction or exclusion of the risk of over-heating accidents. Examples are low over-reactivity core concepts, or carbide cores (for the long term);

Develop and irradiate innovative non-swelling claddings (manufactured with oxide dispersion strengthened steels), allowing a decrease of the sodium content in the core, and an increase in fuel burn-up potential;

Develop and validate innovative safety features, aiming to strengthen the lines of defence (objective: three, diversified) against core fusion risks, such as passive anti-reactivity insertion devices or advanced core control systems;

Develop 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.

Safety

Define and validate advanced methods for minimising sodium leaks, detecting them in a totally reliable way, and for mitigating the consequences of sodium fires, so as to avoid any chemical consequences at the site boundary;

Develop 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;

Develop and validate mitigation provisions and simulation methods concerning defence-in-depth situations, such as core fusion (core catcher design), aircraft crash or very large earthquakes.

Reactor and system design

Conceive an adapted reactor design and in-sodium telemetry or non-destructive examination techniques enabling efficient and practicable in-service inspection campaigns;

Develop and test advanced cost-efficient steam generator concepts in order to improve the global thermal efficiency of the plant. This may involve developing 9Cr ferritic steels for nuclear use;

Develop efficient fuel and component handling systems that allow availability objectives to be reached by reducing fuel and component replacement durations.

Develop an advanced instrumentation and control system, adapted to sodium fast reactors challenges (sodium leak detection, individual subassembly temperature and leak control…).

ESNII-1.2 Prototype conception, licensing and construction

Bringing the prototype on line will include several tasks:

- Pre-conceptual design;
- Conceptual Design and Safety Options Report;
- Basic Design and Preliminary Safety Analysis Report;
- Detailed Design and Final Safety Analysis Report;
- Construction;
- Commissioning and Start-up.

In parallel, R&D activities will need to be continued and increased, in order to validate innovations and component feasibility and performance through representative mock-ups. This will also allow the industry to recover industrial competencies, e.g. through the construction of sodium loops and the testing of components.

This will be particularly necessary for the primary system components (mock-up in water for primary system and pump hydraulics), steam generators (sodium mock-ups for limited bundle), fuel handling and absorber mechanisms (full-scale sodium mock-ups); subassemblies (water and sodium mock-ups), instrumentation and in-service-inspection (sodium mock-ups), safety innovations - such as passive anti-reactivity devices, core catcher - that will require analytical and representative tests both in non-active and in-reactor environments.

The fuel will require also some out-of-pile and in-pile tests, in order to qualify new cladding geometries, even if the prototype is started with a "conventional" cladding material (Ti-stabilized stainless steel).

ESNII-1.3 Prototype operation and experimental programme

The operational and experimental programme attributed to the prototype will include:

- Demonstration of consistency with industrial objectives (efficiency, availability, licenseability, in-service-inspection and maintainability, operator friendliness…);
- Irradiation programme concerning innovative cladding materials (oxide dispersion strengthened steels), innovative proliferation-resistant fuel fabrication processes, actinide recycling solutions and performance.

■ 3.3 Expected Impact

The ESNII programme on sodium fast reactors will allow Europe to maintain its expertise (the experienced scientists and engineers who participated in the design and construction of Phenix and Superphenix are now close to retirement), to save the knowledge and skills accumulated during 50 years in this field, and to develop a reactor concept of the fourth generation, adapted to European needs and safety requirements.

3.4 Preliminary Cost Analysis

The total budget is still to be elaborated in detail and will depend, in particular, on the extent of innovations to be developed and assessed, and on the power level chosen for the prototype. A first assessment gives:

- About 1000 M€ for innovations, investigations and assessments (ESNII-1.1 and innovation validations during ESNII-1.2);
- About 4000 M€ for the prototype's design and construction.

3.5 Milestones

R&D innovation and pre conceptual studies

- 2012: Consortia for funding, construction, operation;
- 2012: Assessment of innovations & design / GEN IV requirements.

Design & construction: robustness of safety demonstration

- 2017: License, enabling commissioning by 2022;
- 2017: Start of construction;
- 2022: Commissioning.

4 ESNII-2: LFR – the Lead cooled Fast Reactor

4.1 Objectives

Design, construction and operation of an innovative lead cooled fast reactor demonstrator:

- Develop a lead cooled fast neutron system that features equal safety performance and economic competitiveness, with comparable uranium utilisation and reduction of waste burden, to SFR;
- Finalise the design and obtain a license for the construction of the European Technology Pilot Plan (ETPP) in the range 50-100 MWth, with full operation in 2023; MYRRHA in sub-critical and critical mode will play this role;
- Finalise the design and obtain a license for the construction between 2015 and 2025 of an LFR Demonstrator (named ALFRED) with a power of approximately 100 MWe that will allow connection to the grid;
- Demonstrate safety and waste minimisation performance by operational feedback and prepare the design and construction of an LFR Prototype of the order of 600MWe at the horizon of 2025-2030.

4.2 Work Programme

ESNII 2.1 Support R&D programme

Material qualification: steel for the reactor vessel, lead-corrosion-resistant material for the steam generators, protective coating for fuel cladding and fuel element structural parts, and special materials for the impeller of the mechanical pumps;

Fuel development and qualification: MOX driver fuel, and in a later phase advanced minor actinide bearing fuel, lead-fuel interaction;

Heavy liquid metal technology: lead purification/filtering techniques, oxygen & chemical control;

Components development: safety & control rods, pumps, heat exchangers, in service inspection and repair technologies;

Develop models & tools: to study the nuclear/thermal-hydraulic feedback, the reactor stability, as well as the reactivity margin for not reaching prompt-critical conditions, response and resistance of structure to lead sloshing;

Conduct large scale integral tests: to characterise the behaviour of the main systems, especially for licensing procedures, key component performance and endurance demonstration, benchmarking of thermal-hydraulics in a rod bundle;

Starting of the zero power facility Guinevere in 2010 for core design qualification and reduction of design uncertainties (critical mass, power distribution as well as reactivity coefficient).

ESNII 2.2 LFR ETPP conception, licensing and construction

The realisation of the LFR ETPP will include several phases (2010-2023): finalisation of the conceptual design, detailed engineering, specifications drafting and tendering, construction of components and civil engineering, on site assembly and commissioning. In parallel, the support R&D programme will provide during the 2010-2014 period the necessary answers to the remaining technical challenges. After 2014, the fuel qualification programme and to a lesser extent the material qualification programme will remain the main topics of the R&D support programme. Comparing the scope and specifications, the calendar and the current status of the MYRRHA project with those of the LFR ETPP (with no need for electricity production), the MYRRHA project will fulfil the role of the LFR ETPP.

ESNII 2.3 LFR ETPP experimental program

The main mission of the LFR ETPP (MYRRHA) is to demonstrate both technologies of fuel and heavy liquid metals, and the endurance of materials, in-service inspection and repair, components and systems to control industrial risks (obtain reactivity feedback at power) for the LFR demonstrator and LFR prototype over the commissioning period 2020-2023 and during the operational phase in the years 2023-25.

ESNII 2.4 LFR Demonstrator (ALFRED): conception, licensing and construction

The realisation of the LFR Demonstrator ALFRED will include several phases (2010-2025): conceptual design, decision point (2013), detailed engineering, specifications drafting and tendering, construction of components and civil engineering, on site assembly and commissioning. In parallel, the feedback from design and experience from the LFR ETPP (MYRRHA) will serve to optimise the final design of ALFRED.

ESNII 2.5 LFR Demonstrator: operation and feedback from experience

The LFR Demonstrator has the mission to demonstrate the correct operability of all heat transport systems including the power production system. Therefore, the LFR Demonstrator will be connected to the grid. The demonstration reactor is a scaled down version of the (industrial) prototype, with similar (not necessarily identical) characteristics.

The objectives of the LFR Demonstrator are:

- to achieve the safety standards required at the time of deployment and to enhance non-proliferation resistance;
- to assess economic competitiveness of LFR technology, including high load factors;
- to demonstrate better use of resources by closing the fuel cycle;
- to validate materials selection.

■ 4.3 Expected Impact

The current experience base for heavy liquid metal cooled systems includes 80 reactor years of operating experience in the former Soviet Union and then in the Russian Federation with lead-bismuth cooled reactors for strictly military purposes. During the last decade, significant expertise on heavy liquid metal cooled reactors and ADS technology has been acquired through various Framework Programmes of the European Union.

With the construction and operation of a LFR ETPP and Demonstrator reactor, Europe will be in an excellent position to secure the development of a safe, sustainable and competitive fast spectrum technology. The programme will allow the main technological issues that can then be implemented in the LFR prototype around 2020-2035 to be investigated and addressed. This LFR prototype will pave the way for industrial deployment of LFR by 2050, and hence contribute significantly to the development of a sustainable and secure energy supply for Europe from the second half of this century onwards.

■ 4.4 Preliminary Cost Analysis

The cost of the ETPP is included in the cost of the MYRRHA facility, taken into account in ESNII-4.

Based on a scaling down exercise of the cost analysis performed in the framework of the ELSY project for the LFR prototype, a preliminary cost estimate for the LFR demonstrator ALFRED was obtained and is in the order of 1000 M€. A more detailed cost analysis is foreseen in the framework of the FP7 LEADER project, taking into account more detailed design choices.

■ 4.5 Milestones

Consortium set-up, R&D innovation and pre conceptual studies

- 2012: establishment of MYRRHA International Consortium.

- 2013: Demo consortium agreement, site identification.
- 2013: Assessment of innovations & design with regard to GEN IV requirements.

Design & construction: robustness of safety demonstration

- 2014: MYRRHA licensing by Belgian Federal Agency for Nuclear Control, construction permit.
- 2023: MYRRHA full operation.
- 2021: Licensing of ALFRED by a European leading safety authority.
- 2025: Commissioning of ALFRED.

5 ESNII-3: GFR –
the Gas Fast Reactor

5.1 Objectives

Design, construction and operation of an innovative gas-cooled fast demonstrator reactor:

- Develop a gas-cooled fast neutron system that proposes an alternative solution to liquid metal technology using an inert and transparent coolant, with uranium utilisation and reduction of waste burden comparable to SFR;
- Investigate fuel, materials, components and reactor design leading to a safe and economic reactor technology;
- Study improvements in the safety demonstration, in particular by reducing the risk of severe accidents, and taking benefit from simpler in-service inspection and repair and coolant management;
- Implement those innovative technologies through the development, licensing and operation in a European country of a demonstration scale prototype ALLEGRO, the world's first gas-cooled fast reactor, in the range of 70 to 100 MW, with construction in the 2020s;
- Test high temperature heat delivery and utilization for industrial purposes;
- Demonstrate safety and waste minimisation performance by operational feedback 2025-2030 and prepare the design and construction of a GFR Prototype coupled to the grid circa 2030-2035.

5.2 Work Programme

ESNII-3.1 Support R&D program

Fuel Development

For continuous high power density and high temperature operation, dense fuels with good thermal conductivity are required. In this respect, carbide and nitride appeared more attractive than oxide. Oxide remains a back up because of a lot of experience feedback. For cladding, standard alloys cannot reach the foreseen temperature. Refractory cladding materials have to be envisaged (metals or Composite Matrix Ceramic), while oxide dispersion strengthened steels can be considered as backup materials for lower temperature GFR core concepts.

For the development of these innovative fuel elements, the R&D activities include fuel element design, core materials studies (cladding materials and fissile phase), fuel fabrication and irradiation programme. Specifically, the areas that have been identified are:

- Fuel element and assemblies modelling and design;
- Basic cladding and fuel material studies;
- Basic core material studies;
- Development of cladding and fuel fabrication processes;
- Fuel element and assembly development and irradiation testing;
- Analysis of behaviour during fault conditions.

Development of analysis tools and qualification

Computational tools are needed to design the system and to analyse operational transients (normal and abnormal). This area of the work concentrates on adapting and validating these tools through benchmarking and comparison with experimental data. An important output from this work is the specification of test facilities required to fill the gaps in the available experimental data for the tools qualification. These computational tools fall into five main areas:

- Core thermal-hydraulics;
- Core neutronics;
- System operation;

- Fuel performance;
- Other (materials performance, structural assessment, codes & standards, etc.).

Helium technology and components development

Sufficient knowledge of the technology related to helium under pressure is needed to build ALLEGRO. This includes:

- Management of gas impurities;
- Development and qualification of heat insulation techniques;
- Construction and qualification of main specific components (helium blowers, fuel subassembly, leak tightness of circuits, fits and valves, control rod mechanism, fuel handling system, …);
- Development of advanced instrumentation techniques in hot gas (optical 3D temperature measurements).

ESNII-3.2 ALLEGRO: a GFR demonstrator

ALLEGRO Design Studies

The main goal of this work is to prepare the consistent design of the ALLEGRO reactor. This design must be consistent with the GFR choices and include specific devices and monitoring systems for experimental purposes. It aims at providing experimental safety demonstrations under suitable conditions. This work is divided into three areas:

- Review of the exploratory and pre-conceptual studies;
- Core studies – a conventional technology start-up core with a transition to an all-ceramic GFR core;
- Mission & design consistency – continuous monitoring of the mission requirements for ALLEGRO and its consistency with the GFR system.

ALLEGRO Safety Studies

This work is essentially the same as for GFR but is dedicated to the ALLEGRO specific case and has thus a tighter schedule. This work will use the ALLEGRO Safety Options Report as input which is due at the end of the ALLEGRO conceptual phase.

ESNII 3.3 Future GFR plant prospects

GFR Design Studies

The main goal is to define a consistent, high-performance GFR meeting the requirements below:

- The GFR core should be at least self-sustaining in terms of the consumption and production of plutonium and should be capable of plutonium and minor actinide multi-recycling;
- The GFR system should have an adequate power density to meet requirements in terms of plutonium inventory and breeding gain, economics and safety;
- A coupling between the reactor and process heat applications must be possible.

Alternative design features should also be identified and studied for the core, the balance of plant, the decay heat removal system design and performance.

GFR Safety Studies

The safety analysis for the GFR system and its alternatives runs in parallel with the GFR design process. These safety studies are needed to establish a safety case for GFR and will be based upon the definition of a relevant safety approach for GFR. It consists of performing mainly the following tasks:

- Recommending and evaluating specific safety systems and requirements for fuel and material behaviour to manage accident conditions;
- Analysing accident transients (loss of coolant accident / depressurisation, reactivity insertion faults, seismic events, etc.) to establish both the natural, un-protected behaviour of the system, and to demonstrate that adequate protection systems are available;
- Implementing a core melt exclusion strategy;
- Conducting a probabilistic risk assessment for the system.

In common with other reactor concepts, the safety studies will be based on first establishing a safety approach. A combination of deterministic and probabilistic methods will be used to demonstrate that the safety objectives have been met. Finally, severe accident studies will demonstrate that containment performance is satisfactory, that adequate mitigation has been provided and that the off-site impact is acceptable.

5.3 Expected Impact

Europe has a leading position in the field of gas reactor, high temperature reactor and fast reactor technologies. The GFR is an integration of all three of these technologies and presents an excellent opportunity for Europe to maintain its lead in these areas. Three of the four international partners working on GFR within the Generation IV International Forum are European (France, Switzerland and Euratom). GFR is technically very challenging, but the potential benefits are great; in a future in which natural uranium is scarce, the GFR will potentially be able to power applications that, at the moment, are only in the domain of high temperature thermal reactors. GFR is an open-ended technology, its operating temperature is not limited by phase changes or chemical decomposition of the coolant, and the coolant is chemically inert. Therefore this system will allow high thermal efficiency, minimising the fuel consumed and the volume of wastes generated.

5.4 Preliminary Cost Analysis

The total budget will be elaborated in detail at the end of the basic design of ALLEGRO. A first assessment gives:

- About 400 M€ for the R&D programme in support to the construction of ALLEGRO;
- 700 to 800 M € for the ALLEGRO design and construction.

5.5 Milestones

R&D innovation and pre-conceptual studies

- 2012: Confirmation of the feasibility;
- 2012: Assessment of innovations & design / GEN IV requirements.

Design & construction: robustness of safety demonstration

- 2014: Preliminary design & environmental impact studies, consortium, site identification;
- 2018: License, enabling commissioning by 2025.

6 ESNII-4:

the Support Infrastructures

6.1 Objectives

Design, construct and operate the necessary irradiation tools and devices to test materials and fuels;

Design, construct and operate the necessary fuel fabrication workshops, dedicated to uranium-plutonium driver fuels, and to minor actinide bearing fuels;

Design, construct, upgrade and operate a consistent set of experimental facilities for component design, system development, code qualification and validation, that are essential to perform design and safety analyses of the demonstration programme of ESNII (see ESNII-1, ESNII-2 and ESNII-3), including zero-power reactors, hot cells, gas loops, liquid metal loops.

6.2 Work Programme

ESNII-4.1 Research and testing facilities

Experimental irradiation capacities

There is a clear need to update European irradiation facilities given that existing facilities are close to end of life. Three reactors are currently considered in Europe:

- JHR, the Jules Horowitz Reactor (Cadarache, France) dedicated to materials testing for nuclear fission; its construction has started in March 2007, the start of operation is foreseen in 2014;
- MYRRHA (Mol, Belgium), a flexible fast neutron irradiation facility, dedicated to test lead coolant systems and accelerator-driven sub-critical systems (ADS) for transmutation. MYRRHA can also address the possible need in a European context for an ADS demonstrator, since in its current design it is able to work in both subcritical and critical mode. As pointed out in the roadmap for LFR (see ESNII-2), MYRRHA also acts as the ETPP for LFR. MYRRHA is scheduled to be fully operational in 2023 and its cost is estimated at 960 M€;
- PALLAS (Petten, The Netherlands) mainly dedicated to radioisotope production for medical applications, which may provide a complementary irradiation capacity.

Irradiation devices for experiments

The irradiation experiments necessary for screening, characterising, testing and qualifying materials and fuels will be performed either in dedicated material testing reactors or in industrial reactors or prototypes. Beyond the availability of these irradiation capacities, it is necessary to develop new experimental devices taking into account cutting-edge progresses in modelling, instrumentation and modern safety standards. Europe has a worldwide leading position in this field and has to keep it through intra-European synergistic developments to overcome shortage of resources.

Experimental facilities for reactor physics

Dedicated experimental facilities are needed for the development of SFR, LFR and GFR reactor systems. They are essential for component design, system development and code qualification and validation, which are mandatory to sustain the safety analysis.

Zero-power nuclear facilities are also needed for neutronics code validation.

Experimental facilities for civil, structural and safety case support work

More specifically, we can identify the need for the following supporting facilities:

For the development of SFR:

- facilities to support the SFR material and coolant physical-chemistry studies;

- facilities to support the SFR studies on thermal-hydraulics, heat transfer, safety, fuel behaviour under accidental conditions, severe accidents;
- facilities to support the SFR system/component validation such as for fuel handling systems, core control system, primary mechanical pumps, energy conversion systems, coolant quality control systems;
- facilities to support the development of SFR instrumentation, in-service inspection and repair, maintenance.

For the development of LFR:

- facilities to support the LFR material, coolant physical-chemistry and corrosion/erosion studies;
- facilities to support the LFR safety experimental studies;
- facilities to support LFR studies of moving mechanisms, instrumentation, maintenance, in-service inspection and repair;
- facilities to support the LFR studies in thermal hydraulics and heat transfer.

Some facilities may have a dual use for both SFR and LFR studies due to similarities of the two liquid metals.

For the development of GFR:

- facilities to support the GFR material studies;
- facilities to support the GFR studies on thermal-hydraulics and heat transfer;
- facilities to support the GFR system and component validation, such as fuel handling systems, compressors, heat exchangers, valves, pipes and heat insulation;
- facilities to support the development of GFR primary and emergency systems operation and transients;
- facilities to support the safety study of the behaviour of specific materials at very high temperatures during transients.

Recycling capacities

Concerning facilities for recycling processes development, the need for new large facilities seems less urgent. Existing large research facilities (ATALANTE at CEA in France, ITU at JRC in Germany, the Central Laboratory at NNL in the United Kingdom) offer effective potentialities at lab-scale, and should be used in the future to develop suitable processes, and to perform demonstration runs on samples of spent fuel or on irradiated targets at up to pin-scale.

For oxide fuel processing, minor actinide recovery processes under development at lab-scale mainly rely on well-known and industrially mature solvent extraction technologies. The important background coming from industrial plant feedback, or from the very important work carried out over past decades to design modern reprocessing plants, make extraction a well-mastered technology.

Therefore, considering that there are no important issues for scaling-up hydrometallurgical processes, the requirements in this field could be postponed.

ESNII-4.2
Fuel manufacturing capacities

Beside existing facilities (ATALANTE, ITU, the UK's new Central Laboratory facility), it is important to improve capability in the field of experimental fuel fabrication.

A Prototype Core Facility (PCF) will be needed around 2016 for the production of the MOX driver fuel to be loaded into the core of the SFR prototype and the experimental reactors. Suitable technologies should be chosen to allow for a timely production and licensing of the MOX driver fuel. What is needed here could be several tons of MOX fuel per year; an industrial facility to fulfil the needs of prototype reactors is under preliminary design in France by AREVA and CEA.

There is also a need for a pin-scale facility, able to provide in an efficient manner the (very diverse) experimental pins to be irradiated in experimental facilities during the early phases of the design of possible future fuels (MA-bearing fuel, other than oxide fuel…). Such a facility could be located in existing hot labs, in ATALANTE (CEA/Marcoule) or the Central Laboratory (NNL) for instance. The goal is an efficient, modern and flexible tool with the capacity to produce from a few pellets up to a few pins per year to address the many and diverse experimental needs expected from the R&D fuel research community.

The construction, if necessary, of a "pilot-scale" fuel fabrication facility will enable, in further steps, demonstrative irradiation experiments at a larger scale.

6.3 Expected Impact

Successful deployment of a demonstration FNR system whether it is SFR, LFR or GFR requires a comprehensive set of large and medium-sized research infrastructures including irradiation facilities, fuel cycle facilities and experimental facilities for reactor physics.

6.4 Preliminary Cost Analysis

- Fuel fabrication workshops: 600 M€ (U-Pu fuel) + 250-450 M€ (prototype fuel)
- Fast spectrum irradiation facility: 1000 M€
- Experimental facilities: 600 M€.

6.5 Milestones

- 2011 complete identification of the necessary facilities;
- 2012 construction or upgrade initiated of the necessary facilities including:
    - fuel manufacturing workshop;
    - micropilot for advanced separation of minor actinide bearing fuel.
- 2016 start of the construction of the irradiation facility MYRRHA;
- 2017 initiate start-up fuel production for prototype and demonstrator.

7. Indicative costs for ESNII

A first evaluation of the cost of ESNII is summarized in the table below. These cost assessments will be improved as design activities for each prototype or demonstrator progress.

ESNII Components	Costs (currently under detailed analysis)
ESNII-1 Prototype SFR	■ 1000 M€ for innovation and component development; ■ 4000 M€ for the construction phase (ASTRID). Includes basic and detailed design, licensing, testing and qualification of components, construction and start up operations.
ESNII-2 Alternative technology LFR	■ (960 M€ for the LFR ETPP MYRRHA, already included in ESNII-4); ■ 1000 M€ for the ALFRED Demonstrator.
ESNII-3 Alternative technology GFR	■ 400 M€ for R&D activities including design activities before construction (2012-18); ■ 800 M€ for the construction phase (ALLEGRO). Includes basic and detailed design, licensing, testing and qualification of components, construction and start up operations (2018-24).
ESNII-4 Supporting infrastructures	■ 600 M€ for the U-Pu fuel fabrication workshop; ■ 450 M€ for the prototype fuel fabrication workshop; ■ 960 M€ for the fast spectrum irradiation facility (MYRRHA); ■ 600 M€ for the other experimental facilities; ■ A provision of 1000 M€ for the research programmes performed in these facilities (equivalent to 100 M /yr over 10 years), to be consolidated with ESNII-1, ESNII-2 and ESNII-3.
TOTAL	**10 810 M€**

The costs included in the above table are still first estimates. The deployment of the implementing plan for 2010-12 and the results of the corresponding R&D will give a rationale for an updating of these figures before go/no-go decisions for the next steps of reactor design and construction are taken.

Major research infrastructures and development of prototypes for reactors or fuel cycle technologies can be funded at EU level through private/public partnerships (PPP), involving national governments, regions, research organisations, industry, and the European Institutions. Contributions from international partners outside the EU can also play a role. Research can be accomplished through coordinated national programmes, but it must also be supported at EU level, especially for the short term issues, to give confidence to future private partners and to stimulate participation of Member States.

In particular the Euratom Framework Programmes can play an important role, provided the funding for nuclear fission is substantially increased in the 8th Framework Programme. The initiative shall also take advantage of EU loans. The European Investment Bank has declared itself ready to help the financing of nuclear energy infrastructures, and the potential loans from this financial institution must also be explored.

The SFR prototype, which will mostly demonstrate the maturity of the technology for future industrialisation and commercialisation after the “first of a kind”, would be typically funded in the frame of a Private Public Partnership:

- **Financial contributions from utilities and industry and loans from the EIB based on a business plan;**
- **Public funds to cover the extra cost of going beyond Generation III reactors, and so to cover the corresponding additional risk beyond classical industrial risk.**

The alternative LFR or GFR technologies are further from the market, from an industry point of view. Therefore, the development of such technologies in the spirit of the SET-Plan will require a stronger involvement of Member States and of the European level for funding, even if some private funding might be foreseeable.

A specific study has been performed in 2009 in order to explore both the potential funding mechanisms and organisational schemes for achieving the ESNII objectives. It gives first indications for the future consortia in charge of each of the specific projects to be undertaken within ESNII.

8. Key Performance Indicators for ESNII

Overarching Key Performance Indicators can be used to assess and monitor ESNII technologies:

- **Levelised cost of electricity production by each of the considered systems,**
- **Capacity and availability offered by these systems.**

These indicators are rather generic, and can be applied to each of the low carbon energy technologies to be considered under the SET Plan.

Specific Key Performance Indicators for ESNII can be grouped under the following headings:

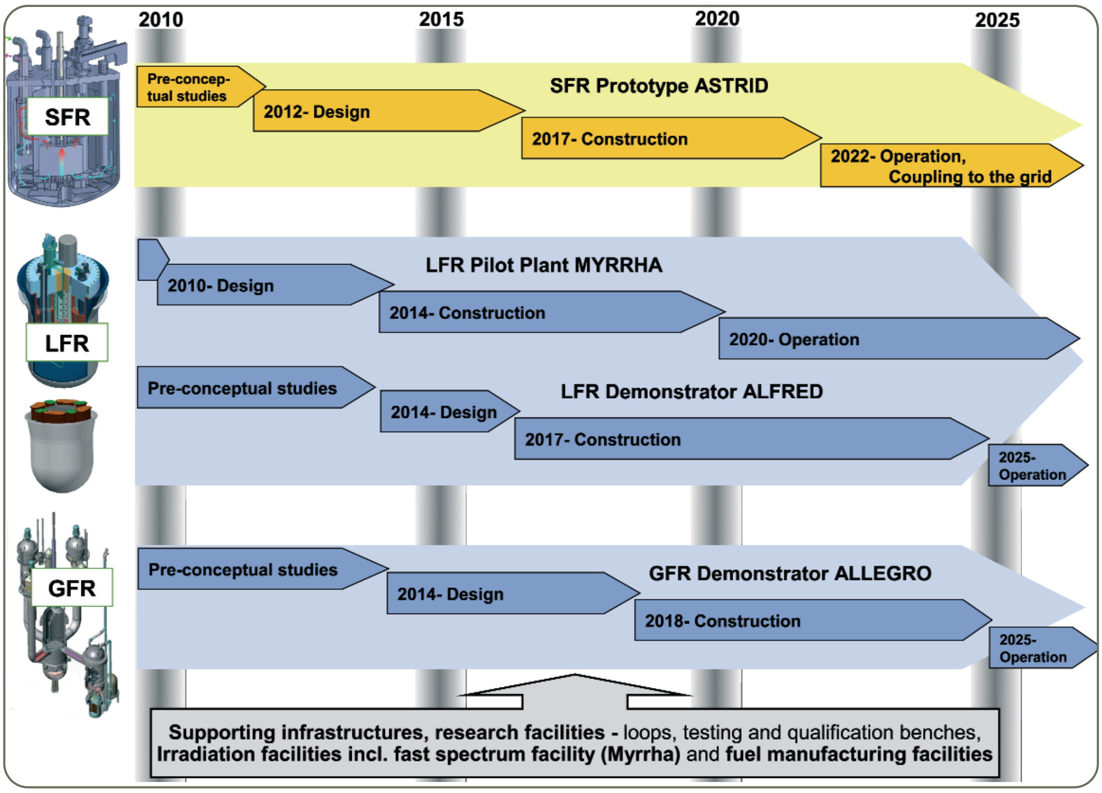
- **Sustainability:**
  - Fuel usage;
  - Demonstration of actinide burning (waste reduction).
- **Economical Performance:**
  - Construction cost;
  - Reactor operation and maintenance costs;
  - Fuel cycle cost; Decommissioning & Disposal cost;
  - Plant lifetime.
- **Availability and Robustness:**
  - Duration of the outages for refuelling;
  - Cycle duration;
  - Maximum frequency of unplanned outages.
- **Safety and Proliferation Resistance:**
  - Compliance with safety requirements for Gen III reactors;
  - Compliance with IAEA and Gen IV Risk & Safety and PRPP WGs recommendations.
- **Implementation Effectiveness:**
  - Compliance of specific projects with their planning forecasts (design / license / construction).

Appendices: Roadmap & Glossary of acronyms

Roadmap

The figure below indicates the foreseen timing for the major steps of the initiative.

- For the SFR technology, ASTRID is a prototype coupled to the grid (typically 600 MWe). It will be followed by a "First of a Kind" when industrial deployment has been decided.
- For the LFR technology, the technology pilot plant MYRRHA will be quickly followed by a demonstration reactor ALFRED scheduled to enter into operation in 2025, then by a prototype foreseen to enter into operation ten years later.
- For the GFR technology, the demonstration reactor ALLEGRO is foreseen to enter into operation by 2025.



Glossary of acronyms

ADS:	Accelerator Driven Systems
ALFRED:	Advanced Lead Fast Reactor European Demonstrator
ALLEGRO:	European Gas Fast Reactor Demonstrator Project
ASTRID:	Advance Sodium Technological Reactor for Industrial Demonstration
EERA:	European Energy Research Alliance
ETPP:	European Test Pilot Plant
GFR:	Gas cooled Fast neutron Reactor
GIF:	Generation IV International Forum
LFR:	Lead cooled Fast neutron Reactor
M€:	million Euro
MWe:	Megawatt electrical power
MWth:	Megawatt thermal power
MYRRHA:	Multi-purpose hybrid research reactor for high-tech applications
SFR:	Sodium cooled Fast neutron Reactor
SNETP:	Sustainable Nuclear Energy Technology Platform

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