SNETP
Sustainable Nuclear Energy
Technology Platform

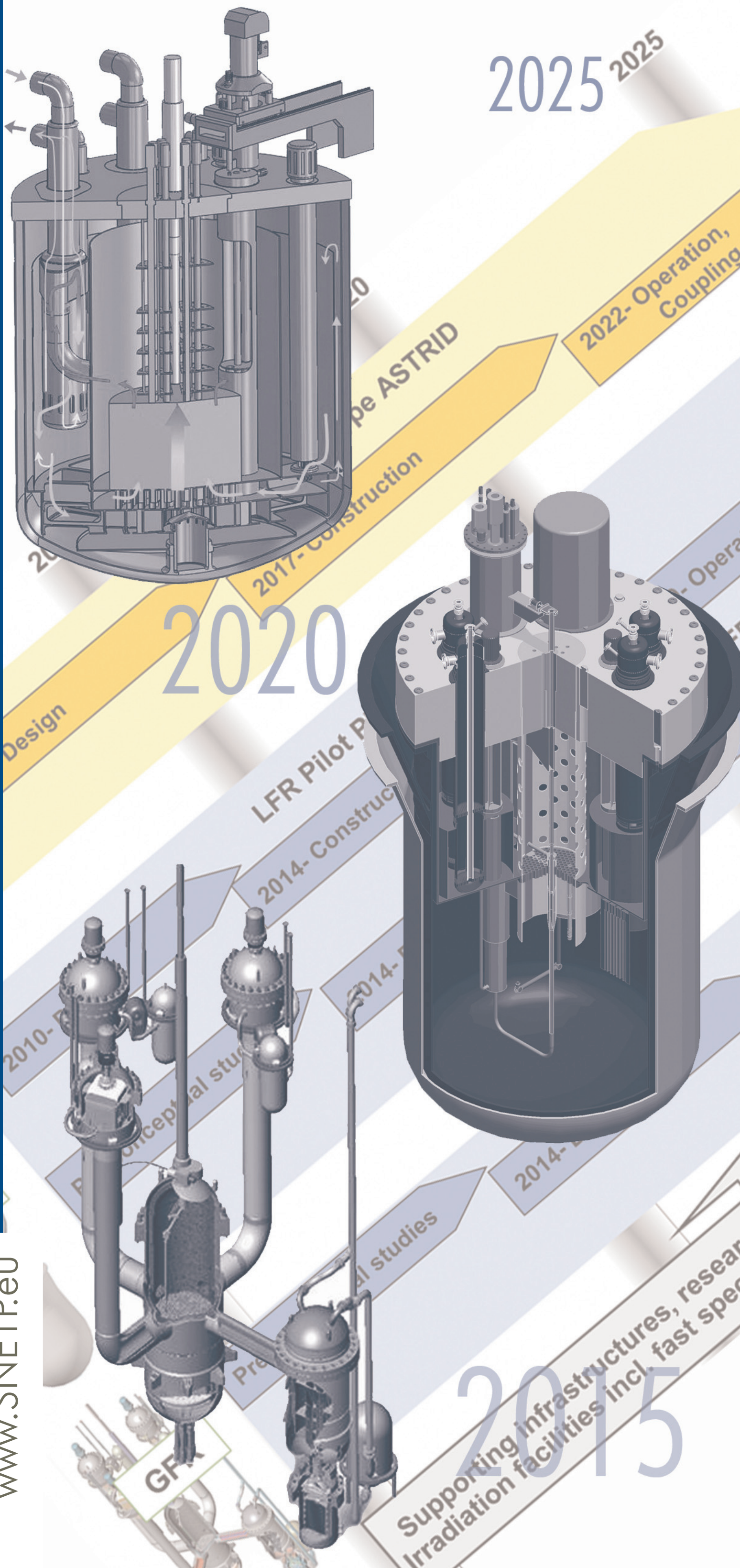
# ESNII
## The European Sustainable Nuclear Industrial Initiative

May 2010

## A contribution to the EU Low Carbon Energy Policy:

## Demonstration Programme for Fast Neutron Reactors

# Concept Paper



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# 1. Introduction

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 both energy and water 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 $CO_2$ 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.

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

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 realisation 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.

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 requested 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.

# 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 2012. Japan's efforts since 1995 where 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 water reactors and SFR with respective plans to start a prototype fast reactor (PFBR, 500 MWe) and an experimental reactor (CEFR, 65 MWth) 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. This is the so-called Generation IV. 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.

As an alternative to sodium, lead does not react with water or air, has a very low vapour pressure,

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

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

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.

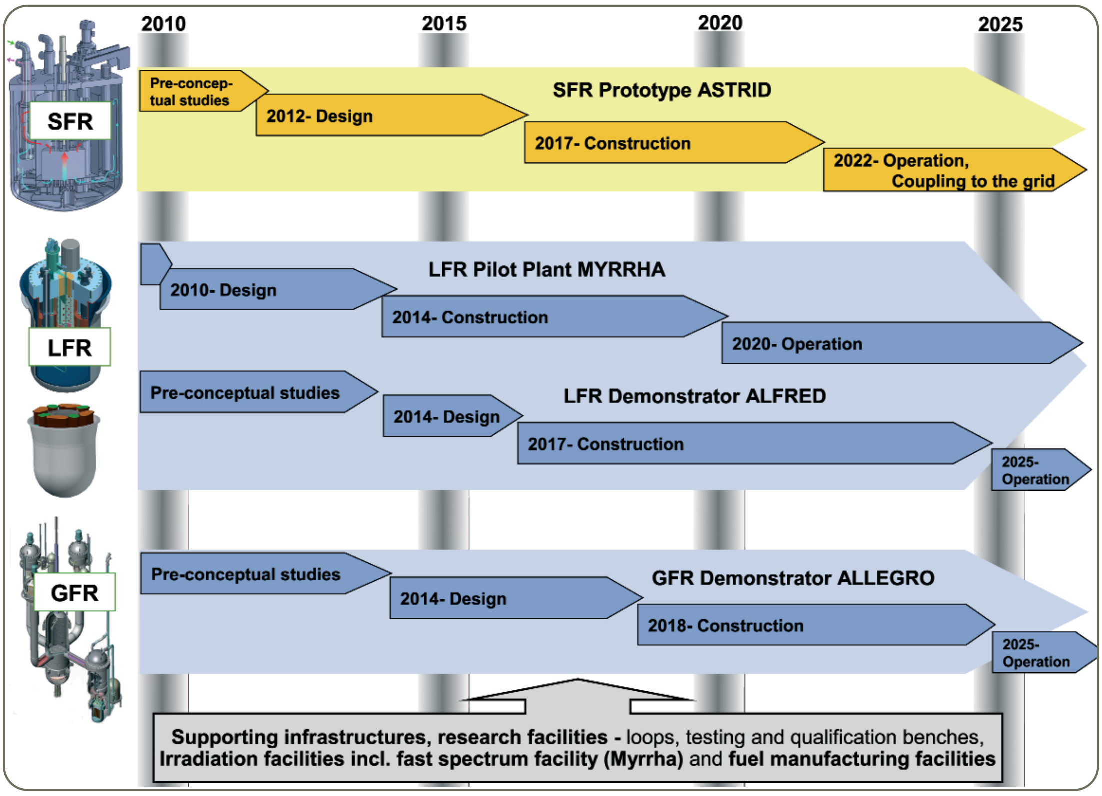
As another alternative, the gas fast reactor offers enhanced safety using a totally inert coolant, with low risk of core disruptive accidents (no core voiding effect), simplified inspection and repair due to the non activated and transparent gas coolant, and potentially high temperature heat delivery 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 reactors 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 through advanced fuel cycles, 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 put on 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 organisations 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 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, ADS are not considered in the ESNII initiative as potential energy production systems, but as fast neutron irradiation and testing tools 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 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 disposal;
- can attain safety levels at least equivalent to the highest levels attainable with Generation II and III reactors;
- reinforce proliferation resistance by avoiding separation of individual fissile material at any point during the fuel cycle;
- 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) defines 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 other 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 initiative

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).

## 2.4 ESNII-1: SFR – the Sodium cooled Fast Reactor

### 2.4.1 Objectives

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

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

- 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 & mitigation of severe accidents including those linked to sodium, and minimizing proliferation risks;
  - 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 ultimate radioactive waste for final geological disposal through recycling and transmutation in the reactor of all actinides (including minor) 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 in the range of 250 to 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.

## 2.4.2 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 overheating accidents. Examples are low overreactivity 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 detecting sodium leaks in a totally reliable way, and to mitigate 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, eg 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 demonstrator 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.

## 2.4.3 Expected Impact

Today the players in the field of fast neutron reactors are Japan (JSFR project), Russia (construction of BN-800), India (construction of PFBR), and China (construction of CEFR). However these prototype reactors are not adapted to European safety requirements and to European past experience and social acceptance criteria. It is therefore necessary for the future of nuclear energy in Europe to develop systems adapted to its specific needs and constraints.

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.

## 2.4.4 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 demonstrator. A first assessment gives:

- About 1000 M€ for innovations, investigations and assessments (ESNII-1.1 and innovation validations during ESNII-1.2);
- 2000 to 4000 M€ for the demonstrator’s design and construction.

## 2.4.5 Milestones and Key Performance Indicators

### 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 operation to start by 2020;
- 2017: Start of construction;
- 2022: Start of operation.

### After Commissioning: sustainability

- Capability for recycling plutonium, depleted uranium and reprocessed uranium, for self-burning in the reactor or for feeding other reactors;
- Conversion ratio > 1;
- Demonstration at the sub-assembly scale of the feasibility of minor actinide incineration (reduction by a factor of 1000 of the thermal load of high level waste in geological disposal).

### After Commissioning: adequacy of meeting operators' needs

- Availability of advanced in-service inspection systems, adapted advanced I&C system, tolerant and robust systems and components.

### After Commissioning: economic competitiveness

- Thermal efficiency for the commercial plant =42%;
- Efficient fuel handling and in-service inspection systems enabling, after 5 years of operation, a technical availability factor of 80% to be reached (to be increased to 90% for the commercial plants);
- Demonstration that the cost for electricity generation using future SFRs is comparable with the costs of other sources of low carbon electricity.

### Specific issues

- Definition and implementation of a first R&D programme to address:
    - MOX fuel and innovative fuel development and qualification;
    - Innovative advanced structural material qualification.

## 2.5 ESNII-2: LFR – the Lead cooled Fast Reactor

### 2.5.1 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 start of operation around 2020; MYRRHA in sub-critical and critical mode will play this role;
- Finalise the design and obtain a license for the construction of an LFR Demonstrator in the region of 100 MWe (2015-2025) that will allow connection to the grid;
- Demonstrate safety and waste minimisation performance by operational feedback 2025-2030 and prepare the design and construction of an LFR Prototype of the order of 600MWe at the horizon of 2025-2030.

### 2.5.2 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;
- HLM 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 project will include several phases (2010-2020): 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 is continued. 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 2018-2020 and during the operational phase in the years 2020-24.

### ESNII 2.4 LFR Demonstrator: conception, licensing and construction

The realisation of the LFR Demonstrator project 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 the LFR Demonstrator.

### 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.

## 2.5.3 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.

## 2.5.4 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 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.

### 2.5.5 Milestones and Key Performance Indicators

#### R&D innovation and pre conceptual studies

- 2012: MYRRHA owner consortium and management structure;
- 2013: Demo consortium agreement, site identification;
- 2013: Assessment of innovations & design with regard to GEN IV requirements.

#### Design & construction: robustness of safety demonstration

- 2013: MYRRHA licensing by Belgian Federal Agency for Nuclear Control, construction permit;
- 2020: MYRRHA start of operation;
- 2021: Demo licensing by a European leading safety authority;
- 2025: Demo start of operation.

#### After Commissioning: sustainability

MYRRHA:

- Contribution to advanced options for waste management: capability to accommodate up to a full minor actinide bearing fuel assembly.

Demo:

- Capability to recycle plutonium, depleted uranium and reprocessed uranium, for self-burning in the reactor and feeding to other reactors;
- Conversion ratio=1 with long fuel cycle ($>$ 5 years).

#### After Commissioning: adequacy of meeting operators' needs

- Availability of advanced in-service inspection systems, of adapted advanced I&C system, tolerant and robust systems and components.

#### After Commissioning: economic competitiveness

Demo:

- Thermal efficiency = 40%;
- Efficient fuel handling and in-service inspection systems allowing the targeting of availability factor of 80% for the demonstrator (to be increased to 90% for the commercial plants).

#### Specific issues

On the basis of the operational feedback from MYRRHA and the LFR Demo:

- Design and construction of an LFR prototype to start in 2035;
- Design and construction of a "first of a kind" LFR power plant between 2035 and 2050.

## 2.6 ESNII-3: GFR – the Gas Fast Reactor

### 2.6.1 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.

### 2.6.2 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 & 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.

## 2.6.3 Expected Impact

Europe leads the world in 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. Of the four international partners working on GFR within the Generation IV International Forum, three of these are European (France, Switzerland and Euratom). GFR is technically very challenging, the benefits are great – GFR will be a reactor that can power the range of applications that, at the moment, are only in the domain of high temperature thermal reactors, in a future in which natural uranium is scarce. GFR is an open-ended technology, the operating temperature is not limited by phase change or chemical decomposition of the coolant and the coolant is chemically inert. Thus the system will allow high thermal efficiency to be achieved, minimising the amount of waste heat that has to be rejected, the fuel consumed and the volume of wastes generated.

## 2.6.4 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.

## 2.6.5 Milestones and Key Performance Indicators

### 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 operation to start by 2025.

### After Commissioning: sustainability

- Capability to recycle plutonium, depleted uranium and reprocessed uranium, for self-burning in the reactor and feeding to other reactors;
- Conversion ratio=1 with long fuel cycle (> 5 years).

### After Commissioning:
### adequacy of meeting operators' needs

- Minimisation of the helium leakage rate, reduced likelihood of cladding failures, reliability and availability of fuel and component handling systems and the helium management system.

### After Commissioning:
### economic competitiveness

- Thermal efficiency > 45%;
- Efficient fuel handling and optical in-service inspection systems enabling the targeting of an availability factor of 80% for the demonstrator (outside periods where ALLEGRO is used as an irradiation facility).

#### Specific issues

- Demonstration of the viability of the GFR concept on the basis of operational feedback (components and core behaviour, confirmation of the safety case);
- Definition and implementation of the qualification programme for an innovative ceramic fuel;
- Demonstration of the high temperature and cogeneration potential of the GFR concept;
- Demonstration of reliability as a fast neutron irradiation reactor.

## 2.7 ESNII-4: the Support Infrastructures

### 2.7.1 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.

### 2.7.2 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 operational in 2020 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.

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

Besides 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 to get 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.

## ■ 2.7.3 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.

## ■ 2.7.4 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€.

### 2.7.5 Key Performance Indicators

- Demonstration of the fabrication of advanced minor-actinide-bearing fuel at the pilot scale;
- Operational facilities to enable completion of post-irradiation examination in order to support fuel validation;
- Demonstration of the preferred advanced recycling flowsheet process at the pilot plant scale;
- Experimental data to support multi-scale assessment of structural materials (including data from the fast neutron irradiation facility MYRRHA);
- Computational facilities in place for a full suite of simulation and modelling covering fuel, reactor, fuel cycle, reactor dynamics etc;
- Operational facilities to support civil and external hazard assessment for demonstration plant safety cases.

### 2.7.6 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.
- 2015 start of the construction of the irradiation facility MYRRHA;
- 2017 initiate start-up fuel production for prototype and demonstrator.

# 3. 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**<br>Prototype SFR | ■ 1000 M€ for innovation and component development;<br>■ 2000-4000 M€ for the construction phase (ASTRID), depending on the electrical power (250-600 MWe) and technical options. Includes basic and detailed design, licensing, testing and qualification of components, construction and start up operations. |
| **ESNII-2**<br>Alternative technology LFR | ■ (800-1000 M€ for MYRRHA as the Test Power Plant, included in ESNII-4);<br>■ 1000 M€ for the Demonstrator. |
| **ESNII-3**<br>Alternative technology GFR | ■ 400 M€ for R&D activities including design activities before construction (2012-18);<br>■ 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**<br>Supporting infrastructures | ■ 600 M€ for the U-Pu fuel fabrication workshop;<br>■ 250-450 M€ for the prototype fuel fabrication workshop;<br>■ 1000 M€ for the fast spectrum irradiation facility (MYRRHA);<br>■ 600 M€ for the other experimental facilities;<br>■ 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** | **8650-10850 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 FOAK, 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 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.

# 4. Indicative Key Performance Indicators for ESNII

The Key Performance Indicators which are necessary to monitor the progress of ESNII in the SETIS system are defined for each demonstration or prototype reactor along the three main phases:

- 2010-2012: mainly devoted to the R&D programme necessary to enable the go/no-go decision for construction of the demonstration or prototype reactor;
- 2012-2020 or 2025: consolidation of preliminary design, basic design and detailed studies before the construction and full licensing process;
- Beyond 2020 or 2025: prototype or demonstration reactor operation to demonstrate that they achieve their objectives.

## 4.1 Key Performance Indicators for ESNII-1, ESNII-2, ESNII-3

The table below presents the key performance indicators for the three components of the initiative corresponding to the three major technologies: SFR, LFR, GFR.

| ESNII 1 – SFR<br>ASTRID | ESNII 2 – LFR<br>MYRRHA and Demo | ESNII 3 – GFR<br>ALLEGRO |
|---|---|---|
| R&D innovation and pre conceptual studies | | |
| 2012: Consortia for funding, construction, operation.<br>2012: Assessment of innovations & design / GEN IV requirements. | 2012: MYRRHA owner consortium and management structure.<br>2013: Demo consortium agreement, site identification.<br>2013: Assessment of innovations & design with regard to GEN IV requirements. | 2012: Confirmation of the feasibility.<br>2012: Assessment of innovations & design / GEN IV requirements. |
| Design & construction: Robustness in the safety demonstration: | | |
| 2017: License, enabling operation to start by 2020.<br>2017: Start of construction.<br>2022: Start of operation. | 2013: MYRRHA licensing by Belgian Federal Agency for Nuclear Control, construction permit.<br>2020: MYRRHA Start of operation.<br>2021: Demo licensing by a European leading safety authority.<br>2025: Demo Start of operation. | 2014: Preliminary design & environmental impact studies, consortium, site identification.<br>2018: License enabling operation to start by 2025. |
| After Commissioning: Sustainability | | |
| ■ Capability to recycle plutonium, depleted uranium and reprocessed uranium, for self-burning in the reactor and for feeding other reactors.<br>■ Conversion ratio > 1. | ■ MYRRHA: Contribution to advanced options for waste management: capability to accommodate up to a full minor actinides bearing fuel assembly. | ■ Capability to recycle plutonium, depleted uranium and reprocessed uranium, for self-burning in the reactor and for feeding other reactors. |

| ESNII 1 – SFR<br>ASTRID | ESNII 2 – LFR<br>MYRRHA and Demo | ESNII 3 – GFR<br>ALLEGRO |
|---|---|---|
| After Commissioning: Sustainability (continued) | | |
| ■ Demonstration at the sub-assembly scale of the feasibility of minor actinide incineration (reduction by a factor 1000 of the thermal load of high level waste in geological disposal). | Demo:<br>■ Capability to recycle plutonium, depleted uranium and reprocessed uranium, for self-burning in the reactor and for feeding other reactors.<br>■ Conversion ratio=1 with long fuel cycle (> 5 years). | ■ Conversion ratio=1 with long fuel cycle (> 5 years). |
| After Commissioning: Adequacy to operator's needs | | |
| ■ Availability of advanced in-service inspection systems, of adapted advanced I&C system, tolerant and robust systems and components. | ■ Availability of advanced in-service Inspection systems, of adapted advanced I&C system, tolerant and robust systems and components. | ■ Low level of helium leak, reduced number of clad failure, availability of fuel and components handling systems, and helium management system. |
| After Commissioning: Economic competitiveness | | |
| ■ Thermal efficiency for the commercial plant = 42%.<br>■ Efficient fuel handling and in-service inspection systems allowing, after 5 years of operation, the targeting of a technical availability factor of 80% (to be increased to 90% for the commercial plants).<br>■ Demonstration that the cost for electricity generation using future SFR is comparable with costs of other sources of low carbon electricity. | Demo:<br>■ Thermal efficiency = 40%.<br>■ Efficient fuel handling and in-service inspection systems allowing the targeting of an availability factor of 80% on the demonstrator (to be increased to 90% for the commercial plants). | ■ Thermal efficiency > 45%<br>■ Efficient fuel handling and optical in-service inspection systems allowing the targeting of an availability factor of 80% on the demonstrator (outside periods where ALLEGRO is used as an irradiation facility). |
| Specific issues | | |
| ■ Definition and implementation of a first R&D programme to address:<br>■ MOX fuel and innovative fuel development and qualification;<br>■ Innovative advanced structural material qualification. | ■ On the basis of the operational feedback from MYRRHA and the LFR Demo:<br>- Design and construction of a LFR prototype to start in 2035.<br>- Design and construction of a "first of a kind" LFR power plant between 2035 and 2050. | ■ Demonstration of the viability of the GFR concept on the basis of the operational feedback (components and core behaviour, confirmation of the safety case).<br>■ Definition and implementation of the qualification programme for an innovative ceramic fuel.<br>■ Demonstration of the high temperature and cogeneration potential of GFR concept.<br>■ Demonstration of reliability as a fast neutron irradiation reactor. |

## ■ 4.2 Key Performance Indicators for ESNII-4

In order to monitor the Initiative, we also introduce key performance indicators for the Support Infrastructures:

MYRRHA as an irradiation facility:

- **Operational availability and flexibility: efficient fuel handling and in-service inspection and repair systems enabling an operational up-time factor of 65% as an irradiation facility to be reached.**

R&D and testing facilities:

- **End of 2011: shared identification of the needed supporting research, development and testing facilities for each of the components ESNII-1, ESNII-2 and ESNII-3 (ADRIANA FP7 project);**
- **End of 2012: Definition of an investment plan for the corresponding facilities taking into account opportunities for international cooperation.**

Fuel manufacturing facilities:

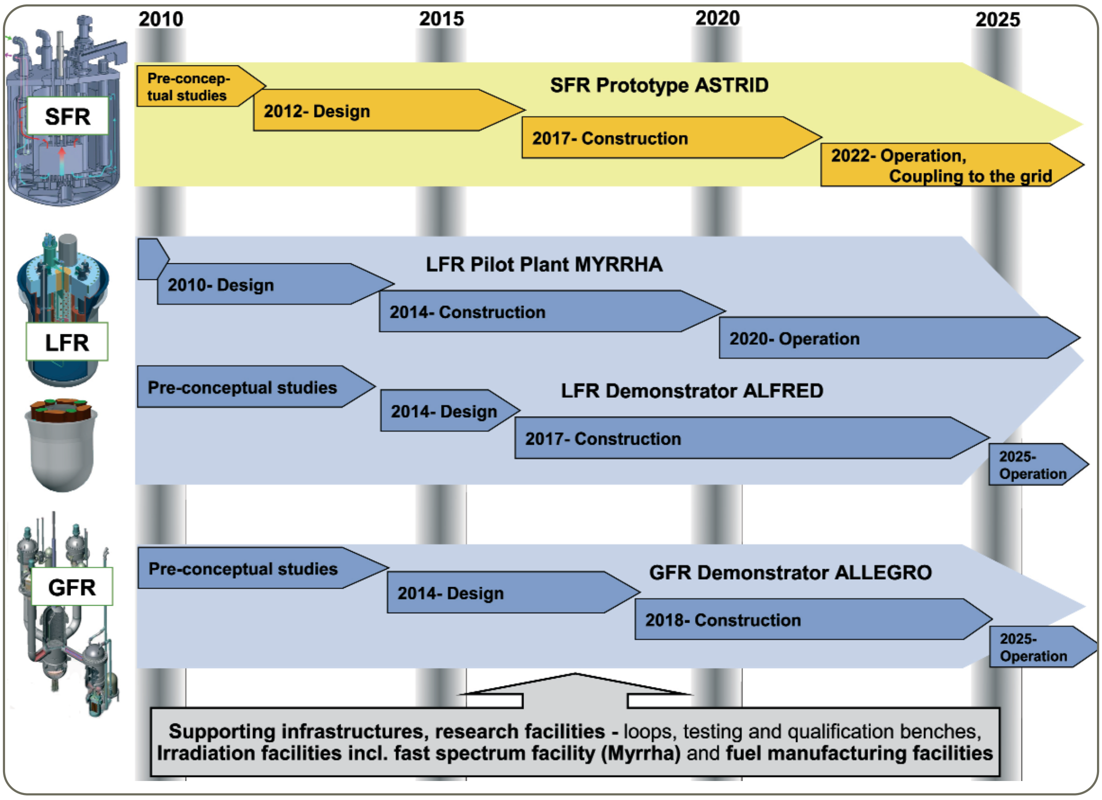
- **Definition of preferred advanced recycling flow sheet process at the pilot plant scale;**
- **By 2016: through the operation of the fuel fabrication workshops:**
  - Production of up to several tonnes of driver fuel per year;
  - Development of high performance minor actinide-bearing fuel with a production of up to tens of kilograms per year.
- **After 2025: definition on the most suitable flow sheet for a pilot plant facility for advanced fuel and a decision to go on.**

# 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 (250 to 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 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 |
| 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 |
| SFR: | Sodium cooled Fast neutron Reactor |
| SNETP: | Sustainable Nuclear Energy Technology Platform |

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