SNETP
Sustainable Nuclear Energy Technology Platform

Strategic Research Agenda

May 2009

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The Strategic Research Agenda of the Sustainable Nuclear Energy Technology Platform is composed of the following documents:

- the Executive Summary,
- the main Strategic Research Agenda.

Both are included in this document.

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Executive Summary

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Executive Summary

The Sustainable Nuclear Energy Technology Platform (SNETP) was officially launched on the 21st September 2007, in the presence of EU Commissioners for Science and Research, J. Potočnik, and Energy, A. Piebalgs. At this event, the Vision Report of the technology platform was presented. It highlights the role nuclear energy plays in Europe's energy mix as the main provider of low carbon electricity (providing 31% of EU's electricity and representing a non-emission of almost 900 million tonnes per year), and identifies future research, development and demonstration (RD&D) tracks that the nuclear fission sector must follow to address three objectives (see figure):

1 maintain the safety and competitiveness of today's technologies,

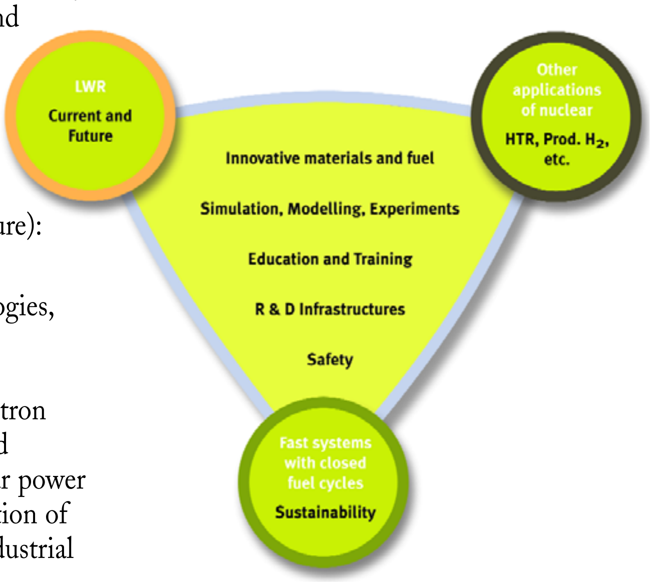
2 develop a new generation of more sustainable reactor technologies – so-called Generation IV fast neutron reactors with closed fuel cycles, and

3 develop new applications of nuclear power such as the industrial scale production of hydrogen, desalination or other industrial process heat applications.

SNETP aims to support fully through RD&D programmes the role of nuclear energy in Europe's energy mix, its contributions to the security and competitiveness of energy supply, as well as to the reduction of greenhouse gas emissions. To achieve this objective, SNETP has elaborated a Strategic Research Agenda (SRA) that identifies and prioritises the research topics. A summary of this SRA is presented here.

SNETP: www.snetp.eu

Vision Report: available at www.snetp.eu



Role of nuclear fission in Europe's low carbon energy policy

On the 10th January 2007, the European Commission published a seminal communication, An Energy Policy for Europe, which for the first time underlined the benefits of nuclear energy: low carbon emissions, competitiveness, and stable prices. In the context of an anticipated increase in use of nuclear energy in the world, the Commission also recognised that *"there are therefore economic benefits in maintaining and developing the technological lead of the EU in this field"*. This communication was endorsed by the Council in March 2007, which also committed the EU to meet ambitious objectives by 2020 of 20% reduction in greenhouse gas emissions (compared to 1990), 20% renewable energies in the energy mix, and 20% reduction in energy consumption through better energy savings and management.

An Energy Policy for Europe: http://ec.europa.eu/energy/energy_policy/doc/01_energy_policy_for_europe_en.pdf

SET Plan:
http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2007:0723:FIN:EN:PDF

WETO Report:
http://ec.europa.eu/research/energy/pdf/weto_final_report.pdf

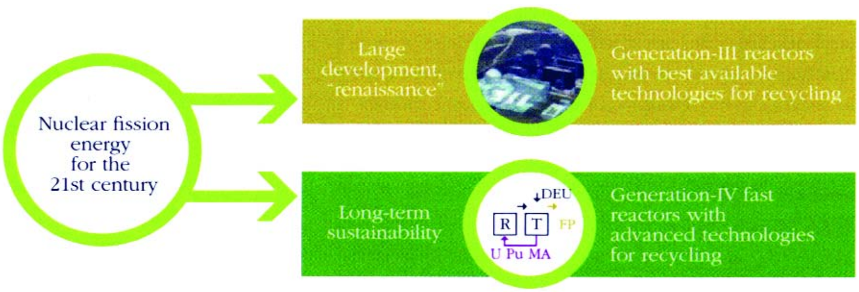
In order to achieve these goals and realise the longer term vision of a low carbon society by 2050, the Commission identified RD&D prospects of key low carbon energy technologies in a follow-up communication, the Strategic Energy Technology (SET) Plan, published on the 22nd November 2007. *"Europe needs to act now, together, to deliver sustainable, secure and competitive energy. The inter-related challenges of climate change, security of energy supply and competitiveness are multifaceted and require a coordinated response. We need a dedicated policy to accelerate the development and deployment of cost-effective low carbon technologies."*

Nuclear fission is cited together with other low carbon technologies such as renewables and Carbon Capture and Storage (CCS) technology as one of the contributors to meet the 2020 challenges. By maintaining *"competitiveness in fission technologies, together with long-term waste management solutions"*, fission energy will continue to be leading low carbon energy technology in Europe. Projections published in the WETO report indicate that by 2030, nuclear energy will continue to produce more than half of the electricity produced by non fossil fuel-based technologies.

Beyond the 2020 objectives, the SET Plan also identifies fission energy as a contributor to the 2050 objectives of a low carbon energy mix, relying on a new generation of reactors and associated fuel cycles. This objective is to be achieved by acting now to *"complete the preparations for the demonstration of a new generation (Gen-IV) of fission reactors for increased sustainability"*.

From 2040 onwards, it is envisaged that this new generation of Fast Neutron Reactors will be operating in parallel to the advanced Gen-III Light Water Reactors now being built in Europe, thereby maintaining the current 1/3 share of nuclear electricity in Europe.

The Strategic Research Agenda of SNETP precisely addresses the key issues of fission technologies as identified in the SET Plan.



2020 Objectives: Maintain the competitiveness of nuclear energy with long term waste management solutions

Assure safe, secure and economic operation of existing and future Light Water Reactors (LWRs)

Given the present share of low carbon electricity produced by nuclear reactors, it is essential that European energy policy supports the long term operation of current plants. To achieve this objective, priority actions must be undertaken:

- Enhance knowledge to understand, prevent and mitigate the effects of ageing, and
- Harmonise long-term operation justification methodologies at European level.

In addition to the operation of existing plants, it is essential to facilitate the construction of new Generation III Light Water Reactors. Design certification should be harmonised so that requirements necessary for licensing should be the same throughout Europe.

- European harmonised plant design and justification methodology.

Gen-III reactors will contribute significantly to Europe's low carbon electricity production. Future units shall benefit from experience feedback from the first ones and from integration of RD&D results addressing:

- improvement of system, structure and component design,
- upgraded man-system interface, simplified reactor systems, and
- advanced fuel and power performance.

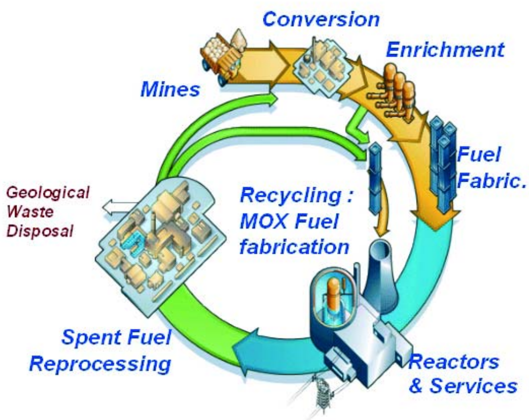
The impact of external issues, such as industrial obsolescence, impact of the environment on power generation, or evolution of regulatory requirements will also be taken into account.

Artist's view of Generation III EPR under construction in Olkiluoto, Finland

- **Develop advanced fuel cycles for waste minimisation and resource optimisation**

Nuclear waste is often perceived by the general public as a problem without a solution. However, the technical feasibility and safety of geological disposal sites are now undeniable, and within a decade the first geological repositories for conditioned high-level nuclear waste are expected to be in operation in the EU.

However, to increase the sustainability of nuclear energy, more efforts should be dedicated to the development of advanced fuel cycles (see figure top right).



This will further improve the competitiveness of nuclear energy, for instance though use of more efficient cores and fuels for an optimal exploitation of the energy content of uranium fuel:

- Improve uranium and plutonium usage in LWRs

Advanced fuel cycles will also enable a reduction in volume, thermal impact, radio-active inventory and longevity of the ultimate waste for disposal in a geological repository.

Fuel cycle pilot plant

To minimise the high level long lived waste, research on Partitioning and Transmutation (P&T) must be continued, with the view to separate ("partition") from the spent fuel the Tran-uranic elements (plutonium and minor actinide) which are responsible for the highest heat loads and radioactive inventory in the long term. The next step is to burn or "transmute" these minor actinides, something that can only be envisaged in fast spectrum systems.

- Continue research on partitioning technologies and Fast Neutron Systems (reactors and Accelerator-Driven Systems - ADS) well adapted to transmutation

The objective of this research is to assess the industrial feasibility of the minor actinide reprocessing option.

Geological disposal of nuclear waste:
http://www.nea.fr/html/rwm/reports/2008/nea6433-statement.pdf

2050 Vision: Gen-IV fast neutron reactors with closed fuel cycle for increased sustainability

Generation IV International Forum (GIF): http://www.gen-4.org/

To address the issue of sustainability of nuclear energy, in particular the use of natural resources, fast neutron reactors (FNRs) must be developed, since they can typically multiply by over a factor 50 the energy production from a given amount of uranium fuel compared to current reactors. FNRs, just as today's fleet, will be primarily dedicated to the generation of low carbon base-load electricity. Demand for electricity is likely to increase significantly in the future, as current fossil fuel uses are being substituted by processes using electricity. For example, the transport sector is likely to rely increasingly on electricity, whether in the form of fully electric or hybrid vehicles, either using battery power or synthetic hydrocarbon fuels. Here, nuclear power can also contribute, via generation of either electricity or process heat for the production of hydrogen or other fuels.

FNRs have been operated in the past (especially in Europe), but today's safety, operational and competitiveness standards require the design of a new generation of reactors. Important R&D is currently being coordinated at the international level through initiatives such as GIF. Europe, through SNETP, has defined its own strategy and priorities for FNRs: the Sodium-cooled Fast Reactor (SFR) as a proven concept, as well as the Lead-cooled Fast Reactor (LFR) and the Gas-cooled Fast Reactor (GFR) as alternative technologies (see figure below).

R&D topics for all three FNR concepts include:

- primary system design simplification,
- improved materials,
- innovative heat exchangers and power conversion systems,
- advanced instrumentation, in-service inspection systems,
- enhanced safety,

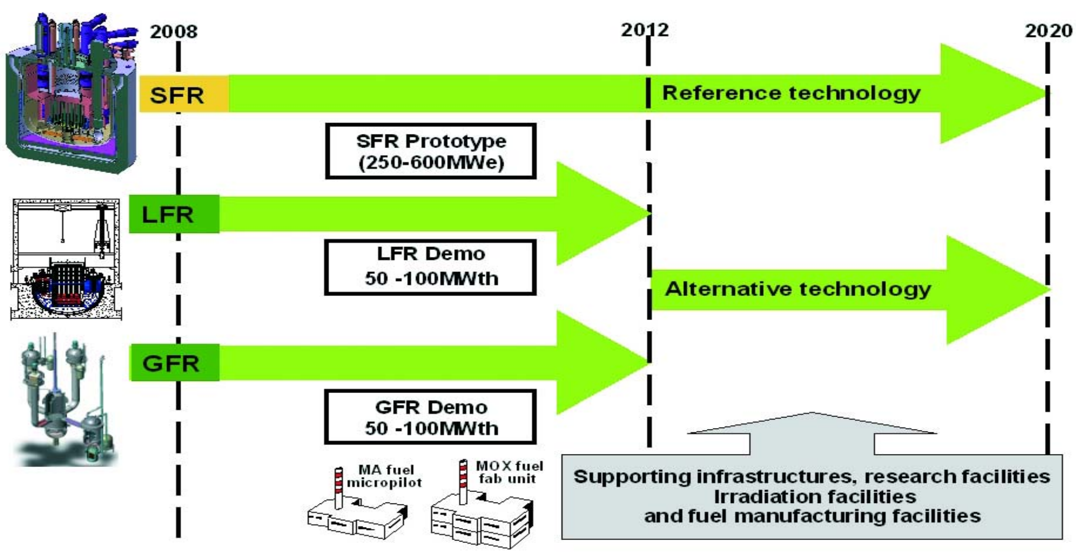
and those for fuel cycle issues pertain to:

- partitioning and transmutation,
- innovative fuels (incl. minor actinide-bearing) and core performance.

Beyond the R&D, demonstration projects are planned in the frame of the SET Plan European Industrial Initiative for sustainable fission.

These demonstration projects include the SFR prototype ASTRID whose construction is planned in France in 2020 and the construction of a demonstrator of an alternative technology – either LFR or GFR – to be decided around 2012. In addition, supporting research infra-structures, irradiation facilities, experimental loops and fuel fabrication facilities, will need to be constructed.

Regarding transmutation purposes, the ADS technology must be compared to FNR technology from the point of view of feasibility. It is the objective of the MYRRHA project in Belgium to be an experimental demonstrator of ADS (XT-ADS) technology. From the economical point of view the ADS industrial solution should be assessed in terms of its contribution to the closure of the fuel cycle.

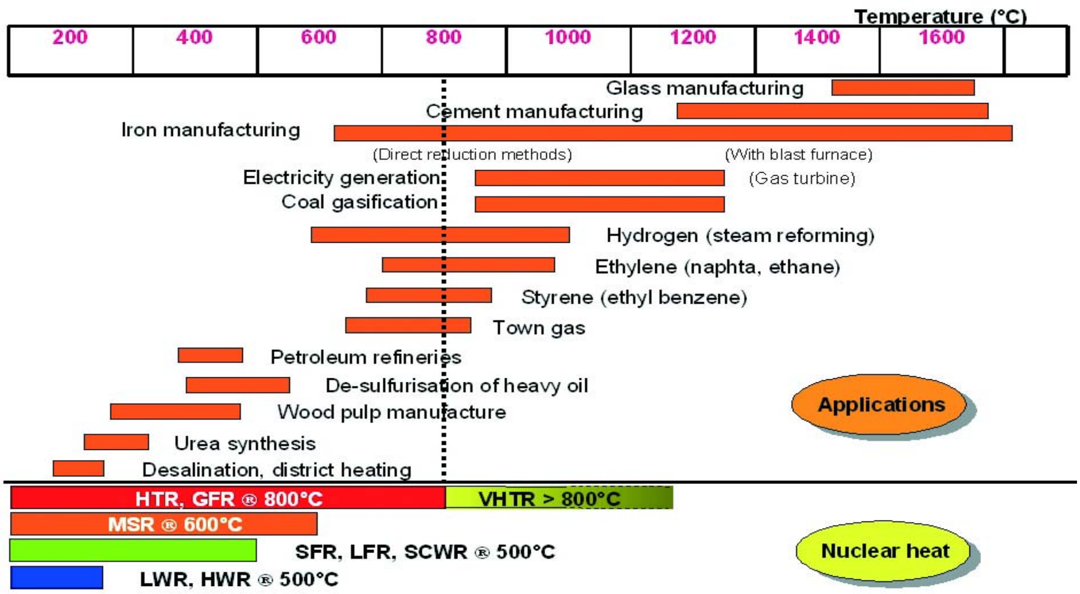


High temperature heat processes, developing other applications of nuclear energy

Increasingly, fossil fuel-based industrial processes will be substituted by processes which use low carbon energy supplies. These processes typically require large and continuous amounts of energy in the form of heat, electricity and hydrogen, all of which can be supplied by a nuclear reactor. Examples of such processes include the large scale production of hydrogen for synthesising fertilizers, for refining heavy crude oil, for optimizing the production of synthetic hydrocarbon fuels from coal or biomass, or for other industrial processes (see figure below).

High temperature gas-cooled reactors have long been identified as the most appropriate supplier of nuclear heat, and a first prototype of such a reactor coupled to the process heat application could be built around 2020. Other types of advanced reactors may also be suitable. The main R&D challenges lie with the technology of the coupling of the reactor to the industrial processes, and with the licensing issues:

- technology developments: heat exchangers, heat transport systems, adaptation of industrial processes to specific aspects of nuclear heat supply,
- material and fuel improvement and qualification,
- tools and methodologies for licensing of nuclear reactor coupled to industrial process,
- management of waste (esp. graphite).



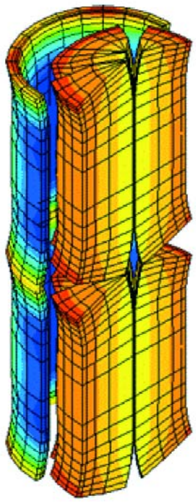
Developing research infrastructures and competences

In order to carry out successfully the above R&D programmes and demonstration projects, the nuclear sector must address the need to reinforce and further develop its competence pool, manage the existing knowledge, and organise a network of research infrastructures.

Basic research needs for cross-cutting topics

- **Material research:** Material research is one of the most important topics for energy research, in particular for fission, where ageing, performance and safety issues all need to be addressed. New materials as well as fabrication and welding processes need to be developed to achieve higher performance levels and longer lifetimes, as well as to withstand more extreme conditions. Challenges remain in the area of multi-scale modelling of material behaviour under irradiation, which together with irradiation experiments will be the key techniques in development of new materials.

- **Pre-normative research** for the development of European codes and standards to be used for future construction of Gen-IV reactors must also be performed. R&D performed under quality assurance will contribute to this objective.



Thermo-mechanical simulation of fuel pellets

- **Modelling, simulation and methods.** The development of more advanced physical models and computational approaches benefiting from the increase of computational power allow for very detailed simulation of reactor behaviour over a range of scenarios from normal to accident conditions and provide best estimate safety evaluations.
  This can be achieved by coupling neutronics, thermal-hydraulics, and fuel performance codes, at various physical and time scales. Particular efforts shall be directed at the development of CFD (Computational Fluid Dynamics) methods for reactor design and safety analysis, and at the development of uncertainty and sensitivity analyses.
  A further area of application of best estimate methods with statistical analysis is the mechanical analysis of components. To exploit fully the potential of these tools, new basic data and specific separate and integral effect validation experiments using advanced measurement techniques will be required.
- **Fuel research.** Basic research is needed to develop and improve modelling tools for innovative fuels (including minor actinide bearing fuels) for Gen-IV reactors. This research aims at establishing fuel properties and behaviour under representative operating and accidental conditions, as well as addressing fabrication processes. Experimental programmes aiming at qualifying the fuel must also be carried out.

Nuclear Safety

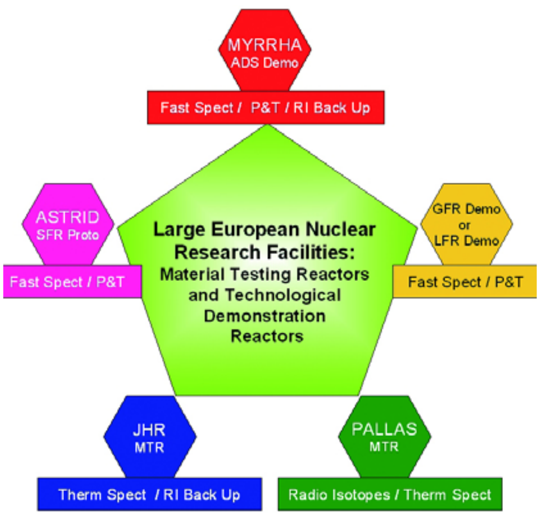
Nuclear reactor research in Europe has always had a strong focus on safety, and this will continue so as to ensure that European reactors continue to operate at the highest level of safety. Besides further research to increase knowledge in the basic nuclear sciences, research on human and organisational factors and plant-relevant issues such as Instrumentation and Control (I&C) and electrical equipment, or external hazards, will be addressed. Research must also be carried out specifically to:

- support long-term operation of nuclear power plants and,
- contribute to the design of intrinsically safe Gen-IV FNRs.

Building a European Research Area of nuclear R&D infrastructures

Fission research has always relied on experimental programmes for validating models, qualifying materials, and more generally, for developing knowledge. Since the cost of maintaining research infrastructures is high, and following a more integrated approach to carrying out research programmes, a network of complementary facilities must be established in support of the Strategic Research Agenda. Some facilities will need to be upgraded to support the R&D programmes. New facilities will also need to be constructed to replace old ones. Among the new facilities:

- Very large scale nuclear research infrastructures provide irradiation capabilities that are essential for material and fuel development, and safety experiments. Three major facilities are being planned in Europe, the Jules Horowitz Material Testing Reactor (whose construction started in Cadarache, France, in March 2007), the Myrrha fast spectrum irradiation facility, and the Pallas reactor which will replace the JRC High Flux Reactor of Petten as Europe's leading provider of radioisotopes (RI) for medical applications and a back-up Material Test Reactor. In addition to these facilities, the fast spectrum Gen-IV demonstrators will also provide experimental irradiation and minor actinide transmutation capabilities.



- **Fuel cycle facilities**
  Gen-IV demonstration reactors and associated irradiation facilities also call for the construction of pilot manufacturing facilities for their driver and experimental fuels.

• Education and training

Education and training of young researchers and engineers is necessary to maintain existing knowledge and to carry out the research and development programmes described above. SNETP has set up a specific Working Group dedicated to Education, Training and Knowledge Management (ETKM) issues with essential support in this area being provided by the European Nuclear Education Network (ENEN) Association, through its activities in FP6 (ENEN-II) and FP7 (ENEN-III) programmes. This trained work force will in part also provide qualified staff to Europe's nuclear industrial sector to accompany the development of the sector in the next decades – though this need will primarily be addressed by specific industry-led initiatives discussed in the European Nuclear Energy Forum. More detailed information on ETKM activities can be found on the platform's website.

European Nuclear Education Network (ENEN):
http://www.enen-assoc.org/

European Nuclear Energy Forum (ENEF):
http://ec.europa.eu/energy/nuclear/forum/bratislava_prague/

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Foreword

In September 2007 was launched the Sustainable Nuclear Energy Technology Platform. At this occasion, more than 30 European organisations presented their common vision for the short, medium and long-term development of nuclear fission energy technologies. The second generation of light water reactors, already in operation, and the third generation under construction, designed to be operated for sixty years, will contribute to the energy mix of the European Union during the forthcoming decades. The fourth generation of reactors will progressively come on line during the second half of our century, and bring new means to preserve natural resources and optimise waste management through the use of fast neutron reactors and advanced closed fuel cycles. High Temperature Reactors will also open new applications of nuclear energy, in particular for industrial processes requiring heat or hydrogen.

Each of these three generations of nuclear systems faces its own challenges, and will involve extensive research and development activities.

The Sustainable Nuclear Energy Technology Platform now gathers more than 70 organisations (research organisations, utilities, vendors, technology providers, technical safety organisations, universities, consultancy companies and non-governmental organisations), and produced this first edition of the Strategic Research Agenda (SRA). This document was edited by a dedicated Working Group drawing on contributions from more than 150 persons and the feedback obtained from an open public consultation. The SRA provides the foundation for the establishment of joint research priorities that will enable European stakeholders, with the support of the European Commission, to transform a shared vision into reality, thus contributing to European energy policy and in particular, via the Sustainable Nuclear Energy European Industrial Initiative, to the objectives of the European Strategic Energy Technology Plan.

Philippe PRADEL
Chairman of the Sustainable Nuclear Energy Technology Platform

Introduction

Current forecasts indicate that primary energy consumption worldwide by 2050 will probably be double that of the year 2000. Energy security is becoming a major global concern. Fossil fuel reserves, particularly for crude oil, are confined to a few areas of the world. Political, economical, and ecological factors often result in volatile and expensive fuel prices. Simultaneously, to combat climate change, a global environmental policy which includes a major reduction in greenhouse gas emissions is required. Thus, availability of affordable, secure and sustainable energy is necessary to preserve the living standards of Europe's population. The nature and scale of this challenge has been recognised by the European Union and its Member States.

The Sustainable Nuclear Energy Technology Platform (SNETP) is the European Technology Platform[1] aimed at promoting the research, development and demonstration of European nuclear fission technologies.

SNETP aims at promoting the research, development and demonstration of European nuclear fission technologies.

It was launched on September 21, 2007 in Brussels, in the presence of the Commissioner for Science and Research J. Potočnik, and the Commissioner for Energy A. Piebalgs. The platform's Vision Report was distributed at this event, and can be downloaded from www.snetp.eu.

Following this launch event, the Governing Board set up a Working Group under the chairmanship of Prof. Dr. Hamid Aït Abderrahim of SCK•CEN to establish the first edition of the Strategic Research Agenda (SRA). The objective of the SRA is to provide decision makers as well as the scientific community with clearly identified technological road-maps for fission technologies. In the context of a new ambitious energy policy in Europe, the SRA of SNETP will support the further development of nuclear energy as one of Europe's main low carbon energy technologies.

Over 150 scientists, researchers and engineers have contributed to the drafting of the SRA. They come from the 60 or more member organisations of SNETP, representing industry, research organisations, technical safety organisations and academia. The SRA is a living document open for revision every 3 to 4 years.

Context of energy policy

Climate change due to excessive greenhouse gas emissions from developed and developing economies is now a scientifically proven fact. Security of energy supply has become a major strategic and economical issue, threatening both standards of living of citizens and competitiveness of industries. Though a global problem, Europe has realised that a new energy policy is needed to address the three energy challenges:

- **security of energy supply,**
- **limitation of greenhouse gas emissions,**
- **competitiveness of energy-reliant economies.**

Following the Communication from the European Commission in January 2007 entitled "An Energy Policy for Europe"[2], the Council of the Member States committed in March 2007 to very ambitious goals putting Europe at the forefront of the fight against climate change. The so-called 3x20 objectives for 2020:

- **20% reduction in greenhouse gas emissions compared to 1990,**
- **20% energy savings,**
- **20% share of renewable energies in the total energy mix,**

[1] **See this link for more information about European Technology Platforms:** http://cordis.europa.eu/technology-platforms/individual_en.html

[2] **Communication from the European Commission (COM 2007) 1 final, see this link:** http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2007:0001:FIN:EN:PDF

lead the way to the vision of a low carbon economy in Europe around the middle of the century. To achieve both the medium term goals (2020) and the long term vision (2050), it is clear that Europe needs to develop and deploy a set of competitive low carbon energy technologies. This is the object of the so-called "Strategic Energy Technology (SET) Plan" which the Commission published in November 2007[3].

Fig. 1: Strategic Energy Technology Plan logo

The SET plan identifies nuclear fission as one of the key low carbon energy technologies which Europe must develop and deploy. For the 2020 objectives, the objective is to *"maintain the competitiveness in fission technologies together with long term waste management solutions"*. This can be translated as maintaining at least the current level of nuclear energy in Europe's electricity mix (around 31%) through long term operation of existing plants and an ambitious programme of new build. For the waste management, decisions are needed at political level to implement technical solutions for long term high level waste management in the form of deep geological disposal.

For the vision of 2050, the SET Plan recommends to act now to "complete the preparation for the demonstration of a new generation (GenIV) of fission reactors with increased sustainability". This demonstration phase could be the object of a European Industrial Initiative, a process by which Europe intends to accelerate the demonstration phase of the most competitive low carbon energy technologies.

Role of nuclear energy

As mentioned above, nuclear energy addresses the following key issues: greenhouse gas emissions, competitiveness and security of supply.

Nuclear energy is one of the energies which emit the least greenhouse gas during its lifecycle. Even Carbon Capture and Storage technologies applied to gas or coal power plants cannot compete with nuclear energy in terms of greenhouse gas emissions[4] (Fig. 2).

The role of nuclear energy in limiting Europe's greenhouse gas emissions cannot be denied.

Nuclear energy is the most important low carbon technology in Europe's energy mix.

With 31% of Europe's electricity produced from nuclear, this is the most important low carbon technology in Europe's energy mix. It is estimated (see the platform's Vision Report) that compared to a representative mix of alternative base-load capacity (essentially gas and coal), Europe's nuclear power plants represent a saving of almost 900 million tonnes of CO_2 per year, i.e. approximately the level of emissions from the whole transport sector.

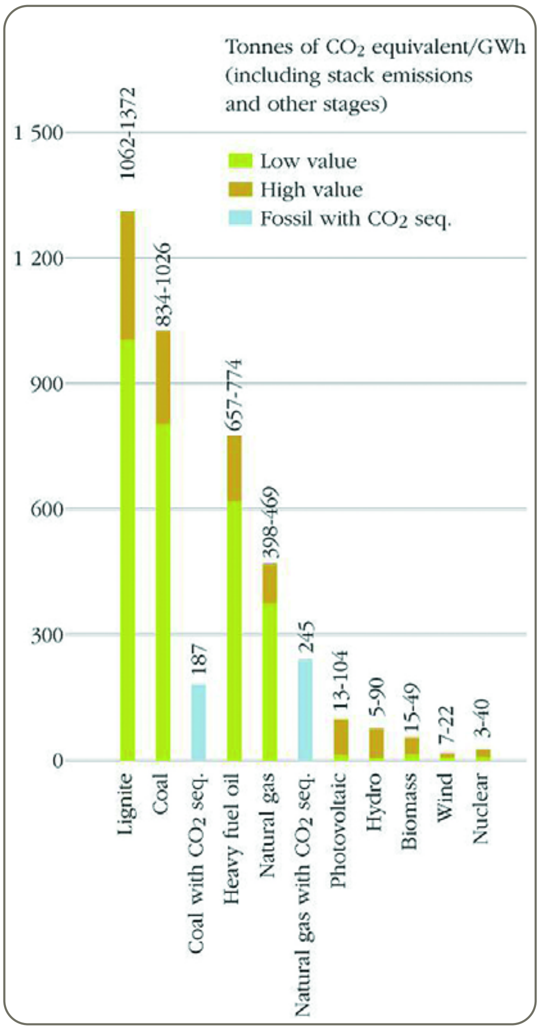

Fig. 2: Greenhouse gas emissions (in tonnes of CO_2-equivalent) per GWh for different electricity production means

[3] Communication from the Commission COM (2007) 723 final, see this link: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2007:0723:FIN:EN:PDF

[4] Comparison of energy systems using life-cycle assessment, Special Report, World Energy Council, London, 2004

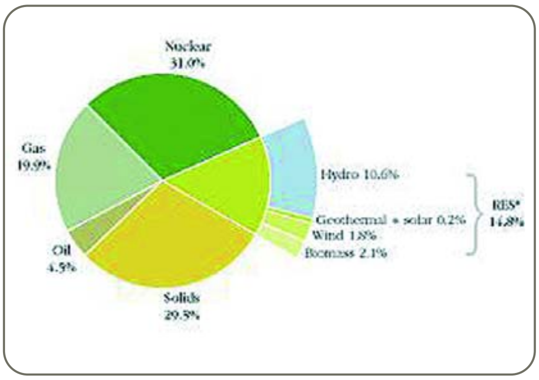

Fig. 3: Electricity generation shares in EU-25 in 2004[5] (*RES: renewable energy sources) [Source: Eurostat]

The competitiveness of nuclear energy has been established by independent expert studies such as the EUSUSTEL project[6], and more recently by a dedicated working group of the European Nuclear Energy Forum (ENEF)[7]. The competitiveness of nuclear energy (compared with fossil fuel alternatives) will be further improved by CO_2 pricing established by emissions trading schemes. Improving still further the competitiveness of all aspects of nuclear energy, while maintaining the high level of nuclear safety, remains one of the objectives of research and development, as emphasised in this document.

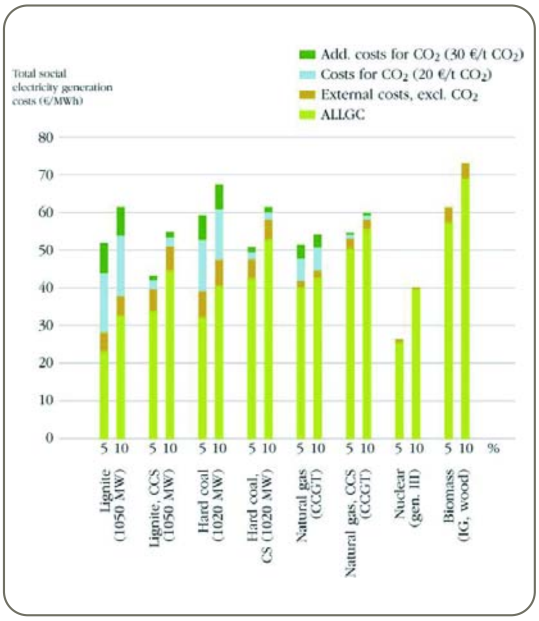

Fig. 4: Estimated total social costs for different electricity generation technologies in 2030. (ALLGC: average lifetime levelised generation costs) [From the EUSUSTEL project[8]]

Security of supply

Known global uranium resources can cover a hundred years under current conditions and are distributed worldwide in politically stable countries. These resources would last for thousands of years when considering future fast neutron reactors.

The 31% of electricity produced by nuclear power in Europe corresponds to the saving of 190 Mtoe of natural gas per year[9].

Technology platforms

Technology platforms have been proposed by the European Commission as a tool to promote research and development in technological domains. They *"provide a framework for stakeholders, led by industry, to define research and development priorities, timeframes and action plans on a number of strategically important issues where achieving Europe's future growth, competitiveness and sustainability objectives is dependent upon major research and technological advances in the medium to long term"*.

Technology platforms play a key role in better aligning EU research priorities to society's needs, and address challenges through:

- shared vision of stakeholders (i.e. the Vision Report[10]),
- positive impact on a wide range of policies,
- reduced fragmentation of research and development efforts,
- mobilisation of public and private funding sources.

Technology platforms play a key role in better aligning EU research priorities to society's needs.

The Strategic Research Agenda is one of the most important outputs from a Technology Platform, as it provides decision-makers as well as the scientific community at large with research, development and demonstration road-maps to achieve a shared vision.

The vision of "Sustainable Nuclear Energy"

Sustainable development has been defined in many ways, but the most frequently quoted definition is from "Our Common Future", also known as the Brundtland Report[11]: "Meeting the needs of the present generation without compromising the ability of future generations to meet their own needs".

Access to secure and affordable energy is vital if societies are to meet these needs. Because of its polyvalence, access to electricity is particularly important.

[5] **Nuclear Illustrative Programme (PINC),** COM(2006) 844, published in Jan 2007, and Annexes 1 and 2, SEC(2006) 1717 and SEC(2006) 1718

[6] **http://www.eusustel.be**

[7] **http://ec.europa.eu/** energy/nuclear/forum/bratislava_prague/working_groups/opportunities/competitiveness_en.pdf

[8] **A.Voß, I. Ellersdorfer, U. Fahl, M. Blesl (2007):** Determination of the total social costs of electricity generation. European Sustainable Electricity; Comprehensive Analysis of Future European Demand and Generation of European Electricity and its Security of Supply (EUSUSTEL), Final Technical Report

[9] **European Energy and Transport** – Trends to 2030 – Update, EC-DG TREN, published in 2008

[10] **The Sustainable Nuclear Energy Technology Platform,** A vision report, available at www.snetp.eu

[11] **World Commission on Environment and Development (WCED).** Our common future. Oxford: Oxford University Press, 1987 p. 43. Also available as a scanned copy of UN General Assembly document A/42/427, hosted by the Center for a World in Balance: http://www.worldinbalance.net/agreements/1987-brundtland.php

To be sustainable, energy production must avoid endangering the well-being of future generations, not only by reducing the use of natural resources but also by minimising detrimental effects on public health and the environment. In particular, electricity production must achieve high levels of safety and limit harmful emissions over the full lifecycle of the plant (cradle to grave).

Sustainability:
"Meeting the needs of the present generation without compromising the ability of future generations to meet their own needs."

However, the current situation is clearly unsustainable. Climate change is a reality and is becoming increasingly threatening, especially for poorer countries. Action is needed urgently to mitigate all of our greenhouse gas emissions. In the EU, 80% of greenhouse gas originates from energy use, so a primary objective must be to improve energy efficiency thereby reducing fossil fuel consumption as much as possible. Secondly, there needs to be a swift transition to a low-carbon economy by promoting research and development (R&D), innovation and commercial deployment in all low-carbon technologies. Though the costs of this transition may appear high, they are small compared with the costs to society of climate change[12].

Security of supply, competitiveness and sustainability are the fundamental considerations in Europe's energy policy agreed by the EU Council in March 2007. The aspect of sustainability is particularly important in the current context of climate change, and relates not only to the use of resources but also to how energy use impacts on the environment.

The SRA of SNETP has been based on three pillars as in the Vision Report (Fig. 5).

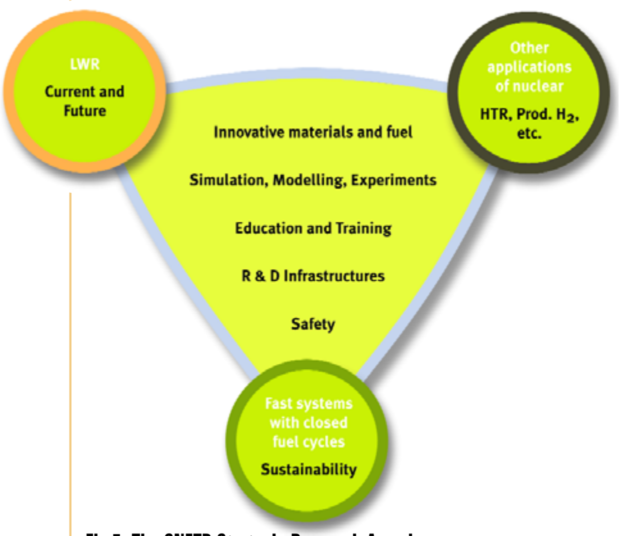

Fig.5: The SNETP Strategic Research Agenda

[12] **Cambridge University Press, 978-0-521-70080-1, The Economics of Climate Change, The Stern Review, Nicolas Stern.** The report can be downloaded at: http://www.hm-treasury.gov.uk/stern_review_report.htm

[13] **The SRA does not address the R&D needs of other existing reactors operating in Europe**, such as Advanced Gas-cooled Reactors (AGRs) in the UK, Heavy Water Reactors such as CANDUs operating in Romania, or the RBMK reactor in Lithuania, as these reactors do not represent a significant part of the fleet or a technology to be pursued in Europe.

GenII LWR nuclear reactors contribute already very positively to the objectives of the EU's energy policy, as will GenIII reactors in the very near future. Existing reactors have an outstanding safety track-record and they offer inexpensive base-load electricity; uranium supply is secure; moreover nuclear power plants emit very low lifecycle greenhouse gases.

Innovative GenIV fast reactor systems with a closed fuel cycle will offer greatly improved sustainability. They will produce up to 100 times more electricity than current reactors from the same amount of uranium enabling natural resources to last thousands of years and thorium has the potential to provide even greater resources. In addition, with advanced fuel cycles and the partitioning and transmutation (i.e. recycling) of minor actinides and long-lived fission products, they will produce significantly less waste for disposal (in terms of volume, thermal load and radio-active inventory) thereby further reducing environmental impacts and optimising geological disposal.

Other GenIV reactors operating at very high temperature will provide low carbon process heat for the mass production of hydrogen and other industrial processes, thereby replacing oil or extending its exploitation.

Molten salt reactors may represent a sustainable nuclear energy system in the long term. However they are still far from industrial application and are not considered in the main body of this report.

Structure of the Strategic Research Agenda

The Strategic Research Agenda of SNETP has been organised to address the short (around 2012), medium (around 2020) and long term challenges (2040-2050) of the SET Plan with respect to fission technologies.

The first chapter deals with R&D to support present and future Light Water Reactors (LWRs) and their further development, with the aim to guarantee the present contribution to security of supply and CO_2-free energy mix and enhance their competitiveness[13]. Key issues are related to meeting safety requirements for long term operation focussing on ageing of structures, systems and components. Other important issues are ageing mechanisms, ageing monitoring and prevention and mitigation of ageing. Finally, the chapter deals with various aspects of enhancement of plant performance.

In the second chapter, the R&D challenges to further improve the current fuel cycles are addressed, with two objectives: improving the use of natural resources in LWRs through recycling strategies, and minimising the final waste. Although the optimal use of uranium and the minimisation of the final waste after multi-recycling can only be achieved with Fast Neutron systems together with a closed fuel cycle (developed in the following chapter), improved designs of LWR combined with fuel reprocessing and recycling can contribute significantly to the competitiveness of nuclear energy.

In the third chapter, the development of fast neutron systems (both GenIV Fast Neutron Reactors (FNR) and Accelerator-Driven Systems (ADS)) is addressed, together with the need for demonstration. As already indicated in the Vision Report, European stakeholders have chosen to concentrate their efforts to develop fast neutron reactors along two directions. The first direction is that of the sodium-cooled fast neutron reactor as a known and proven technology but for which innovations are necessary to fulfil the criteria of GenIV reactors. The second direction is to develop an alternative coolant technology to sodium, either lead or gas, to offer decision makers a choice of reactor systems, and to limit technological risks. The construction of technology demonstration plants or prototypes for fast neutron reactors is the object of a European Industrial Initiative of the SET Plan which SNETP is preparing. Finally, in this chapter, R&D for ADS for transmutation of high level nuclear waste is described. The decision to select a technology for transmutation, either fast neutron reactors or ADS, will be made around 2012 on the basis of industrial and economic prospects.

Beyond the need to maintain the capability of existing nuclear reactors and the need to develop more sustainable reactors to produce electricity there is another large market, which is new for nuclear energy, and in which nuclear energy could play an important role: industrial heat application processes which today rely on fossil fuel. This is the object of the fourth chapter. Among industrial heat processes, the production of hydrogen may need to be increased significantly if the market for hydrogen-fuelled vehicles develops. Production of alternative fuels (coal to liquid, 2nd generation biofuels, etc.) could also benefit from nuclear heat. This chapter looks closely at the High Temperature Reactor (HTR) technology as one having much potential for such new applications (but other reactor technologies could also be used).

Finally, the last chapter of the SRA addresses the need to develop competences and research infrastructure to support the R&D needs, and to maintain safety research and develop expertise in new systems. The chapter focuses on several key cross-cutting topics (material research, modelling and simulation, fuel research, as well as pre-normative research) for which a large R&D effort is needed in the short and medium term. To support the global R&D effort of the SRA, research infrastructures are needed, from small scale experimental loops to large scale nuclear facilities. The construction and operation of such facilities can only be achieved today through a European effort, hence the description in this document of the most important facilities for Europe's nuclear research. Last but not least, education and training needs are briefly described in this document, but more detailed proposals are addressed by the Education, Training and Knowledge Management Working Group of the platform.

1. Current and future Light Water Reactors

Along the 21st century, it is foreseen that Light Water Reactors (LWR) will still produce the major part of nuclear electricity in Europe.

In the period 2010-2050, the successful operation and management of GenII LWRs beyond their originally foreseen lifetime, will be vital to the security of supply of electricity in Europe. The next evolutionary design of LWRs, GenIII, will be deployed over many decades and will represent a large part of the worldwide reactor fleet throughout the 21st century. The sections below are equally applicable to GenII and GenIII.

Based on feedback from operation there could be a need for targeted R&D for GenIII, such as the improvement of passive safety features, system design and fissile resources use.

Fig. 6: Isar Nuclear Power Plant (GenII), Germany
[Copyright © Rolf Sturm / D – 84034 Landshut Germany]

1.1 Long term operation

The vision: to move towards 60 or more years of safe and economic operation of nuclear power plants.

Realising the vision: the supporting research priorities are presented, starting with concepts and design and focusing on safety justification; progressing to consideration of the ageing of the chosen systems, structures and components, and then addressing associated economic and external factors.

The challenge: European harmonisation of long term operation methodologies.

1.1.1 Safety justification

Traditionally, regulation of design and operation of nuclear plants have been based on deterministic engineering analysis methods. The resulting criteria continue to assure that plants can be placed in a safe condition following a number of postulated design basis accident scenarios. These criteria also provide the basis for identifying which plant Structures, Systems and Components (SSC) and activities are important to safety. Regulation of these "safety-related" SSC and activities is controlled through regulatory requirements. Compliance with evolving regulatory requirements will require innovative deterministic and probabilistic approaches of safety assessment for existing nuclear power plants.

Medium term challenge:
European harmonised plant design and justification methodology. A specific goal shall be to facilitate the adoption of common criteria for the acceptance of nuclear power plant designs in EU member states.

Design basis

At the design level, the ageing mechanisms during operation are generally considered, based on basic knowledge and international field experience. The different aspects considered are:

- safety requirements in terms of needs to assure different safety functions,
- operating conditions and external/internal hazards,
- design of the components, structures and systems: design life (through analysis or qualification tests), trends and boundaries for degradation from ageing and enabling recovery of design,
- fabrication, examination and protection of the different components and structures with margins according to safety classification.

Medium term challenge:
European harmonised safety justification methodologies, enabling evolution in design or operation[14].

Safety margins and probabilistic assessment

Deterministic engineering analysis methods have been applied in the past to demonstrate compliance with safety margins. However, in order to integrate the knowledge collected in the past 50 years of reactor design and operation, probabilistic approaches need also to be considered.

A quantitative understanding of material properties and ageing mechanisms is a prerequisite for the probability of failure to be correctly estimated, since in-service failures are very rare events.

Probabilistic models can be improved greatly through well designed experiments leading to physical insight and qualification of computation tools.

Medium term challenges:
- **harmonise deterministic safety methodologies,**
- **harmonise probabilistic safety methodologies,**
- **combine the use of both methodologies for safety assessment.**

This will lead to improved quantification of deterministic safety margins (e.g. at end of life). It will also promote the harmonisation of probabilistic safety goals (e.g. reactor core damage frequency).

Integrity assessment

The underlying principles of structural integrity assessment are equally applicable to all generations of reactor designs.

Short term challenge:
lessons learned from GenII nuclear power plants (validation of the integrity assessment).

When proof of life expectancy requires a demonstration that a component will sustain certain loadings during given conditions, the following issues need to be considered:

- better knowledge of conditions under which the demonstration must be sought,
- better knowledge of loadings[15]; better understanding, validation and use of modern codes for assessing loading (e.g. computational fluid dynamics codes),
- better knowledge of the criteria for end of life component ranking:
  - direct comparison between an indicator describing the component status and some acceptable limit value,
  - more complex criteria generally related to the capacity of the component to sustain the loadings induced by some operating conditions, which are not necessarily the normal ones.

Medium term challenges:
- **European harmonised methodologies to assess integrity and performance in the case of internal and external hazards,**
- **selection of indicators and agreement upon end of life criteria.**

Test procedures for initial qualification, though fully appropriate at the time when older nuclear power plants were built, might be no longer state of the art. The operating conditions of the plants may also have varied considerably from the planned mode of operation. The first question refers then to the relevance of the qualification tests. The next question treats the extension of this initial qualification to a service life longer than the design life. The third question relates to the qualification procedures to be used in case of the replacements of obsolete[16] materials or components. Simplifications of some procedures based on state-of-the-art understanding of ageing mechanisms could be very beneficial.

Short term challenge:
reviewing safety justification methodologies for the possible effect of extended service.

Medium term challenge:
common position on the relevance of qualification tests and on their extension to cover longer-term operation.

Periodic safety review

Periodic safety review is used in many countries throughout the plant service life.

During this review, as one of the tasks, all the ageing mechanisms of systems, components and structures are reviewed, applying the knowledge

[14] e.g. preclusion of brittle failure

[15] water hammer, thermal mixing, seismic events, fire, flooding, induced vibrations etc.

[16] Obsolete material: no longer under production; however, replacement material may only differ marginally from the original composition

collected from previous analysis. Risk informed processes are already used in optimising design, operation, maintenance and inspection but are capable of considerable further development and application.

A key issue to comply with safety requirements is to confirm the safety margins throughout the life of the plant. In order to do that surveillance, inspection, monitoring and collection of relevant data is done by the operator in a proactive way.

Some repairs and replacements have to be considered in these tasks, with their remaining life evaluation.

Medium term challenge:

- **harmonisation of periodic safety review process through integration of knowledge of different plants,**
- **development of generic data bases to support risk informed methodologies.**

1.1.2 Ageing mechanisms of Structures, Systems and Components

Effective life management of any facility requires sufficient knowledge of the life expectancy of each important SSC and its governing parameters.

In many cases, ageing assessments have been undertaken during the design phase but generally with very conservative[17] assumptions, methodologies, data and models.

More realistic and more exact SSC lifetime assessments are needed in some cases for both a nominal lifetime and in general for an extended lifetime.

R&D can provide some key elements along the chain of the studies:

- Better knowledge of initial conditions. These initial conditions (component design, materials, and manufacturing conditions) should ideally be documented in design and construction reports. In case this data is not complete R&D programs can compensate for this lack of knowledge through the development of technologies for in-situ non-destructive measurement of ageing relevant parameters or through the estimation of these parameters by numerical simulation of the fabrication process.
- Better knowledge of operating conditions. These can usually be obtained by appropriate instrumentation. In that case, R&D will focus on technology and methodology for data acquisition, transmission and e.g. data reconciliation. Numerical simulation may also be useful to calculate local values of some parameters when existing instrumentation provides only average or inadequate estimations. However, in case of simulations, appropriate experimental validation of the numerical models is necessary.

  (Initial conditions and operating conditions are inputs to ageing mechanisms.)
- Better knowledge of ageing mechanisms. This is a top priority for R&D. The goal is to anticipate and acknowledge ageing issues that may evolve during the foreseen extended life. Identified priorities are corrosion fatigue, irradiation embrittlement, stainless steel cracking and concrete ageing. In case of very long times, possibly exceeding 60 years of operation, several ageing mechanisms that previously have been deemed of lesser importance, such as creep and thermal ageing, may become life limiting factors that need to be addressed.

A better physical understanding of all relevant ageing mechanisms and their driving parameters is necessary.

Improvements are needed in a better physical understanding of all relevant ageing mechanisms and their driving parameters: to identify not only the thresholds for defect initiation and the kinetics for defect propagation, but also the precursor state that leads to defect nucleation. There is a need to be able to make reliable long-term predictions of ageing and its effects. This entails being able to model fundamental phenomena in physics and chemistry at different scales from atomic to macroscopic. Model parameters must be validated against data from laboratory experiments or, most importantly, from operating experience feedback.

Short and medium term challenges:

- **relevant and reliable material properties for extended service,**
- **a common understanding of relevant ageing mechanisms on material and component properties from a long-term operational perspective,**
- **development of advanced multi-scale modelling tools.**

Long term challenge:
European common integrated and qualified physics-based modelling tools.

[17] **There are three reasons for this built-in conservatism:**
to cover regulatory demands anticipated during the protracted construction phase,
to provide sufficient margins to cover large uncertainties due to the fact that, at the time of the design work, operating conditions were not always perfectly known, and most importantly, ageing laws had not been validated through actual operating experience of the plant itself,
to make studies more simple because reducing the uncertainty (and the counterpart margins) often requires complicated and time-consuming, costly studies, calculations (refined mesh in finite element analysis, direct coupling of codes, more realistic model which, in turn, requires more experimental data for its validation).

1.1.3 Ageing monitoring

Component ageing has to be monitored over the nominal and extended service life, in order to determine ageing mechanisms correctly. The overall goal is to monitor and understand environmental conditions in the power plants as well as their impact on the functionality of safety relevant components and structures.

One way is to correlate the evolution of microstructure and material damage with applied loadings and conditions. This will be particularly useful in the case of infrequent transients.

This will enable the operator to verify the suitability of maintenance programs and in-service inspection, thus making sure operation remains within allowed limits.

R&D activities may help to identify indicators of ageing phenomena and demonstrate their relevance.

Another area for R&D is the development of technologies to monitor such indicators and process the data. Examples may be monitoring of thermal ageing of other components than the reactor pressure vessels, irradiation and embrittlement monitoring of the reactor pressure vessel and water chemistry monitoring by on-line fluid sampling or off-line monitoring e.g. using micro samples or replicas.

Medium term challenges:
- **development and justification of in-service inspection qualification and risk-informed in-service inspection procedures,**
- **a feasibility demonstration of intelligent plant condition monitoring systems.**

Long term challenge:
implementation of intelligent plant condition monitoring systems.

1.1.4 Prevention and mitigation of ageing

Prevention[18] and mitigation methods to avoid initiation or limit propagation of defects and onset of ageing need to be developed. These methods should be common and acceptable to all types of reactors as well as for different regulatory positions within the European countries.

Medium term challenges:
- **best practices guideline for ageing prevention and mitigation and operational deployment,**
- **advanced repair and replacement technologies.**

Industrial obsolescence

Conceptual ageing, i.e., at what point is further life extension/optimisation not defendable from external points of view, could be seen as industrial obsolescence at a plant design level.

Component obsolescence refers to components that are no longer manufactured so that replacement can go as far as a complete change of the system or a real change in design.

An emblematic example is Instrumentation & Control systems, with the forced transition from analogue to digital technology. R&D can help to adapt the safety justification (e.g. qualification of software). Furthermore a common approach should be developed either to create versatile technologies, possibly with other industries, or to adapt nuclear procedures to even faster evolving domains, vendors using more and more off-the-shelf technologies and components.

1.2 Performance improvement

1.2.1 Employee dose reduction

New technologies and tools supporting maintenance tasks may be fed with information related to radiation-protection[19]. Reducing dose received by personnel is clearly a major safety target for all utilities, with the additional benefit that it reduces anxiety induced by working in a nuclear power plant.

1.2.2 Man-system interface

Plant operation can be facilitated and general performance improved by simplifying operating procedures, thereby enhancing human performance and reliability. Human reliability science has made remarkable progress in recent years and is now capable of providing insight far beyond human errors or deviations from the prescription.

Direct visualisation of phenomena as they occur

[18] **For instance qualification of higher resistance materials**, advanced repair methods or welding techniques, water chemistry improvements to avoid environmentally assisted ageing while controlling the effects on other mechanisms, radiation shielding, preclusion of thermal fatigue.

[19] **Virtual reality model with data about radioactivity**, real-time data about dose automatically sent to a dedicated control room, etc.

in the reactor systems could be made possible, improving greatly the understanding of any situation. Testing decisions or actions before applying them could enable their consequences to be checked and the right choice to be made especially when facing unusual operating conditions.

Human reliability science can now provide insight far beyond human errors or deviations from the prescription.

Virtual reality models can be further developed to enhance the training of maintenance personnel and prepare them for maintenance tasks before outage. The added value of simulators is greater in the reactor containment building where access is not easy before the outage. During the maintenance tasks themselves, general use of Radio Frequency Identification technology could make it possible to ensure that people are working on the right component. With portable computer and wireless connection, workers will have access to needed information and will report more quickly. Communication among individuals will also be improved, reducing the risk of error or misunderstanding.

Large component handling can also benefit from these new approaches: handling and storage during outages can be better prepared, reducing the component ageing due to eventual mishandling and the duration of the outage.

Medium term challenge:
common basis for simulator to design performance improvements.

1.2.3 Operational lessons learned and improved design

The objective is to enable long-term operation of the nuclear power plants by collecting and structuring updated information on operational experience and incorporating advanced repair and replacement technologies, as well as implementing the lessons learned from the operation of the current fleet of nuclear power plants to the proposed next generation of Light Water Reactors.

The added value of this knowledge and know-how must be demonstrated within the context of pre-normative and codification conclusions in order to maintain and disseminate European industrial leadership. This effort must cover materials, destructive or non-destructive examination (non-destructive-examination-friendly design), welding, fabrication, in-service inspection, mechanical design and analysis, extended use of passive safety features -- all parameters involved in a safe and high quality design.

Medium term challenges:
- **methodology and databases for systematic interpretation of operational experience and lessons learned from extended service,**
- **development, testing, and assessment of passive safety system designs for future LWRs.**

1.2.4 Fuel performance and core optimisation

Fuel performance has to fit different duration of fuel cycles or various operating modes (such as higher burn-ups). R&D has to create new methodologies for safety demonstration e.g. taking advantage of multi-scale and multi-physics core calculations.

R&D has to create new methodologies for safety demonstration e.g. taking advantage of multi-scale and multi-physics core calculations.

To obtain advanced reactor design and support core optimisation, significant progress is required in the area of reactor physics, neutronics and thermal-hydraulics codes. To address the relevant parameters and estimate the code accuracy, progress is also required in the development of uncertainty and sensitivity analysis.

1.2.5 Power upgrades

Power upgrades are currently implemented or considered to improve the plant output. They lead to higher reactivity, which can increase radioactive releases (boron, tritium and carbon 14). Power upgrades generally induce higher loadings either by increasing flow rate (affecting vibrations) or pressure (affecting temperature) in the primary circuit. These adverse phenomena can have an impact on lifetime. A proper balance therefore needs to be established between beneficial and adverse effects of a planned power upgrade.

1.2.6 Efficiency improvement

The efficiency of fossil-fired power plants has been improved significantly in the last decade. With supercritical steams up to 600°C and 30MPa, such plants reach more than 46% net efficiency, while nuclear plants still use a saturated steam cycle of around 7MPa, almost the same as those used in the 1960s when turbine blade resistance was the limiting factor. Today one could consider designing a LWR in the supercritical water regime. Such a design, the Supercritical Water Reactor (SCWR), has been proposed within the scope of the GenIV family of reactor systems.

Some advantages of the SCWR are:

- plant simplification, e.g. no steam separators or primary pumps are needed,
- use of supercritical water would physically exclude boiling crisis, which implies an additional safety characteristic to this concept.

However, supercritical water introduces new challenges:

- Aiming at steam temperatures similar to those achieved in fossil fired power plants, density differences of the coolant in the core will exceed those of a boiling water reactor, resulting in a lack of moderator if not compensated by other means.
- The hotter coolant will result in hotter cladding temperatures of fuel pins, so that other materials than Zircalloy are required.
- The ten times higher enthalpy rise in superheated steam with respect to current reactors implies a more sophisticated core design to avoid hot spots caused by a non-uniform power profile or by uncertainties and allowances for operation.

The development strategy of SCWR assumes that most required components can be derived from future LWRs or from supercritical fossil fired power plants. Only a few components, in particular core components and components of the passive safety systems, will require a dedicated test and development programme covering:

- the fuel assemblies,
- the water chemistry and its interaction with reactor materials,
- passive safety.

The results will then be used to complete the assessment of SCWR against the European Utility Requirements and estimate costs. Therefore, as a next step, the SCWR concept needs to be further evaluated, including an assessment of necessary safety systems.

Short term challenge:
quantification of advantages and challenges presented by the supercritical water reactor (SCWR) concept.

Depending on the outcome of this evaluation a plan can be made in a later version of the SRA on further development steps towards an industrial deployment of the SCWR.

1.2.7 Plant level analysis

Results from ageing kinetics of major SSCs (including turbine, generator, cooling tower) can be integrated at the plant level with transverse items such as exploitation mode, efficiency, waste, dose reduction, etc. in a quantitative method based on occurrences and consequences. It allows collecting, structuring and capitalising the technical and economical data and knowledge.

2020 challenge:
accepted European procedure and tool to support long term operation and plant level analysis.

Examples:

- continuing operation of ageing GenII plants versus already available GenIII plants,
- future shift from GenIII to GenIV depending on fuel availability.

1.3 External factors

1.3.1 Environmental impact on generation

Although there is undoubtedly public concern about the impact of generation activity on the environment, plant operators also know that the environment has an impact on the generation activity.

Unavailability of plants triggered by environmental hazards is increasing and climate change is likely to make the situation worse in the next decades. One issue is the availability of sufficient water for plant cooling purpose, with the risk that flow rate and water temperature in rivers might undergo changes in average values or reach more frequently extreme values. Other climate hazards may threaten safe and cost-effective plant operation: blockage of water intake by seaweeds and sand, rising sea levels, etc…

R&D could help in making predictions to assess the future situation and prepare timely decisions. Systems to help operate plants in changing external conditions (e.g. advanced cooling systems based on ammonia-air cycle) could be developed, tested and evaluated.

1.3.2 Impact of changing regulatory requirements

Regulatory requirements are becoming ever more stringent, particularly in the field of safety and environmental impact. Operators need to demonstrate that their plants fulfil these new requirements. The fact that issues related to safety and environmental impact have been addressed in design will generally not be considered as sufficient. So plant operators will have to carry out studies and assessments that used to be vendor issues.

R&D can help in many respects:

- develop methodologies, knowledge, models, codes and data for assessments never carried out before,
- develop approaches such as risk-based approaches to support realistic assessment of new issues,
- develop technologies necessary to meet new requirements if needed, e.g. earthquake and fire protection.

Plant operators will have to carry out studies and assessments that used to be vendor issues.

Such R&D programs could provide the opportunity of performing definitive assessment of certain longstanding issues in order to reach an international consensus: either a measure must be taken or the issue is closed. They will help to complement design rules and standards only when necessary.

Beyond Design Basis Accidents is a good example. A group in SARNET (European Network of Excellence set up under the Euratom Framework Programme) has ranked priorities on LWR severe accident management for further investigation.

Long term challenge:
maintain and transfer the severe accident knowledge gained from one reactor generation to the next: GenII, III and evolutionary GenIII then GenIV reactors.

1.3.3 Human resources availability and knowledge management

Extension of life to 60 or more years requires transmission of knowledge and expertise between two or three generations of workers. Information and communication technologies can provide suitable tools for making documentation easily available to new employees and to define customised training paths, keeping track of evolutions of plants and of related safety issues. These tools shall present more than raw data: understanding and analysis as well. When licensed operators have a clear responsibility on Know-How, academic and research institutions need to take the lead role on Know-Why.

University–industry interactions are needed to guarantee the education of a new generation of nuclear technicians, engineers and scientists.

A short term target is the migration of technical documentation of nuclear power plants towards easily accessible databases. This process in particular needs to be completed for some VVER[20] reactors, whose design documents were issued in non-EU languages and from institutions which may no longer exist. Interaction between university and industry is necessary to guarantee the education of a new generation of nuclear technicians, engineers, and scientists and to avoid the risk of forgetting the lessons of operational experience. This action needs to be supported by suitable educational programs at the European level. R&D has a special role to play as a recognised contributor to Education & Training.

Short term challenge:
contribute to European educational programs to increase the number of nuclear experts.

1.3.4 Public acceptance

The best way to improve public acceptance of nuclear power plants is to operate them in a safe and cost-effective manner. Communication and education should address the contribution that fission provides to low carbon energy production.

Transparency must rule and the issues that the nuclear industry is facing (such as waste) or may

[20] Russian-type Pressurised Water Reactor

have to face (such as emergency crisis management) should also be explained to the public, together with the solutions proposed by efficient collaboration between industry, research and regulatory bodies. It should be pointed out that these solutions are backed by strong scientific evidence. The R&D community can better communicate to the public and provide technical expertise to various fora (e.g. European Nuclear Energy Forum).

The issues that the nuclear industry is facing or may have to face should be explained to the public, together with the solutions proposed.

[21] **Nuclear Plant Life Prediction (NULIFE)**

[22] **Severe Accident Research Network of Excellence (SARNET)**

1.4 Waste and decommissioning

A first important task is to define procedures for making the inventory of expected waste resulting from the decommissioning activity. This will require the development of on-site characterisation and sampling methods and the appropriate radiochemical analysis methods and activation prediction tools.

Shut-down and decommissioning of some old plants should also be viewed as a notable opportunity to obtain long service time materials, for instance with a high irradiation dose. These invaluable sources of data should be protected and used to assess present ageing mechanism models and to build a consistent understanding of failure modes.

Short term challenge:
common position on waste classification and release criteria, including decommissioning waste.

Medium term challenges:
- **full scale qualification of decommissioning and decontamination techniques on a European scale,**
- **integration of decommissioning issues at the design stage.**

1.5 Implementation

So far, most safety demonstrations required experimental testing in reactors with very expensive and time-consuming test programs. Tomorrow, high performance computing capacities with extensive multi-physics and multi-scale modelling will allow the performance of many of those through calculations. Besides saving time and money, such simulations will make it possible to test larger number of configurations, thus reducing the uncertainties. Some heavy testing infrastructures will remain necessary for validation purposes, but surely less than in the past.

Most of the nuclear R&D is still performed within national programs and only 10-20% within the framework of international collaboration. Even though there might be contrasting needs of various stakeholders, this shall change and even reverse in the future pushed by several drivers:

- **the cost since R&D becomes more and more expensive,**
- **the credibility of any assessment is significantly increased when it results from international cooperation with all stakeholders reaching common conclusions.**

Efficient use of the various existing networks carrying out collaborative research, such as NULIFE[21] and SARNET[22] (both networks set up under the Euratom Framework Programme), to promote and support such cooperation, should be a priority.

NULIFE is well placed to launch a research programme addressing the key issues of long-term operation, transverse to GenII and GenIII reactors: understand, prevent and mitigate ageing.

Most of the nuclear R&D is still performed within national programs and only 10-20% within the framework of international collaboration.

Such a programme would cover most of the challenges presented in this chapter while being linked to many others in the SRA. One of the priorities of this programme is to address the needs for experimental facilities.

Short term challenge:
identify needs of R&D infrastructure.

Medium term challenge:
establish European competence networks for experimental and verification facilities.

2. Advanced Fuel Cycles for waste minimisation and resource optimisation

2.1 Introduction

The present reactors have proven to be a very competitive, reliable and safe technology for electricity production with almost no CO_2 emissions and small environmental impact. However they use less than 1 % of the uranium (U) available in nature. With such a low efficiency, the presently economically extractable uranium worldwide resources will be sufficient for only about 100 years depending inter alia on the nuclear power growth rate in the next decades. In order to get a long-term sustainability with nuclear energy from fission, new technological solutions improving the usage of this natural resource by up to 100 times are being developed. The new technology is based on the combination of fast neutron systems with multi-recycling of the fuel in advanced fuel cycles.

In fact, advanced fuel cycles are being designed to improve the three pillars of sustainability for nuclear energy: resource optimisation, waste minimization and improved economical competitiveness. The new reactor concepts under development will be able to re-use most of the uranium, plutonium (Pu) and other actinides[23] present in the nuclear fuels, making what today is waste in many countries a valuable asset for electricity production.

"The waste of today is the fuel of tomorrow".

This will be achieved while maintaining or improving the safety, economical competitiveness and minimal risks of proliferation.

The change to this future enhanced sustainability will be a progressive process that has already started. Indeed some of the technologies for recycling fuels are commercially available and operated industrially in some countries, e.g. France and UK. The combination of these and other existing technologies with improvements on the present reactor designs could enable progress both on optimisation of natural resources utilisation and economical competitiveness.

This chapter will describe the potentiality and required R&D associated to these advanced fuel cycles.

2.2 Nuclear Fuel Cycle

In the broadest sense, the Nuclear Fuel Cycle (NFC) encompasses all the steps and facilities needed to produce electricity by the nuclear reactors, including the preparation of the fuel which will be used in nuclear reactors, the "front end" of the fuel cycle, and the "back end" or management of the fuel after its use in the reactors (the spent fuel), with two main options (both implemented in Europe):

- the direct disposal of the spent fuel, called the "open cycle",
- the recycling of valuable materials, called the "closed cycle" (Fig.7).

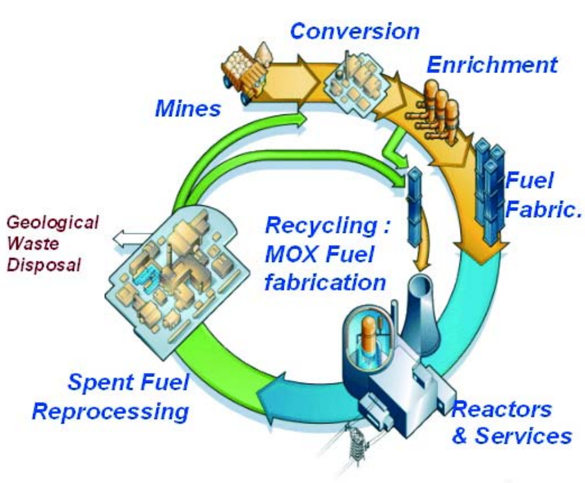

Fig. 7: The closed cycle illustrating recycling of valuable materials [Source: AREVA]

[23] **Actinides are the chemical elements with atomic number larger than the Actinium (89).** Transuranium actinides are the chemical elements with atomic number higher than uranium (92), e.g. neptunium, plutonium, americium, curium. Minor actinides are actinides present in small amounts in the LWR spent fuel as neptunium, americium, curium and others with higher atomic number.

More precisely, the nuclear fuel cycle includes the following steps:

- The "front end" of the fuel cycle, which consist of uranium (or thorium) prospecting, mining and on site purification, uranium (or thorium) conversion (to get pure UF6 or UO2 or metal, depending of its future use), uranium enrichment (if needed), and fuel fabrication.
- The fuel irradiation in nuclear reactors to produce electricity.
- "The back end" of the fuel cycle, which consists of interim storage of spent fuels, recycling (if this option is implemented), which includes reprocessing of the spent fuel to recover recyclable materials and fabrication of new fuels with these materials, transportation of radioactive materials (spent fuels, conditioned radioactive waste, etc.), final disposal of nuclear waste (spent fuel for "open cycle" option or ultimate waste for the "closed cycle").

2.3 R&D to improve sustainability of Nuclear Fuel Cycles

Many studies have been carried out worldwide, and particularly in Europe but also within the framework of the GenIV roadmap, to analyse the meaning of "sustainability"[24] when it is applied to the NFC. From these works, there is a clear consensus today that a sustainable NFC is mainly linked to the durability of the solutions addressing the two following issues:

- optimum use of natural resources,
- nuclear waste minimization.

These two objectives must be pursued while maintaining or increasing at the same time the safety and the economic competitiveness and ensuring the non-proliferation of the technologies.

Therefore, before addressing R&D challenges for the NFC, one must elaborate on the two topics related to sustainability, taking into account their temporal framework, in order to better define the framework in which these R&D challenges fall.

[24] The general UN definition of sustainability is "Meeting the needs of the present without compromising the ability of future generations to meet their own needs".

2.3.1 Short term objectives: Optimum use of natural resources

There are only two kinds of "natural resources" for nuclear fission on earth:

- Uranium, containing mainly 2 isotopes: one fissile, 235U, which constitutes only 0,71% of the natural uranium and one fertile, 238U, which constitutes 99,29 % of the natural uranium,
- Thorium, containing exclusively one kind of isotope, 232Th, which is a fertile isotope (producing the fissile isotope 233U). Although technically possible, the fuel cycle based on thorium requires a supply of a fissile isotope (235U or plutonium) to be deployed and is not implemented today in any European country.

The optimisation of natural resources, to maximise the electricity obtained per unit of uranium mined, is progressively achieved by the industry at each step of the NFC, through the market laws and the current technical knowledge. This is the case for example, in the front end by the choice of cut grade of uranium deposits or tail enrichment; fuel management inside the reactor; or spent fuel recycling, in the back end.

R&D challenges to "optimise" natural resources:

The optimisation of natural resources is progressively achieved by the industry at each step of the Nuclear Fuel Cycles.

The optimisation at each step of the NFC deserves R&D programs. However, the "front end" steps of the NFC, such as uranium prospecting and mining or enrichment process and fuel fabrication (UO2), are more a matter for industry, and in the phase of commercial competition. Consequently, the SRA in this area should focus on enhancing the usage of mined uranium and generated plutonium in the present and future reactors, and the NFC back end options.

Core with high conversion ratios

Nuclear reactors are able to convert a part of fertile isotopes which are loaded in the fresh fuel, into fissile isotopes, e.g. 238U into 239Pu. The ratio between the total amount of artificial fissile material created inside the reactor core and the total amount of fissile isotope "consumed" is called "conversion ratio". A part of the artificial fissile isotopes is burned in situ contributing to the generation of electricity and saving natural fissile isotopes. However, the part of the created artificial fissile isotopes which is not burned in situ remains in the spent fuel when unloaded. The recycling of this part can further contribute to saving the natural fissile isotopes.

Consequently, one of the most efficient routes to reduce natural uranium consumption is to increase the conversion ratio of present and future reactors and to recycle fissile material.

Fast nuclear reactors can be designed to reach a conversion ratio equal or even greater than one, in such a way that no more natural fissile isotope is needed to sustain nuclear energy since the reactors generate more fissile isotopes than they consume to produce energy. These reactors, called "breeders" need to be fed only with fertile isotopes (U238 or even Th232) which are available in huge amounts.

An efficient way of reducing the natural uranium consumption is to increase the reactor conversion ratio and to recycle fissile material.

Therefore it must be underlined that "breeder" reactors, in practice Fast Neutron Reactors (FNRs), are the only solution which can lead to the long term sustainable development of nuclear energy, with regard to the "optimum use of natural resources".

Because of this critical role in the nuclear energy sustainability, a specific chapter of this SRA is devoted to the developments on FNRs, where the associated R&D for feasibility and resource optimisation are addressed.

Before the FNRs are commercially deployed, the natural resource usage can still be improved by optimising the conversion ratio of LWR, its fuel design and the associated back end of the NFC, as discussed here:

R&D in the short term should concentrate on: parametric studies reactor cores of Advanced GenIII reactors with High conversion ratios (for LWR) (neutronic, thermal-hydraulic, mechanic, safety, control, and economic assessments).

In the medium term:
core and component tests on experimental loops and critical mock-up towards the design of an experimental high conversion ratio reactor.

Very high burn-up fuels

A way to improve the uranium utilisation in the LWR is to extend the time it is used in the core. When this extended irradiation allows extracting more energy per unit of fuel, it is described as increasing the fuel burn-up. Higher fuel burn-ups do not lead, per se, to a reduction of natural uranium consumption as normally it requires higher fissile enrichment. However, a higher burn-up allows the optimisation of other parameters of the in-core fuel management, such as an increase of the reload fraction of the core, resulting in a net reduction of natural uranium consumption.

R&D in the short term should concentrate on: feasibility studies of fuels able to reach very high burn-ups (100 GWd/tHM) for LWR and possibly deep burn High Temperature Reactors (HTR).

In the medium term:
irradiation and qualifications tests of these fuels must be performed.

Recycling of the plutonium and reprocessed uranium

Plutonium recycling in LWRs is implemented, at industrial scale, in a few European countries (France, Belgium, Germany, and Switzerland) for a long time (inside the so called MOX – Mixed Oxide - fuel). However, it is limited to a single recycling, a small fraction of the core and to a 12% plutonium concentration. Therefore, increasing these parameters could enhance the energy obtained from the plutonium, reducing the fissile uranium needs. Furthermore, some other reactor types such as High Temperature Reactors (HTRs) are potentially better than LWRs for plutonium burning and it could be worthwhile to further investigate these solutions.

A higher burn-up indirectly leads to a net reduction of natural uranium consumption.

Investigating advanced fuel cycles for LWR fuels, e.g. co-extracting plutonium and uranium, could add significant benefit in terms of proliferation resistance.

R&D in the short term should concentrate on: studies on 100 % MOX cores and on plutonium multi-recycling for LWR and on 100% plutonium cores for HTR.

In the short and medium term: scenario studies of nuclear materials management issues at the European level on the evolution of nuclear reactor fleet, including uranium and plutonium availability in the case of delayed deployment of FNRs.

Finally, it should be mentioned that there are no short or medium term industrial prospects in Europe for the deployment of the thorium cycle and thus, it will not be a R&D priority. However, thorium could become an attractive option in the long term and a minimum level of basic studies on this cycle should be maintained at the European level.

Investigating advanced fuel cycles for Light Water Reactor fuels could improve significantly the proliferation resistance.

2.3.2 Long term: Optimisation of natural resources with nuclear waste minimisation

Nuclear wastes (NW) are radioactive residues produced by a process involving handling of radioactive materials which are considered as not reusable.

NW are classified in various ways in the different European countries, but generally, according to their intrinsic risk and their possible management. The main parameters are the level of specific radioactivity[25], the decay "half life" and the specific heat produced by the radioactivity of the unstable isotopes contained in the NW. There are commercially available solutions to handle Low level waste (LLW) and most of the Intermediate level waste (ILW), already implemented in several EU countries.

High level waste (HLW), which contains either highly radioactive isotopes, significant quantities of long lived radio-nuclides, or are strongly heat emitting, are mainly generated by the operation of nuclear reactors. HLW can be the spent fuel, the wastes from its reprocessing or from other steps of the NFC. The present solution for HLW is to properly condition them inside isolating and protecting packages that are then disposed of in a Deep Underground Geological Repository (DGR). A number of technological and geological barriers are setup in this way to avoid any hazard to the population or the biosphere. The R&D, technology development and implementation are the topics of another Technological Platform (IGD-TP[26]) and will not be further discussed here.

Several EU countries have implemented commercially available solutions which allow handling low and intermediate level waste.

[25] The specific radioactivity of one object is the number of disintegrations per unit of time in a given unit volume or in a given unit of mass. The half-life on an isotope is the time interval required for its radioactivity to get reduced by half.

[26] Implementing Geological Disposal Technology Platform (IGD-TP)

This solution has been proven scientifically to be reliable and safe and most of its technologies are ready for deployment. The first implementations in the EU are expected in Finland, Sweden and France within 10-20 years. To achieve optimisation of HLW management, research is focused in minimising several parameters of the HLW:

- the mass and volume of conditioned NW to be disposed of,
- the long term "radiotoxic inventory", which is the sum of activities of each radioisotope in the NW weighted by the dose factor that indicate the risk if this material would be dispersed within the population,
- the effective "lifetime" of conditioned NW,
- the heat generation of conditioned NW, as function of time, due to the radioactivity of its unstable radioisotopes. This parameter strongly affects the DGR capacity,
- the "long term radiological impact", that is the calculated biological effect on living species of possible radioactive releases in the biosphere once part of the radio-nuclides (or their radioactive daughters) have reached the surface.

The present solution for HLW is to properly condition them inside isolating and protecting packages that are then disposed of in a Deep Underground Geological Repository.

A first way to minimise nuclear waste is to reduce the amounts of radio-nuclides produced by nuclear reactors. For fission products the production is directly proportional to the electricity generation, so that the only way to reduce their amounts is simply to increase the electrical efficiency of nuclear power reactors. On the other hand, there are several means to act on the production of the different actinides including the choice of reactor types (neutron spectrum) or even the choice of a fuel cycle (for example, thorium based fuel which could generate much less amounts of high mass minor actinides – MA - in the long term).

On the other hand, once the waste has been produced, if the spent fuel is directly disposed of, there is in fact no way to act on the previously indicated optimisation parameters, except the enhancement of confinement properties and its durability (waste matrix or waste container). This research could also contribute to reduce the "long term radiological impact". These topics fall outside the scope of the SNETP and will be probably addressed by IGD-TP.

Fig. 8: Fuel cycle pilot plant [Source: AREVA]

If the spent fuel is reprocessed, many technical options are open to bring improvements in the five NW parameters quoted above. To this regard, studies, carried out, in particular, under European R&D programs, such as Red-Impact[27] and Pateros[28], have shown that one of the most promising route is the "Partitioning and Transmutation" of selected radionuclides (particularly actinides). The general conclusion is that the waste minimisation in advanced fuel cycles should be considered within a global objective of sustainability. Furthermore the implications on the reduction of the number and size of DGRs and other societal aspects need to be considered in the fuel cycle optimisation.

Waste minimisation in advanced fuel cycles should be considered within a global objective of sustainability.

In this sense, three types of objectives are identified:

- integral management of all the transuranium actinides, in a long term sustained nuclear park,
- integral reduction of the transuranium actinides inventories and
- specific reduction of some Minor Actinides (MA) inventories.

These objectives can be achieved conceptually in two generic types of scenarios:

- A park of fast neutron spectrum critical reactors that will simultaneously produce electricity and transmute all types of actinides. Finally the only input of the system (reactors and fuel cycle facilities) will be natural or depleted uranium and the outputs will be electricity and residual HLW plus ILW. In this option, the MA could be homogeneously diluted within the whole fuel or separated in dedicated targets. However, the core design of these reactors should be optimised from the point of view of neutron economy.
- A "double strata" reactor park. The first stratum will be a set of critical reactors dedicated to electricity production using "clean fuel" containing only U and Pu. The reactors in this stratum can be either present or future LWR or fast reactors. The second stratum will be devoted to transuranium actinides or MA transmutation and will be based on special fast reactors or subcritical fast systems, ADS, loaded with homogeneous fuels with high MA content.

In addition it is important to realize that the process of deployment of these advanced fuel cycles with partitioning and transmutation will be progressive. In a first instance, economical competitiveness will favour the extension of the life of present reactors followed by their replacement with advanced GenIII LWR. Later, as the uranium resources become scarcer and waste inventories grow, the fast nuclear systems (FNR and ADS) will appear more attractive and will eventually be progressively introduced.

The evaluation of this type of scenarios indicates that while maintaining the safety of operation and economic competitiveness, they should ultimately be able to strongly reduce the long term Uranium consumption, making the present reserves worth several thousand years. At the same time, the HLW long term radiotoxic inventory could be reduced by more than a factor 100 and its heat load by more than a factor 10. According to available studies, the last figure will allow reducing the DGR size by factors from 3 to more than 10 (in hard rock, clay and tuff geological formations). In the case of large and/or long nuclear reactor parks, the waste minimisation could help to minimise the number of required DGRs. Smaller parks, might need to participate in regional solutions involving the cooperation with a country with large nuclear park to improve the partitioning and transmutation efficiency and its economical feasibility.

There are many uncertainties and options in the definition and evaluations of these advanced fuel cycles, requiring:
R&D in the short term in the partitioning and transmutation scenario studies with clear emphasis in the evaluation of the impact on the final DGR, taking into account the regional and time dependent components.

[27] Impact of Partitioning, Transmutation and Waste Reduction Technologies on the Final Waste Disposal (Red-Impact)

[28] Partitioning and Transmutation European Roadmap for Sustainable nuclear energy (Pateros)

The scenarios studies should include the industrial implementation aspects and, possibly, economical evaluations. These scenarios should account for various reactor type combinations, including FNRs or ADS, in order to identify potential synergies. Furthermore, these scenarios should allow to quantify indicators for decision making that include all aspects of the problem: consumption of natural resources, nuclear material inventories to be managed, environmental impact, costs, time projection to reach equilibrium, industrial capacities required for fuel treatment and fabrication (including MA bearing fuels or targets), technical difficulties, overall safety, secondary waste generation, occupational exposures, proliferation concerns, public acceptance, etc.

On the other hand, the deployment of these advanced fuel cycles needs significant R&D to meet technological challenges on:

- new fuels (targets) bearing significant amount of MA, and their fabrication technology,
- new recycling technologies based on the advanced aqueous and pyrometallurgic technologies, adapted to the high active and hot fuels,
- the technologies of the different Fast nuclear systems (FNR and ADS), including new materials, thermo-hydraulics, simulation tools and nuclear data and in the case of ADS the coupling of an accelerator and a subcritical core. This point is further developed in the next chapter for each of the fast system types and in the chapter on cross cutting R&D topics.

In the short term the R&D can be performed in several existing basic science and validation facilities, but at medium term demonstration plants for the reactors, fuel fabrication, advanced reprocessing technologies.

To summarise, the priorities for the short, medium and long term waste minimisation and resources optimisation are:

Short term common trunk R&D on:
◗ advanced reprocessing of LWR and advanced fuels for MA separation, using either hydro- (including coprecipitation mix oxide uranium and plutonium) or pyro metallurgical processes,
◗ dissolution of MA-bearing MOX and carbide fuels for FNRs and of MA bearing targets (U-free or UO2 matrix),
◗ conversion processes (after the separation steps and prior to the fabrication of fuels/targets.

Medium term R&D for Demonstration facilities:
the decision to develop or not demonstration facilities for Fuel fabrication facilities and Reprocessing facilities should be taken about 2012 depending on the results of the previous steps and the European availability of equivalent facilities.

Within its programme to operate a sodium cooled fast reactor prototype by 2020, France is considering the construction of two facilities, one devoted to the manufacturing of the core fuel and the other one to the manufacturing of minor-actinide bearing pins and assemblies (named experimental pins facility). These facilities, which would be built on the La-Hague site, could also provide fuel fabrication services to test and demonstrate alternative technologies of reactors at the European level.

Meanwhile a smaller facility called ALFA (Atalante Laboratory For Actinides Bearing Fuel Manufacturing) has been proposed to be built in ATALANTE facility (CEA/Marcoule). The objective of this latter facility is to manufacture experimental high activity fuels pins with the capacity of producing from a few pellets up to a few pins par year.

The decision to develop or not demonstration facilities in the field of reprocessing should be taken approximately in 2012. It will mainly depend on the question of including curium or not in the fuel and on the type of management finally envisioned for this element. However, as the experimental pins facility is likely to produce americium only bearing fuels/targets in a first step, no advanced separation workshop should be needed. Then, in a future step, a minor actinide separation facility could be considered, depending on the achievements of R&D, in particular with respect to curium.

Long term R&D towards industrial implementation of partitioning and transmutation:
the implementation of this phase will depend on the results of the previous phases and will be mainly carried out under the control of the nuclear industry.

3. GEN IV Fast Spectrum Systems with Closed Fuel Cycle (SFR, LFR, GFR, ADS)

3.1 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. However, the industrial development of SFRs stopped in Europe when the political decision was taken in February 1998 to abandon Superphenix. It had stopped earlier in the United States with the Non Proliferation Act promulgated in 1978. Russia proceeded with the development of SFRs in spite of budget constraints and it 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 on nuclear power to supply part of the energy needed for their fast economic growth have both aggressive agendas to develop light water reactors and SFRs with respective plans to start a prototype fast reactor (PFBR (500 MWe)) and an experimental reactor (CEFR (65 MWth)) in 2010.

In the current context marked by new builds of advanced SFRs and by internationally recognised needs for fast reactors with a closed fuel cycle around 2040 for a sustainable electricity production, European stakeholders have agreed to develop a new generation of fast neutron reactors, and have identified three fast spectrum systems that were the most likely to meet Europe's energy needs in the long term in terms of security of supply, safety, sustainability and economic competitiveness:

- the Sodium Fast Reactor (SFR) as a first track aligned with Europe's prior experience and
- an alternative fast neutron reactor technology to be determined between the Lead cooled Fast Reactor (LFR) and the Gas cooled Fast Reactor (GFR).

Technology breakthroughs and innovations are needed for all GenIV reactor types.

Even though only SFRs led to prototype so far, all types of fast reactors have a comparable potential for making an 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.

In the chapter on advanced fuel cycles, the role of Accelerator Driven Systems (ADS) as dedicated facility to transmute large amounts of high level nuclear waste (Minor Actinides) in concentrated approach is explained in the context of Partitioning and Transmutation. The development of Accelerator Driven System technology shows large synergetic R&D with fast reactors and in particular the Lead Fast Reactor.

Technology breakthroughs and innovations are needed for all 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 with a high availability factor. In particular, structural materials and innovative fuels 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.

This chapter is organised as follows:

1 – Innovations for a new generation of Sodium Fast Reactor so as to keep Europe among the leaders in this technology. This track is meant to enlarge at the European level the French initiative for the construction of a prototype (ASTRID for Advanced Sodium Technology Reactor for Industrial Demonstration) in France by 2020 with the following milestones: 2009, pre-selection of design options; 2012, confirmation of options, then preliminary and detailed design, safety analysis reports and construction of a prototype in the range 250-600 MWe; by 2020, start of operation, followed by technology improvements and system optimisations leading to commercial reactors.

2 – Selection of an alternative fast reactor technology between 2010 and 2012 as a result of thorough assessments and comparisons of lead- and gas-cooled fast reactors in terms of potential to meet GenIV criteria, R&D needs and quantification of associated efforts and means to support this R&D. This track would lead to the decision to construct an experimental demonstration reactor of the chosen technology in the range 50-100 MWth for operation in the 2020s followed by further technology developments and a prototype in the 2030s.

3 – Assessment of ADS as a dedicated facility for transmutation at industrial scale. This assessment will include transmutation performance, dedicated fuel fabrication and reprocessing, as well as avoidance of MA fuel dissemination in the nuclear park and hence of transports associated. ADS will be assessed together with other systems for their potential to achieve transmutation at industrial level and for the selection in 2012 of systems featuring the best industrial prospects. If the choice of ADS is made, the feasibility of this technology should be demonstrated by 2020 through a European experimental demonstration such as that considered presently with MYRRHA/XT-ADS. Even though ADS is considered in first instance for nuclear waste transmutation, part of the generated power can be used for other purposes.

This three-track research programme on fast neutron systems needs to be supported by research on advanced fuel cycle technologies to possibly recycle minor actinides in fast reactors or dedicated burners, and should afford alleviating the long term burden of radioactive waste to be ultimately disposed as explained in Chapter 2.3.

Furthermore, the development of these fast spectrum reactor technologies requires specific irradiation needs as outlined in Chapter 5, testing and qualification facilities for systems technologies and components (specific liquid metal loops, gas loops and hot cells), as well as code qualification and validation.

Materials for demonstrators and prototypes are other critical issues. Because the development of new structural materials is a very time-consuming 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 possibly increase the plants' thermal efficiencies.

3.2 Sodium Fast Reactor (SFR)

3.2.1 R&D challenges

The main goals for innovation in SFR technology are the following:

- enhanced safety of the plant along the lines that led to progress from GenII to GenIII light water reactors especially towards a higher resistance to severe accidents and external hazards (analysed in a defense in depth approach),
- economic competitiveness of the plant mainly by reducing capital cost and investment risks, as well as by improving plant operability (including easier in service inspection and repair, high availability factor),
- improved sustainability through a better use of fissile materials, reduction of proliferation risks, and minimisation of long lived radioactive waste possibly through minor actinide recycling.

Enhanced safety

R&D challenges to enhance the safety of next generation SFRs include:

- **minimising the risks attached to sodium (flammability, and reactivity with water) while investigating:**
  - **alternative power conversion systems with gas turbines (He-Xe, supercritical CO_2),**
  - **hardened concepts of steam generators,**
  - **innovative concepts of compact and simplified intermediate systems with a relatively non-reactive heat transfer fluids,**

- practically precluding large energy release in case of severe accident (even hypothetical) while investigating:
  - core designs with moderate sodium void effect and other favourable reactivity feedback effects,
  - core designs and reactor vessel internal structures likely to disperse core debris and minimise risks of compaction,
- assessing the impact of minor actinides bearing fuels on the core behaviour depending on various homogeneous and heterogeneous recycling modes,
- diversifying safety systems,
- developing improved instrumentation and techniques especially for in–service inspection,
- minimising the vulnerability to external events and aggressions.

Economic competitiveness

R&D challenges to improve the economic competitiveness of next generation SFRs include:

- simplifying the plant design to reduce the capital investment cost and facilitate the maintenance with:
  - more compact reactor vessel and internal systems Intermediate Heat Exchanger (IHX),
  - combined components (IHX & Primary pumps),
- improving the plant operability trough better monitoring, inspection and repair, and fuel handling operation,
- developing materials to guarantee a plant lifetime of 60 years,
- designing the core with a plutonium hold-up in the range of ~10 t/GWe so as to facilitate the deployment of a fleet of reactors,
- developing materials to extend the fuel burn-up from 100 GWd/t currently to 200 GWd/t.

Better use of resources

R&D challenges to improve the use of uranium, minimise long-lived radioactive waste and enhance non-proliferation include:

- developing advanced mixed U-Pu fuels that will be used as driver fuel for the prototype of SFR,
- developing Minor Actinides (MA) oxide bearing fuels (and associated recycling processes (treatment, refabrication)) that will be used as experimental fuel to test both types of advanced recycling modes (heterogeneous or homogeneous),
- developing dense fuels (carbide, and possibly also nitride or metal) and associated recycling processes (treatment, partitioning, re-fabrication) that will be qualified in a second phase of operation of the SFR prototype as advanced fuel for this type of reactor featuring enhanced safety and improved breeding.

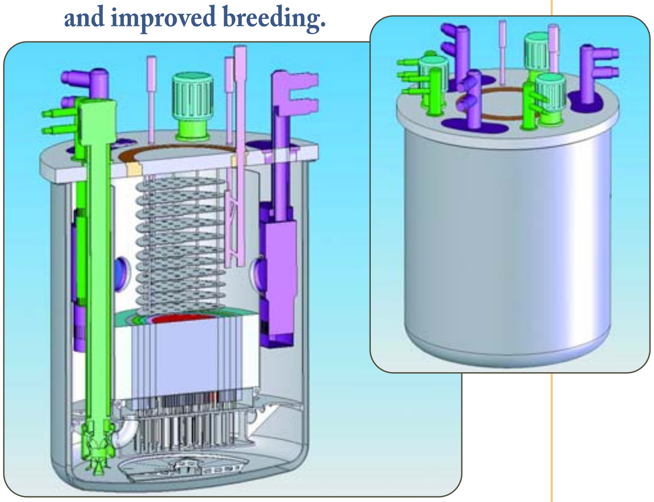

Fig. 9a: 1500 MWe Innovative SFR Pool Design [Courtesy of CEA]

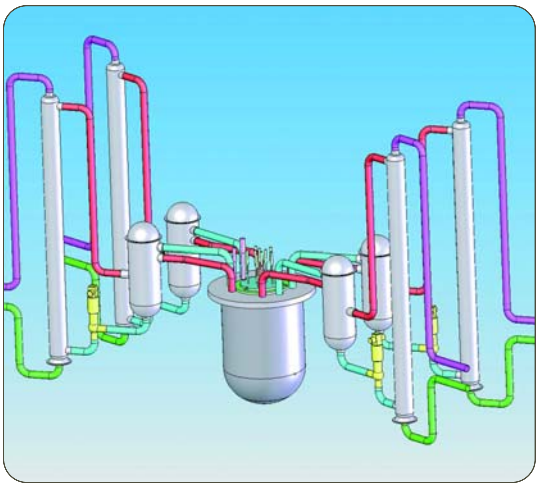

Fig. 9b: 1500 MWe Innovative SFR Loop Design [Courtesy of CEA]

The respective potential of pool- versus loop-type systems to meet the targeted safety and economic goals for new generation SFRs is to be thoroughly assessed and compared. As demonstrated by former prototypes in Europe, pool-type reactors feature a robust confinement of primary sodium (and thus contribute to prevent sodium fires), a high thermal inertia in case of loss of primary flow accident and efficient cooling by means of natural circulation. On the other hand, loop-type systems afford suppressing the intermediate heat transport loop and could offer (besides reduction of overall plant capital cost) easier maintenance and repair conditions for large components (pumps, heat exchangers) as they are outside the reactor vessel and may be integrated in combined components.

The above R&D challenges may be structured into four main areas:

1) core design and associated fuel type (for enhanced safety, performances and actinides management capability),
2) enhanced plant safety and security (including a better prevention and management of severe accidents and an improved physical protection against external aggressions),
3) energy conversion systems and associated materials (including Brayton cycle based energy conversion systems to eliminate risks associated with sodium),
4) optimisation of reactor design and operation (including plant simplification and modular designs of components to enhance the plant economic competitiveness).

3.2.2 R&D milestones

The R&D programme for the SFR development relies essentially on the construction of a prototype, to be followed a few years later by an industrial First Of A Kind (FOAK) reactor. During that period, the R&D should address both the commercial scale reactor (~1500 MWe) and the associated small scale prototype (250-600 MWe).

2008-2010: Innovation / Exploratory phase

This period is devoted to assessing and screening innovative features (design, technology) likely to enhance SFRs' safety and economics with a view to pre-selecting the most promising innovations by 2010.

The main R&D items to be addressed during this phase include:

1) design studies of large scale MOX fuelled SFR cores (1500 MWe),

2) re-establishing a set of modern simulation tools for severe accidents analyses and design studies of robust core catcher,

3) feasibility studies of innovative features to minimise sodium risks,

4) assessment of design features aimed at enhancing SFRs' safety and economics (in particular comparative assessment of "pool" versus "loop" reactor and technologies for in-service inspection, maintenance and repair).

2010-2012: Innovation / Confirmation studies

This period is devoted to confirming by simulation studies and small scale experiments the potential of design features or technologies pre-selected at the previous step. This period should lead to derive specifications for the SFR prototype in 2012 and advance its licensing.

The main R&D items to be addressed during this phase include:

- **dossiers on large SFR MOX cores:**
  - dossier on SFR MOX-fuelled core design including feedback from severe accidents studies and options for recycling minor actinides,
  - dossier on advanced fuels (carbide, and possibly nitride or metal, etc.) to select those of sufficient interest for proceeding with an extensive R&D programme of validation.
- **minimisation of mechanical energy releases in case of severe accident: research of design features allowing to minimise the risk of mechanical energy releases,**
- **design of robust core catcher: design features for adequate containment, sub-criticality and decay heat removal of corium,**
- **selection of a reference energy conversion system and associated materials,**
- **recommendation of innovations for SFRs and preparation of a relevant qualification programme requiring larger scale experiments.**

2012 - 2015: Performance phase / Preliminary design & safety studies

This period is mainly devoted to demonstrating the performances of the European SFR and qualifying the new designs and technologies selected in large experiments (experimental reactors, large sodium loops and other large research facilities).

Preliminary Design and Safety reports will be prepared in time to allow the construction of the prototype to begin in 2015.

The following experiments are to be conducted in order to qualify new technologies, new design features and computational tools that will be used for detailed design studies:

- **qualification of advanced fuels and materials under irradiation,**
- **critical experiments to qualify neutronic calculations,**
- **tests of safety components and instrumentation (in and out of pile),**
- **tests of components and balance of plant (especially tests in sodium loops),**
- **tests of techniques for in service inspection / Core surveillance / Sodium quality control and monitoring,**
- **test of mechanical equipments (e.g. on shaking tables).**

2015: Beginning of prototype construction

2015-2020: Detailed design studies

2020: Start-up of European SFR prototype and demonstration of advanced recycling schemes

Beyond the operation of the prototype, work will continue to design a FOAK reactor using feedback from operation, optimisation etc.

In addition to the reactor technology developments, R&D on the associated fuel cycle must be carried out with the following milestones:

- **2012 – selection of technologies for a closed fuel cycle (e.g. separation, MA fuels) based on technical and economic criteria (e.g. long term radioactive waste radiotoxic inventory and decay heat),**
- **2012-17 – building of fabrication workshops for the driver-fuel and the experimental MA-bearing fuels.**

3.3 Lead Fast Reactor (LFR)

The Lead Fast Reactor technology is one of the two alternative fast neutron systems to be studied. The road-map of LFR foresees the construction of a 50-100 MWth European Technology Pilot Plant (ETPP) by 2020, followed by the realisation of an LFR prototype of the industrial plant at the horizon of 2030 and the commercial deployment of GenIV LFRs by 2040.

The Lead Fast Reactor technology is one of the two alternative fast neutron systems to be studied.

Major technological issues identified for the LFR development include:

- system design and component development (including integrated core designs with appropriate safety features),
- materials qualification and lead technology development,
- innovative fuels and fuel cycle (minor actinides bearing fuels, high density fuels such as nitride or metallic fuels).

3.3.1 R&D challenges

System design and new components development

The main concerns which could challenge the feasibility of the LFR are:

- **corrosion of structural materials,**
- **large mass of lead,**
- **in-service inspection of core support structures,**
- **refuelling at high temperature (400°C) in lead,**
- **managing of the Steam Generator Tube Rupture inside the primary system.**

Corrosion by molten lead of candidate structural steels for the primary system and advanced fuels are the main issues in the design of a LFR. For near term deployment, the use of existing industrial materials for the most parts of the reactor equipment is possible by limiting the core outlet temperature, whereas new materials are being designed for special components such as pump impellers.

Corrosion by molten lead of candidate structural steels for the primary system and advanced fuels are the main issues in the design of a LFR.

The mass of lead is kept low by means of an innovative layout (Fig. 10), e.g. innovative spiral-tube bundle Steam Generating Units, Primary Pumps and Decay Heat Dip Coolers installed in the reactor vessel. It has been verified that, with such a configuration of the reactor vessel configuration, seismic loads defined by the European Utility Requirements can be accommodated by means of 2D seismic isolators of the reactor building.

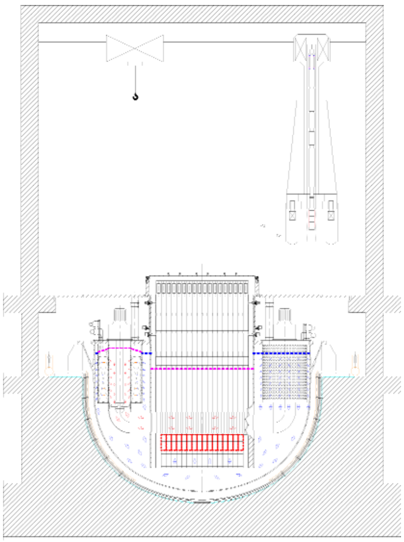

Fig. 10a: ELSY primary system arrangement [Courtesy of ELSY Consortium]

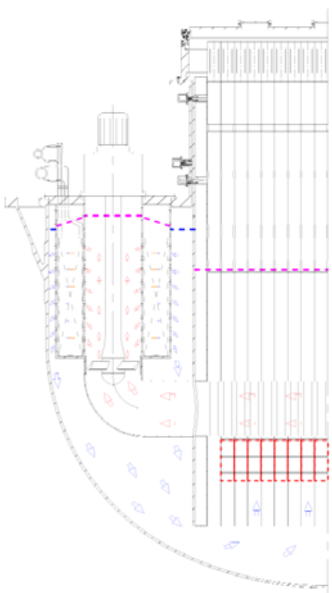

Fig. 10b: ELSY-Primary system arrangements – detail of the lead flow path [Courtesy of ELSY Consortium]

The fuel assemblies are fitted with an extended stem to permit fuel handling using a simple handling machine that operates in the cover gas at ambient temperature under full visibility. This eliminates in-vessel fuel transfer equipment which has never been designed or tested in lead.

■ 3.3.2 R&D milestones

Starting from the year 2010, the design of a small-scale European Technology Pilot Plant (ETPP) with a power of 50-100 MWth, (20-40 MWe) should integrate as much as possible the best technological solutions of all the ongoing international projects.

The ETPP will be initially loaded with conventional enriched uranium or MOX fuel, but will be designed to host different fuels as soon as they are available, including MA-containing fuels.

From 2010, the design of a small-scale European Technology Pilot Plant should integrate the best technological solutions of ongoing international projects.

Moreover, the ETPP will use - at the maximum extent - simple solutions and classical qualified structural materials and will operate at low temperature, in order to minimise technological risks.

The objectives of ETPP are to demonstrate:

- technology of system components and their design lifetime,
- stable and safe operation at any regime including reactivity feedbacks,
- coupling of a high temperature operating steam generator with a steam turbine,
- in-service inspection and repair feedback experience.

To increase the attractiveness of the LFR, heat process applications should also be considered.

Several technical activities will have to be carried out before the construction of the ETPP, including a preliminary design to confirm the main options, followed by basic and detailed designs supported by a consistent experimental programme to be approved in a pre-licensing phase. This includes the development of appropriate models and tools to study the nuclear – thermal-hydraulics feedback and the reactor stability, as well as the reactivity margin for not reaching prompt-critical conditions.

Large-scale integral tests to characterise the behaviour of the main systems are necessary especially for the licensing process.

Key-components testing is necessary for performance and endurance demonstration. Development of physical models is necessary, as well as experimental validation of numerical tools to be used for the system design and the safety analysis. Neutronic code validation by integral experiments will be needed to reduce safety margins and operational constraints.

The steam generator tube rupture accident entails new phenomena related to the in-vessel location and the new design, such as pressure wave generation and propagation in the large pool. Experimental results are necessary for code validation of pressure wave generation and damping.

Lead sloshing (seismic induced or induced by a steam generator tube rupture) is a phenomenon whose importance is related to the high density of lead; even with efficient seismic isolation of the reactor building, the response of structures containing the large mass shall be evaluated.

Thermal-hydraulics in a rod bundle plays an essential role in the reactor core design. Up to now, the LFR thermal hydraulic core design has to rely on best practise numerical tools. However, experimental support to set up a proper benchmark case will be more convincing.

The density of lead is similar to that of fuel (especially oxide fuel), and this opens the possibility of a benign system behaviour even in the case of partial core melt. Code validation for severe accident analysis is nevertheless necessary, including an experimental campaign for lead-fuel interaction.

LFR specific materials qualification and lead technology development

Due to the large database available, austenitic steels, and especially those of low-carbon grade, are candidates for components operating at relatively low temperatures and low irradiation fluence, e.g. the reactor vessel.

> Ferritic-martensitic steels are among the best candidate materials for fuel cladding and structures.

Ferritic-martensitic steels appear to be among the best candidate materials for fuel cladding and structures because of their resistance against swelling under high fast neutron fluence.

The resulting R&D needs consist in the qualification of:

- an austenitic steel for the reactor vessel,
- a lead corrosion resistant material for the steam generators,
- a protective coating for ferritic-martensitic steel for fuel cladding and fuel element structural parts,
- special materials for the impeller of the mechanical pumps.

The use of molten lead as the coolant implies also:

- development and validation of a technique for lead purification before reactor vessel filling and with reactor in operation to prevent/control slag / aerosol formation,
- development and calibration of instrumentation operating in lead and under irradiation,
- development of techniques and instrumentations for in-service inspection of the steam generator tubes and the reactor vessel.

Innovative fuels and fuel cycle (minor actinides bearing fuels, dense fuels such as nitride or metallic fuels)

In the near term an essential goal is to confirm that ready-to-use technical solutions exist, so that fuel can be provided in timing with the ETPP operation.

In the mid-term, it is necessary to confirm the possibility of using advanced MA (Minor Actinide)-bearing fuels. The second goal is to confirm the possibility of achieving high fuel burn-ups.

In the long term, it is important to confirm the potential for industrial deployment of advanced MA-bearing fuels and the possibility of using fuels that can withstand high temperatures to exploit the advantage of the high boiling point of lead. The achievement of this “Advanced high temperature fuel” milestone will demonstrate the sustainable nature and the multipurpose capability of the LFR technology.

The R&D programme may benefit from

synergies with the SFR for what regards the qualification of the cladding materials.

3.4 Gas Fast Reactor (GFR)

The GFR features the unique advantage of fulfilling two missions:

- being an alternative reactor type to the SFR primarily for electricity production with good sustainability and safety characteristics,
- having the potential to deliver high temperature heat for industrial processes like hydrogen production, and, as such, being a sustainable high temperature reactor.

The main R&D topics are identified:

- development and qualification of a refractory ceramic fuel, with ceramic clad;
- design of a high unit power core with GenIV performance,
- design of a safe primary circuit with high temperature gas,
- development of some specific technologies and components,
- design and evaluate a first GFR demonstrator for fuel qualification.

3.4.1 R&D challenges

The main R&D challenges for the GFR are the following:

Fuel development

In order to achieve a power density around 100 MW/m^3, dense fuels with good thermal conductivity are required. Carbide fuel is selected as reference (with oxide as back-up) for its high content in heavy atoms and good thermal conductivity. Fuel cladding is made of refractory materials (ceramic composites (SiC) or metals (Nb, V or Cr alloys) as back-up).

Main R&D challenges for developing GFR fuel include:

- **pre-selection in 2009 of a limited number of viable solutions of fuel elements (design, materials),**
- **selection of front end (fabrication and re-fabrication) fuel cycle processes,**
- **selection of a reference and a back-up fuel around 2013 based on the knowledge of materials properties derived from irradiation tests,**
- **optimisation of the fuel through irradiations at higher burn-up, transient tests, and simulation of accidental conditions,**
- **preliminary design studies and simulation of normal and abnormal operating transients of plate and pin fuel sub-assemblies,**
- **confirmation of reference GFR fuel concept by 2019.**

Fuel fabrication processes also raise specific R&D challenges:

- developing flow-sheets for fabrication process applicable to selected fuel concepts,
- performing feature tests of key “technological blocks” for selected process concepts,
- interfacing fuel fabrication and recycle process,
- assessing fuel fabrication costs,
- assessing scalability to industrial process.

Fuel & sub-assembly development and irradiation qualification

These experiments will concern uranium or uranium/plutonium bearing fuels. They will be performed in MTRs (e.g. BR2, OSIRIS, HFR, JHR), or fast (e.g. Joyo, Monju, BOR60) reactors. These tests include:

- definition of test parameters,
- examination/Evaluation of irradiated fuels,
- interpretation and modelling,
- initiation of the fuels down selection process.

Optimisation of GFR core design

Main challenges for GFR design studies include:

- **core/vessel integration and verification that detailed studies are globally consistent,**
- **optimisation of core design to achieve performances:**
  - **- break even core (conversion =1?),**
  - **- flat power distribution over irradiation time,**
  - **- control rod implementation and reactivity margins for reactor operation,**

- re-activity coefficients (Doppler, expansion, void, etc.) enabling satisfactory safety features,

◗ management of accidents (especially cooling accidents),

◗ thermal-hydraulics computational fluid dynamics calculations at the scale of fuel subassembly and core,

◗ thermo-mechanic calculations to design core supporting structures and core displacements,

◗ other in-core systems studies (e.g. control rods).

Fig. 11a: Lay-out of 1200 MWe GFR [Courtesy of CEA

System studies and balance of plant

▮

Main challenges for GFR auxiliary systems:

◗ pre-design studies of power conversion systems,

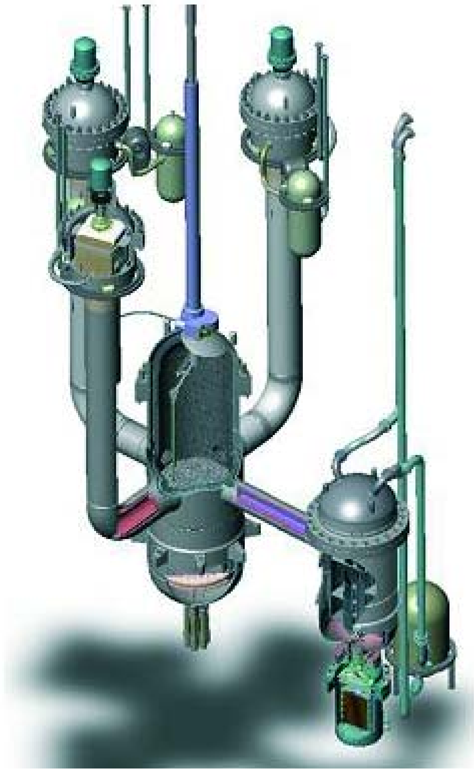

Fig. 11b: Lay-out of 50-100 MWth Experimental GFR (ALLEGRO) [Courtesy of CEA]

◗ detailed study of high temperature intermediate heat exchangers,

◗ simulation of the power conversion system to assess its performances,

◗ pre-design of safety systems.

Safety analyses

Computer codes will be used to perform design studies and operating transient analyses of GFR concepts including demonstration plants. Accidental transient simulations are of particular importance (cooling accident especially) as they strongly contribute to safety demonstrations of the GFR.

In parallel with the deterministic approach, a probabilistic evaluation of GFR safety will be performed. The objective is to demonstrate and quantify that sufficient provisions exist to prevent a core melt accident.

Analyses of severe accidents (in design extension conditions) call for acquiring a sufficient knowledge of the ultimate behaviour of fuel constituents at extreme temperatures (> 2500°C) under several atmospheres and modelling the associated phenomenology. They call also for integrating these models into severe accident simulation codes.

Ultimately, in-pile transient tests on fuel elements at various burn-ups will be required to assess the cooling and fission product retention on the design basis accident.

Analysis tools and experimental qualification

A set of codes for system design and evaluation will be qualified at a first level in 2012: neutronics, local and global thermal-hydraulics, fuel behaviour, mechanics.

Benchmarking and qualifying codes should be continued for both core neutronics and thermal hydraulics codes making use of existing core physics experiments and commissioning new experimental studies where appropriate. On the neutronic side, 3D deterministic calculation scheme will be used after validation on reference Monte-Carlo calculations on key configurations. Uncertainty analyses will include the nuclear data part. A precise evaluation of reactivity coefficients is a key point for GFR's safety assessment.

Development and benchmarking of severe accident codes is an area where much work is required, particularly with regard to analysing the progression of accidents with ceramic clad fuel.

3.4.2 R&D milestones

Taking into account GFR challenges, the year 2012 was chosen to issue a GFR feasibility report, 2020 for starting a demonstration reactor and 2050 for an industrial deployment.

Starting from the existing GFR preliminary feasibility report, R&D challenges to meet 2012 objectives include:

- 2009 – consolidation of reference design options,
- 2012 – GFR feasibility report and preliminary design studies of the demonstration reactor,
- 2012 – decision to engage detailed design studies of the experimental demonstration reactor,
- 2015 – qualification of fuel qualification, technology assessment, optimisation of GFR design,
- 2020 – start-up of demonstration plant.

The Experimental Technology Demonstration Reactor project (called ALLEGRO) will be the first gas-cooled fast reactor in the world. It will be a low-power experimental reactor (50 - 100 MWth) dedicated to validating on a pilot scale the specific GFR technologies and operating principles (fuel element and sub-assembly, and safety systems). ALLEGRO will also contribute to developing and qualifying associated fuel cycle processes. In addition to the GFR studies, the goal of ALLEGRO's preliminary design studies is to be able to take a decision of construction by the end of 2012.

Priority topics for action

R&D priorities for the GFR/ALLEGRO programme include:

- development of refractory fuel,
- design and trade-off studies for the GFR concept to demonstrate its feasibility, safety and performances,
- design studies of the experimental GFR to prepare a decision in 2012.

Priority R&D topics after the preliminary feasibility report issued at the end of 2007 aim at consolidating preselected design features in the reference GFR and screening innovations to achieve by 2012 an updated concept with improved performances:

- irradiation tests of representative GFR fuel samples,
- investigation of innovative processes to improve the SiC cladding technology both for plate and pin fuels,
- assessment of innovative primary system designs to mitigate risks of rapid depressurisation (e.g. pre-stressed concrete reactor vessel),
- resolution of possible issues associated with the evolutionary nature of ALLEGRO's core.

Experience feed-back from the operation of ALLEGRO as well as continuous research on the GFR will allow the design of a first prototype around 2030.

3.5 Accelerator Driven Systems (ADS)

As a first important step for the demonstration of this ADS, the construction of an Experimental Transmutation Accelerator Driven System (XT-ADS) is foreseen by 2020 with a power of 50-100 MWth. The MYRRHA project is proposed by SCK•CEN to respond to this need. In the longer term, a European Facility for Industrial Transmutation (EFIT) is envisaged as the final step of development, prior to full commercialisation.

The major technological issues for the ADS demonstrator are:

- system and plant design,
- necessary dedicated R&D support issues,
  material qualification programme,
  fuel qualification programme,
  high intensity proton accelerator performances and reliability.

For the medium-term (2020), the emphasis will be on the construction of MYRRHA/XT-ADS at the Mol-site (Belgium). For the longer term, the development and qualification of innovative fuels (especially minor actinide bearing inert fuels) with appropriate cladding and associated reprocessing techniques is a challenging item. Having these innovative fuels is mandatory to prove the technological feasibility of transmutation. Since the development of these innovative fuels will need a long lead time, research on this topic has already been started, but for the viability demonstration of ADS, it is of high importance to focus current fuel qualification efforts on the driver fuel for fast spectrum systems.

3.5.1 R&D challenges

The design activities for MYRRHA/XT-ADS are on-going and should produce by 2012 the functional and technical definition of all systems. In parallel the necessary dedicated support R&D and more cross-cutting R&D on materials and fuels will be conducted.

For the mid-term period, component testing, fabrication and installation will be the main issues.

In the medium term (2020), the emphasis will be on the necessary efforts for the construction of MYRRHA/XT-ADS: component fabrication and installation, civil engineering works and the material and fuel demonstration and qualification programme.

For the longer term, feedback on the operation of MYRRHA/XT-ADS will become available and will influence the further design choices of EFIT.

System and plant design

Objectives for the design of MYRRHA/XT-ADS in the short-term period (2012) are:

- high intensity proton accelerator,
- core and core support structure,
- primary system,
- secondary system & DHR system,
- spallation target & loop and their integration in the reactor,
- in-vessel fuel manipulators,
- reactor vessels and cover,
- the lead-bismuth conditioning & control system,
- the in-service-inspection & repair systems.

The aim is to bring all main components to the same advanced design level. This will result in a comprehensive functional description complemented with the characteristics, and main technical requirements, of the auxiliaries to fulfil all plant functions and requirements for both the sub-critical and the critical options, as well as in an overall plant layout.

For the mid-term period, component testing, fabrication and installation will be the main issues.

After a period of demonstration of the performance of MYRRHA/XT-ADS, an industrial prototype (EFIT) can be launched to be operational in ~2035-2040. During the operation of MYRRHA/XT-ADS, specific components in view of EFIT can be tested. Also, innovative materials and fuels for EFIT can be tested first in MYRRHA/XT-ADS. Feedback from the plant performance as a coupled system will also serve as input to the updated design of EFIT as well as for the technological development of the LFR GenIV systems.

Dedicated R&D support

Several dedicated R&D topics have been identified in support of the short-term design activities mentioned previously, namely:

- completing the design and construction of accelerator test sections to demonstrate the capacity to reach the adequate level of beam operational stability, control and reliability. A beam shut-down system in case of a shut-down signal of the accelerator-reactor system should be implemented,
- completing the support experiments for the spallation target design to a confidence level that the feasibility of a windowless spallation target can be demonstrated followed by the construction of a

spallation target mock-up loop for component testing and validation,

- since the scope of zero power experiments currently foreseen is not sufficient to allow a complete validation of the on-line subcriticality monitoring, an extension of the experimental programme needs to be implemented. Also a dedicated experimental programme for the validation of neutronic calculation codes to reduce design safety margins and to support licensing applications for the construction of XT-ADS will be needed,
- continued improvement and validation the high energy nuclear reaction models, particularly in their ability to predict residual nuclei and gas production,
- demonstration of a working ultrasound camera for in-service inspection and repair,
- proof of principle of the feasibility of liquid metal submerged remote handling,
- development and calibration of specific and generic nuclear instrumentation operating in lead-alloys and under irradiation.

Many of these R&D items can be developed in synergy with the R&D for the development of LFR. Specific items such as ultrasound visualisation can also be developed in synergy with SFR.

Mid-term and long-term dedicated R&D needs beyond MYRRHA/XT-ADS in support of ADS development are in first instance related to the U-free fuel heavily loaded with MA (> 40% in weight) and structural materials able to operate at high temperature (> 600°C) and in presence of heavy liquid metal.

Materials qualification programme

The materials qualification programme for MYRRHA/XT-ADS shows a large common trunk with the corresponding work for the Lead Fast Reactor. Due to the large database available, austenitic steels, and especially those of low-carbon grade, are candidates for components operating at relatively low temperatures and low irradiation fluence.

Ferritic-martensitic steels (T91) appear to be among the best candidate materials for fuel cladding and structures because of their resistance against swelling under high fast neutron flux. However, to respect the planning of MYRRHA/XT-ADS, it is possible that for the first cores also austenitic steels might be chosen for the cladding.

To have a qualified T91 material for internal structures and fuel cladding in the mid-term, a thorough demonstration and qualification should be pursued. To go to higher operating temperatures, it is needed to demonstrate and qualify T91 material (coated with Aluminized protective layers) which is corrosion resistant at higher temperatures.

The resulting R&D needs are the same as for the LFR.

Fuel qualification programme

To respect the planning for the construction of MYRRHA/XT-ADS, only well demonstrated and qualified fast reactor fuels can be used. Therefore, the choice for MOX fuel was made for the driver core. Such fuel with austenitic cladding was used in the French SFR reactors. Due to the poor resistance of austenitic steels to swelling under irradiation, the first choice for cladding material for MYRRHA/XT-ADS is however the ferritic-martensitic steel T91. Since the cladding-fuel compatibility of MOX with T91 has not been demonstrated and qualified yet, the first cores of MYRRHA/XT-ADS might be loaded with standard AIM1 cladded MOX fuel.

In the mid-term period, it is necessary to conduct the demonstration and qualification programme for MOX fuel cladded with T91 and possibly coated by aluminium by the GESA technique. Also, meanwhile MA inert fuels should be further developed.

In the long term, test assemblies with MA inert

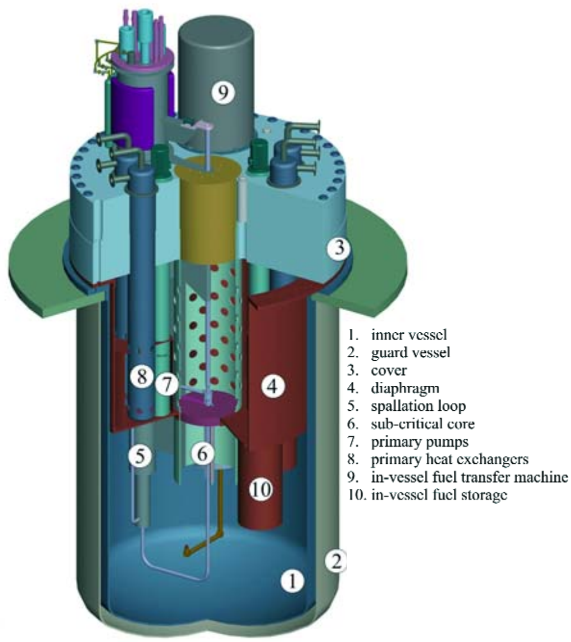

Fig. 12: Overall design of 50-100 MWth MYRRHA/XT-ADS [Courtesy of SCK•CEN]

fuels should be constructed to be loaded in MYRRHA/XT-ADS. Based on this experience, the core design for EFIT can be further detailed.

3.5.2 R&D milestones

The first major milestone in the development of ADS is the construction and full operation of an Experimental Transmutation ADS as proposed by SCK•CEN by 2020. To respect this planning, the following tasks will be accomplished in parallel during the period 2009 – 2013:

- bringing the entire design up to a level of advanced engineering (2009 – 2011),
- drafting of the technical specifications for the manufacturing contracts (2012 – 2013),
- development and testing of key innovative components (for the accelerator, the spallation target/loop and for the reactor),
- licensing activities to obtain the authorisation of construction at the end of 2013.

The construction period of the components and the civil engineering work is to be accomplished in three-year period (2014 – 2016) followed by a one year assembling together of the different components in 2017. The commissioning at progressive levels of power will be accomplished in two year period (2018 – 2019) with the final objective to be in full power operation in 2020.

From 2020 on, MYRRHA/XT-ADS will serve as a test-bed for component qualification for EFIT and LFR development and for demonstration of efficient transmutation in ADS based on MA bearing inert fuels. The facility is intended to be also operated as a critical material and fuel fast spectrum testing facility (see Chapter 5.3).

Based on the work accomplished within MYRRHA/XT-ADS, a prototype for industrial transmutation EFIT can be designed in detail, constructed and put into operation by 2035-2040.

3.6 Framework for demonstration of FNR technologies: European Industrial Initiative

Beyond the R&D, demonstration projects are planned in the frame of the SET Plan European Industrial Initiative for sustainable fission.

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These demonstration projects include the SFR prototype ASTRID whose construction is planned in France in 2020 and the construction of a demonstrator for an alternative technology – either LFR or GFR – to be decided around 2012. In addition, supporting research infrastructures, irradiation facilities, experimental loops and fuel fabrication facilities, will need to be constructed. This strategy is globally summarised in Fig. 13.

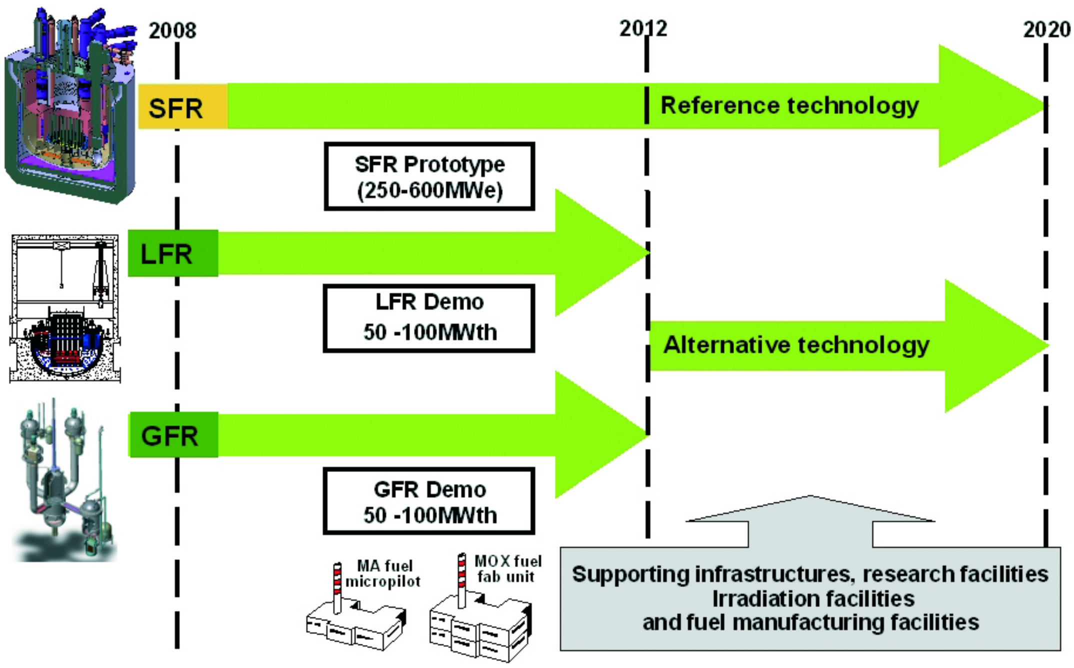

Fig. 13: European Industrial Initiative of the SET Plan, dedicated to the demonstration of GenIV (sustainable fission) technologies

4. Other applications of nuclear energy (HTR)

4.1 Introduction

The High Temperature Reactor (HTR) / Very High Temperature Reactor (VHTR) is an efficient and flexible nuclear system capable of industrial process heat supply and cogeneration. The HTR could therefore extend the contribution of nuclear energy in curbing of CO_2 emissions, reducing energy cost and improving security of energy supply.

However, coupling with industrial processes is a major technological, economic and licensing challenge for nuclear energy. Therefore before a heat market breakthrough, an industrial demonstration is necessary. Such a first demonstration is possible by 2020 if:

- reasonable performance targets and existing industrial applications are selected,
- a strong technology development programme is implemented not only for the nuclear reactor and its adaptation to industrial process requirements, but also for the applications and coupling,
- a strong partnership is built between nuclear and non-nuclear industries.

The heat generated by nuclear reactors is currently used mostly for electricity production, but could also be extensively used in non-electrical applications. The range of possible non-electrical applications of nuclear energy includes all types of large heat uses in various areas, for instance for district heating, desalination, chemical, cement and petrochemical industries, production of synthetic hydrocarbons, coal liquefaction, hydrogen production, steel making, etc. (Fig. 14). These applications currently need huge quantities of fossil fuel.

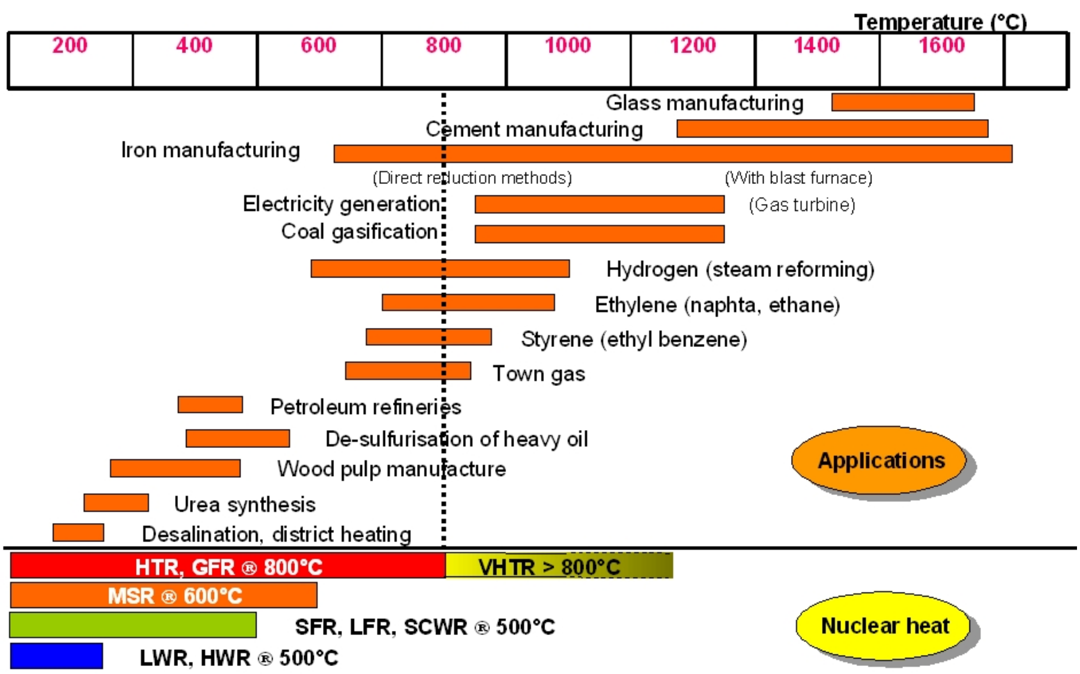

Fig. 14: Range of operating temperatures for heat intensive industrials processes (> 100 MW of heat needed in each plant) (Courtesy of Michelangelo Network FP5 project)

Cogeneration of heat and electricity makes the best use of fissile resources. In principle, all nuclear systems can be operated in cogeneration regimes, at least for medium process temperatures. However a high temperature heat source can serve a much larger range of different applications. Moreover, the modular HTR can offer a competitive, flexible and scalable solution for lower power levels than other types of nuclear systems, in a range which is relevant for most of the industrial process heat applications. Finally, HTR development for heat applications is based on proven reactor technology. In Europe, it can rely on the past (AVR and THTR high temperature reactors) experience of industry, already being applied in international projects (PBMR, NGNP, HTR-PM).

European industry indeed already provides components to some of these projects and can build on the experience of European regulators, already involved in their licensing. It can also rely on the achievements of HTR R&D obtained in Framework Programmes and in national programmes. Compared to other next generation concepts, the HTR is probably the one with the lowest development risk. Therefore HTR can provide an early nuclear process heat offer to the growing non-electricity energy market, without waiting for possible deployment of other Gen-IV systems. For all these reasons, the HTR, for which Europe has strong assets, is in a privileged position to address non-electricity energy needs.

The High Temperature Reactor, for which Europe has strong assets, is in a privileged position to address non-electricity energy needs.

For developing nuclear process heat applications, it is necessary to build a strategic alliance between nuclear and non-nuclear industries. The first challenge is to prove the technical, licensing and industrial pathways for the coupling schemes between a moderate temperature nuclear heat source and process applications. Development of technologies for improving performance or for new applications, possibly at higher temperatures should be pursued in parallel.

To support this approach, continuity of technology developments started in FP5 and FP6 for the nuclear heat source (fuel, materials, design computer codes, etc.) shall be assured and new R&D activities (e.g. instrumentation, fission product transport) shall be initiated.

The HTR demonstrator will be operated first with an open uranium cycle in order to focus on reactor development and on coupling with industrial applications. Solutions with different types of fuel (U, Pu and also thorium which allows better use of fissile resources and minimisation of actinide production) are possible. The industrial feasibility of closed fuel cycles along with graphite decontamination and recycling should be addressed for improved sustainability.

HTR/VHTR development has been launched in the present decade by many countries (US, Europe, Russia, South Africa, China, Japan and Korea). International cooperation (in particular in the frame of the Generation IV International Forum) is an essential dimension of this development that can accelerate industrial deployment.

4.2 R&D challenges for the short term, medium term, long term

The three main milestones for the development of HTR for non-electric applications are deadlines for finalising major stages of HTR development (Fig. 15):

- **2012: confirmation of key technologies, launching the preliminary design of the demonstration plant and selection of target processes,**
- **2020: start of operation of a FOAK industrial HTR with demonstration of industrial process heat and cogeneration applications,**
- **2025-2030: industrial deployment, possible HTR demonstration.**

4.2.1 Challenges for the short term (2012)

The confirmation of the industrial pathway for the coupling of the reactor with process heat applications and cogeneration is the main challenge for the short term. Industrial process heat user requirements will be different from utility requirements for electricity generation, and much more versatile, which will require a high flexibility of the nuclear heat source. Competitiveness of nuclear energy is usually achieved via systematic standardisation. The challenge will be to reconcile competitiveness and flexibility requirements. It will require, through a preliminary design phase, the demonstration of:

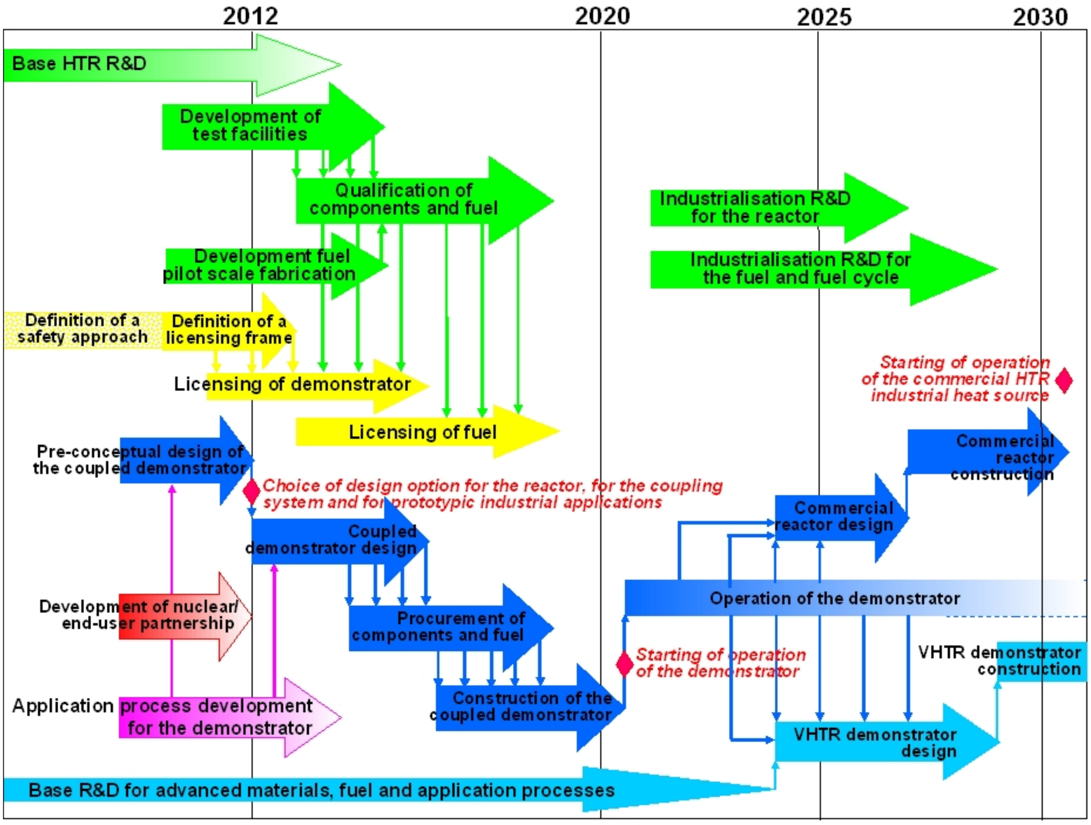

Fig. 15: The scheduling of development of the HTR/VHTR coupling with industrial process heat applications

- a very robust, competitive and scalable nuclear heat source that can accommodate different operational requirements and loads imposed by different applications without significant design changes. In order to keep the design robust, the performance requirements on the reactor, in particular in terms of temperature and burn-up, have to be reasonable, to avoid starting the experience of coupling with innovative materials and fuel with no feedback from operational experience.
- a flexible coupling system matching the nuclear and industrial application systems are aimed at, with major technical challenges (in particular for temperatures higher than 600°C):
  - the development of an intermediate heat exchanger (IHX),
  - the transport of heat at high temperature over significant distances, beyond current industrial practice,
  - the prevention of radioactive contamination of industrial processes and of the products resulting from these processes.
- an adaptation of application processes or the development of new processes, to match the specific features of the nuclear heat source and to reach a global optimisation of the coupled systems, for instance:
  - for some chemical processes, direct fossil fuel combustion in the chemical reactor possibly replaced by nuclear convective heat supply with a complete change in the distribution of heat fluxes might require the development of new chemical reactors and specific heat exchangers,
  - some processes could be modified to better adapt to HTR coupling. For instance, common steam reforming operated at 850°C could be favourably changed into a membrane steam reforming process, which can be operated below 650°C,
  - in many cases the coupling with complex industrial systems requiring different heat, hydrogen and steam conditions will imply a complete re-optimisation of the system.
- the licensing of the coupling of the nuclear and non-nuclear processes requiring consideration of the impact of the non-nuclear production system hazards. The European safety authorities will have to be involved quite early in the definition of this safety approach,
- compliance with requirements for protection of an industrial environment,
- sustainable and proliferation-resistant options not only for the fuel cycle, but also for the management of irradiated graphite, which is produced in much larger quantities than irradiated fuel.

The feasibility aspects of HTR fuel cycle and waste management should indeed be addressed right from the first phase of development of HTR because they are key issues for public acceptance.

The industrial pathway for coupling can be defined only with an active participation of end-users. The need for a strategic alliance between nuclear and non-nuclear industry is therefore an absolute pre-requisite for the development of HTR for industrial process heat applications and cogeneration. The proposal EUROPAIRS presented in the second FP7 call by a consortium of HTR-TN (High Temperature Reactor Technology Network) members and industrial process heat users, is the first step towards initiating such an alliance, which will then have to be reinforced and involved into the development of the demonstrator.

For this strategy to be successful, a funding scheme has to be prepared for the second phase, the Euratom R&D funding clearly requiring to be complemented by other financial supports for this type of demonstration project. Moreover Euratom resources have to be combined in Framework Programme activities with non-Euratom resources needed for the development of applications, which is a challenge, due to the segregation affecting nuclear activities in Framework Programmes. Finally establishing international partnerships will be essential for the success of the demonstrator development.

At the end of the period, a confirmation of the pathway for coupling with industrial process heat applications and an assessment of its economic competitiveness are expected, as well as identification of prototypic applications, for the demonstration.

4.2.2 Challenges for the medium term (2020)

The design of the demonstrator must be finalised in due time for starting operation in 2020. For that purpose, components must be developed and qualified. This implies a particular effort to be started **right now** on the following developments that are on the critical path due to their lead-times and the duration of the subsequent licensing, procurement and on site construction processes:

- fuel qualification, which is critical for licensing (robustness of the first barrier),
- qualification of components and of their materials requiring the development of large test facilities (IHX and possible other heat exchangers, circulator, etc…), long irradiation (graphite) or a long-lead procurement process (e.g. vessels), and the development of associated codes and procedures,
- qualification of the coupling system,
- qualification of computer tools that must be obtained early in the licensing process.

In addition, new developments will be needed for the demonstrator: high temperature instrumentation, modelling of fission product transport, and so on.

On the other hand, between 2012 and 2020, the required developments on the applications selected for coupling with the reactor in the demonstrator will have to be performed. The detailed roadmap for these developments is not defined yet and will be the object of the EUROPAIRS project.

4.2.3 Challenges for the long term (2025-2030)

The milestone of 2025-2030 corresponds to two objectives:

- industrial deployment of HTR coupled to industrial process heat applications,
- extending the application area, in particular to emerging technologies (e.g. synthetic fuel production, CO_2 recycling, water splitting for hydrogen production), requiring performance optimisation (VHTR).

Widening the scope of industrial applications and scaling up manufacturing processes (most particularly for fuel) will require new developments. On the other hand, the industrial deployment will benefit from the feedback from operation of the demonstrator and will likely require some additional developments that cannot be predicted presently.

In order to shorten the development delays, the demonstrator will most likely rely on an open uranium fuel cycle. But large industrial deployment will be possible only with sustainable fuel cycles and minimised graphite waste by closing the graphite cycle. Based on feasibility demonstrations performed in the first phase, industrial processes will have to be developed for application in this area.

Further extension of HTR technology application will be addressed, not only towards higher temperatures (VHTR), but also for increase in fuel burn-up, improving robustness (and therefore in reliability) and enhancing economic competitiveness.

4.3 Main existing and new experimental facilities needed to support R&D, together with required human resources and competences

4.3.1 Fuel development

A laboratory scale facility for manufacturing coated particle fuel set up at CEA Cadarache and a second one, specialised on actinide fuel, soon to be commissioned at JRC-ITU are required for developing the fuel fabrication process. However, with small diameter coaters, they cannot provide process conditions representative of industrial production for qualifying the demonstrator fuel. A pilot plant with a large coater is necessary for that purpose.

An HTR fuel irradiation facility operated in the HFR (Petten) and a second one under development in OSIRIS (CEA Saclay) can satisfy present fuel irradiation needs. These reactors will be decommissioned by 2015 and may no longer be available for final qualification of the HTR fuel. Capacity for HTR fuel irradiation should therefore be preserved in the reactors that will replace them.

Hot laboratories are available for fuel post-irradiation examinations (ATALANTE at CEA Marcoule, JRC-ITU, NRG, etc...), but dedicated characterisation equipment is not sufficiently developed yet. A heat-up facility for loss of coolant accident testing of irradiated fuel has been built at JRC-ITU, but keeping only a single facility might be insufficient and risky for fuel qualification. Subject to future assessment of the reactivity insertion accident risk that might be design dependent, this could also be the case for possible reactivity insertion accident testing, for which there is only one available facility worldwide (NSRR, Japan).

4.3.2 Materials and components

Generic materials expertise, laboratories and material testing reactors available in Europe are sufficient for satisfying most HTR materials development need. However, few specific facilities for tests in helium atmosphere with controlled impurities, essential for HTR materials, exist: corrosion and creep loops, as well as tribometers at CEA, EDF and AREVA and a corrosion loop with an in-reactor test section in UJV Řež. For the large test programme required, additional facilities may be needed to maintain the schedule.

Small facilities including small helium loops for initial testing of components are already available in particular at CEA and at ENEA Brasimone. Larger helium loops will be necessary for future phases: medium size (~ 1 MW) for component and helium technology development, and large size (10-30 MW) for component qualification (IHX, circulator, hot gas duct, isolation valves, etc...). In the medium range, the HELOKA loop under development at FZK for fusion R&D could be adapted to satisfy also some HTR test needs.

Generic materials expertise, laboratories and material testing reactors available in Europe can satisfy most HTR materials development needs.

The large helium loop will also be needed as heat source for testing new industrial processes to be coupled with HTR.

Codes and standards developments have recently been restarted but will require specific adaptation, as non-code established materials are necessary for HTR application. An effort to ensure that these materials are available under European as well as ASME procedures is needed.

4.3.3 Computer codes for design and licensing

Great progress has been made for adapting existing computer codes or developing new ones for HTR design needs. But many experimental data are still needed for code qualification.

For reactor physics, critical experiments will be necessary in available zero power reactors (MASURCA at CEA Cadarache, PROTEUS at PSI, GUINEVERE at SCK•CEN, ASTRA at Kurchatov Institute, etc...). Thermo-fluid dynamics of components requires specific mock-ups, not necessarily in helium. For system transient analysis codes, existing data from different systems (reactors, gas loops) should be sufficient, except for air ingress situations, where the complex interaction of different phenomena requires more qualification tests in

Great progress has been made for adapting existing computer codes or developing new ones for High Temperature Reactor design needs.

the existing NACOK loop (FZJ) as well as in HELOKA, L-STAR and HEBLO helium loops in FZK.

For structural analysis, existing tools are well qualified, except for core seismic behaviour which requires tests on vibrating tables.

Data obtained from tests in fuel qualification facilities will also be used for fuel performance code qualification. Additionally, the acquisition of laws for fuel coating layer material behaviour under irradiation, started in the reactor HFR with the PYCASSO experiment (RAPHAEL FP6 project), should be continued.

4.4 Priority R&D topics

4.4.1 Continuing the development of base HTR/VHTR technology

The new step of HTR/VHTR development towards application for heat supply to industrial processes should not leave in the shade the need to keep continuity in base HTR/VHTR technology developments to be able to design a competitive, safe and reliable HTR industrial heat source. This base R&D is far from being finalised with the FP6 RAPHAEL project:

- **fuel technology**:
  - -the irradiation programmes undertaken in FP5, continued in FP6, should be carried on with PIE (HFR-EU1, PYCASSO) and safety tests (HFR EU1) of previous irradiations and new irradiations (newly manufactured European fuel, advanced fuel, continuation of PYCASSO programme to get additional laws on coating materials behaviour under irradiation),
  - -mastering of fluidised bed fabrication processes using all coaters available in Europe in the frame of a coordinated programme of manufacturing tests for a better understanding of the relationship between process parameters and production attributes, with the support of a programme of refined cross-characterisations,
- **materials qualification - the main objective is to gather sufficient data in complement to those provided by other Generation IV International Forum partners for contributing to European and US efforts for completing and updating codes and standards on materials to be used for HTR/VHTR design**:
  - PIE of FP6 graphite irradiation and new graphite irradiation,
  - optimisation of composites for control rod cladding,
  - coating development for corrosion protection and tritium barrier,
  - development of joining techniques,
  - completing the qualification of Mod. 9Cr1Mo steel for the vessel (large scale tests, irradiation, welding, Leak Before Break, etc…) in cooperation with the fast reactor and fusion technology programmes,
- **computer code qualification (test needs)**:
  - reactor physics: critical experiment,
  - thermo-fluid dynamics: mock-ups of critical zones for fluid flow (most particularly the lower plenum with simulation of mixing and thermal gradient phenomena),
  - more representative air ingress tests,
  - seismic behaviour of the core,
  - the resistance of the reactor to explosions is critical for licensing the coupling of the nuclear reactor with industrial process heat applications, and therefore the relevant computer codes for assessing this resistance should be qualified,
- **new areas of base R&D needed for the demonstrator development**:
  - source term assessment and radio-contaminant retention (experiments on fission product diffusion in graphite, graphite dust deposition and re-suspension in representative conditions, and adsorption of fission products on dust), taking in particular full benefit from AVR experience,
  - high temperature instrumentation (temperature, neutron flux, impurity monitoring, flow rate etc.)

4.4.2 Assessing the sustainability of HTR/VHTR systems and of their possible fuel cycles

In this phase the feasibility of sustainable options for the fuel cycle and the management of irradiated graphite should be assessed. For graphite this task is at least partially addressed through the CARBOWASTE project, but more effort is needed, in particular for demonstrating the feasibility of graphite recycling.

For the fuel:

- **the long term tests on irradiated fuel behaviour in geological disposal conditions which started in FP5 and were continued in FP6, should be extended to FP7,**
- **the feasibility of technologies for separating the irradiated fuel kernel from the matrix of the fuel element and the coating layers should be assessed,**
- **the feasibility of actinide particle fabrication and the assessment of alternative fuel cycles (U-Pu and**

Th cycles, actinide deep burning), possibly in symbiosis with other types of nuclear systems, already studied in the FP6 PUMA project should be confirmed.

4.4.3 Assessing the options for extending HTR use towards higher temperature and burn-up

In this area the following activities are needed:

- Fuel: the development of advanced fuel (in particular with ZrC coating) and alternative fuel designs should be continued and its performance assessed,
- materials and components: assessment of Oxide Dispersion Strengthened materials (ODS) and ceramics potential for heat exchanger applications,
- advanced process development.

5. Developing competences and research infrastructures

5.1 Cross-cutting R&D topics

5.1.1 Structural materials

Introduction

Materials science and new material development are key aspects for a further optimisation of GenII and GenIII LWRs (e.g. with respect to plant lifetime extension) as well as for meeting GenIV nuclear systems objectives.

Significant differences exist among the different innovative reactor concepts (see Chapter 3). At present no definitive design has been established for any of them. The operating conditions envisaged for those systems are demanding and will impact on the performance of the structural materials. For the declared objectives to increase efficiency and enhance economy, high operating temperatures and high burn-ups are important goals from the process engineering point of view. However, the safety and the feasibility of most of these nuclear reactor concepts and their optimisation will depend crucially on the capability of the chosen structural materials to withstand the expected operating conditions.

Therefore, well targeted research activities are required to qualify commercially available materials under the extreme conditions that can be encountered in the innovative concepts as well as to develop and qualify new materials and coatings, for longer term perspectives. Moreover, aspects which are common to the different reactor systems and which affect material performance and therefore component lifetime, e.g. in-service temperature and irradiation exposure, can be addressed on a common platform. This would allow organising and managing the global effort in a more rational fashion and an improved overall knowledge and database to be generated in support of the materials assessment under relevant operating conditions.

The common platform includes the following areas:

- materials ageing under operation conditions,
- development of new structural materials,
- characterisation and advanced qualification including safety related assessments,
- physically based and constitutive modelling,
- supporting R&D for codes and design methods development,
- knowledge management and development of expertise.

R&D challenges

Development of high temperature and neutron irradiation resistant structural material is a major challenge. Fig. 16 indicates schematically operating temperature ranges and irradiation damage (indicated as displacement damage) windows for LWR, the new reactor systems as well as for accelerator driven transmutation systems.

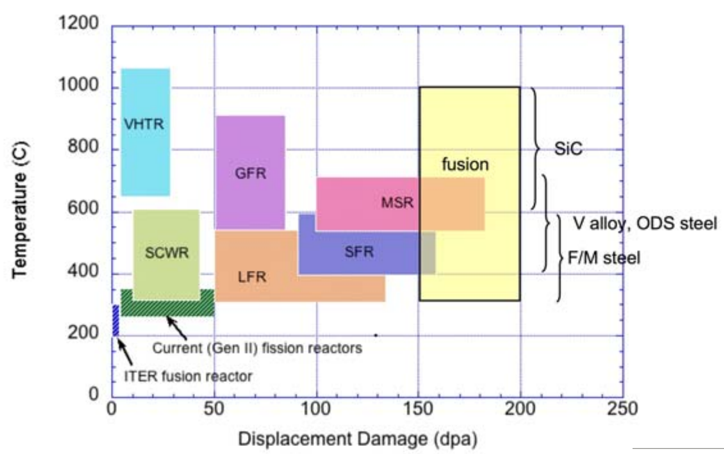

Fig. 16[29]: Operating temperature ranges and irradiation damage for different reactor concepts (dpa: displacement per atom)

[29] S.J. Zinkle , OECD NEA Workshop on Structural Materials for Innovative Nuclear Energy Systems, Karlsruhe, Germany, June 2007

A preliminary classification of candidate structural materials on the basis of maximum allowable temperature can be set as follows:

- low temperature (300-600°C) range: austenitic steels, ferritic / martensitic steels, and Oxide Dispersion Strengthened (ODS) alloys,
- intermediate temperature range (600-800°C): traditional and modified austenitic steels, ODS F/M steels, iron – or nickel- based super-alloys, refractory alloys,
- high temperature (> 800°C) range: Ni- based alloys, ferritic - ODS and refractory based systems, ceramics (silicon carbide composites), graphite and carbon-carbon composite.

Moreover, a pre-selection of structural materials can be suggested on the basis of relevant phenomena that impact their allowable dose. A further factor is their corrosion resistance for the considered type of coolant and under the expected operating conditions. This factor depends on temperature, coolant chemistry, thermal-hydraulics as well as on the possibility of using inhibitor corrosion protection systems.

For long term operation updated design curves, indicators and surveillance programmes of materials behaviour are needed to predict and monitor environment-controlled materials ageing and their impact on lifetime extension of reactor pressure vessels and internals. These items will become necessary for the long-term when the use of new materials has been envisaged.

In the short term, classes of commercially available structural materials, which can answer the option selection criteria for prototypes, are both high Cr ferritic/martensitic steels, due to their favourable physical and thermal properties, and nuclear grade austenitic steels.

However, to support the design selection in the short term and the detailed design and safety analysis in the medium term, R&D programs are needed to validate the material selection and to confirm material performances in steady state operational mode, under operational transients and under accidental conditions.

The lessons learned from the management of the GenII/III reactors should be used as guideline for establishing the best and safest practice in developing new systems.

For the 2040 milestone namely the construction of GenIV type demonstrators, an important effort on innovative materials should be started without delays in a structured manner. In what follows, the R&D needs in mostly cross cutting areas are detailed.

Specific R&D issues

Materials ageing studies under operation conditions

Life-time extension and higher burn-up are high-priority topics for operation of currently running LWRs. As for the plant life management and the plant life extension, the on-going activities are generally aimed at understanding, quantifying and predicting the effect of ageing of structural materials used in critical components of LWRs. In particular, the activities focus on the behaviour of the reactor pressure vessel material and the behaviour of primary circuit components in contact with their environment. For the reactor pressure vessel steels, the mechanical behaviour in terms of neutron irradiation embrittlement measured through fracture toughness is of primary importance, while for the primary circuit materials, stress corrosion cracking and fatigue as well as neutron irradiation induced effects such as creep and swelling for reactor internals are of importance.

The higher burn-up objectives in LWRs are currently addressed by developing new cladding materials. However, these new materials need to be validated for their behaviour under normal, transient and accidental conditions.

The lessons learned from the design, long term operation, increased burn-up and management of the GenII/III reactors should be used as guideline for the establishment of the best and safest practice in developing the new systems. For its use for the next generation of nuclear reactors, it is mandatory to establish rational approaches where the main differences between GenII/III and GenIV in terms of dose rate, neutron spectra, coolant effect, and temperature gradient, could be taken into account on a physically based scenario.

Key material relevance for both GenII/III and GenIV systems are: long-term thermal ageing of austentic steels; reactor pressure vessel steel embrittlement at high flow rates and long term operation; irradiation creep and stress relaxation.

Short term challenge:

establish a platform with industries, manufactures and public research institutions for the knowledge transfer from GenII/III to GenIV.

Development of new structural materials

The new concepts of nuclear plants foresee in-service and off-normal temperatures beyond the current nuclear industry experience. Longer service lifetimes for components and higher burn-up capability for fuels are the main challenges for materials performance.

Consequently, sound knowledge and capabilities need to be developed in Europe to produce and qualify new structural materials that could sustain higher temperatures in a nuclear environment. For this purpose, the construction of a platform or network between public and industrial research laboratories appears as an essential issue to develop the non-conventional and specific technologies needed in the manufacturing processes of materials for high temperature nuclear applications.

The creation of a network between public and industrial research laboratories is essential for the development of materials for high temperature nuclear applications.

Different types of materials could be considered depending on the requirements for critical reactor components which are F/M steels with micro / nano structures (dispersion, carbo / nitride precipitates), ODS iron based alloys, ceramic composites, nickel based alloys, and refractory alloys.

The R&D programme must include in-depth investigations describing the relationship properties/behaviour and microstructure. Moreover, the physical, mechanical and microstructural properties and their evolution need to be characterised under typical thermal, mechanical loading and irradiation environment and possibly chemical environment simulating the in-service conditions.

Forming and working processes as well as joining and weld techniques along with corrosion protection systems need also to be addressed for these innovative materials. In general, the selection, development, fabrication and qualification of a new material for nuclear applications need a very long schedule. So, the programme must be focused as soon as possible on the most promising materials.

Short term challenge:

set up of the fabrication platform between public and industrial labs to develop and improve specific manufacturing processes for relevant metallic and ceramic materials.

Medium term challenges:

fabrication of selected (precursor) materials and of corrosion protection systems, in close collaboration with industry.

Medium term milestone:

- **ranking of the different materials including their joining/welding and corrosion resistance enhancement,**
- **optimisation and specification of fabrication routes for industrialisation and cost assessment.**

Characterisation and advanced qualification including safety related studies

The characterisation and advanced qualification including safety related studies addresses both the needs for the building of prototypes/experimental facilities and FOAK fast reactors. However, the steps to be taken are different due to the different time-lines of the two types of facilities.

For the prototypes/experimental facilities, selection of commercially available structural materials and validation experiments including safety related issues needs to be accomplished, even more if innovative design aspects have to be considered. The R&D activities should also include pre-normative research items.

Concerning the characterisation of materials for FOAK fast reactors, the outcome of the ranking process which concludes the “New Material Development” phase will lead to a selection of reference materials, their join/weld and corrosion resistance enhancement. The characterisation and advanced qualification has the aim to investigate material properties on industrial scale batches. Data bases of mechanical (fatigue, rupture, creep, brittleness, erosion by coolant) as well as surface and bulk corrosion (oxidation, interaction with coolant and impurities) properties should be generated on reference and irradiated materials. In this framework a crucial parameter which has to be considered is irradiation under fully representative conditions (energy and fluxes).

The impact of temperature excursions associated to both normal and accidental conditions will be explored as well. Finally, reasonably detailed information on welding and other metallurgical processing properties will be available.

The databases should be generated as to be of use for validation of physical models and development of constitutive equations, as well as for the pre-normative research.

Short and medium term challenge:

irradiation studies for FNR using the existing facilities in Europe such as the still operating materials test reactors.

Medium term challenge:

qualification programme under nuclear environment as a function of neutron fluence, irradiation temperature and environment.

Tools and facilities

Apart from the setting up of a comprehensive collaboration with industry in order to produce the selected innovative materials, a further crucial issue is the availability of a fast neutron irradiation facility complemented by hot laboratories within which post irradiation experiments (PIE) of the mechanical properties and compatibility with the coolant of the irradiated samples can be performed. Europe seems to be reasonably well equipped with hot laboratories located in several countries. However, the concern appears to be the availability in Europe of a fast neutron reactor in which irradiation experiments can be performed.

The availability, in Europe, of a fast neutron reactor, in which irradiation experiments can be performed, needs to be ensured.

Long term challenge:

it is recognised that a European fast neutron irradiation facility is a necessity for material testing. Within SNETP a decision should be reached urgently to support the construction of a facility in which the irradiation conditions expected within the prospective reactors can be adequately simulated.

Physically based and constitutive modelling

The assessment of the integrity of a structural component over the long term operation requires reliable lifetime prediction tools for the materials from which the component is fabricated. The development of these tools needs detailed knowledge and description of the property changes and the constitutive material behaviour under service conditions (e. g. high temperatures, irradiation, stress, and contact with coolant). Therefore physically based models and predictive constitutive equations have to be developed.

At the base of physical modelling is the understanding and prediction of the structural materials behaviour in the nuclear reactor environment. Moreover, physical modelling should enable the design of structural materials with specific required properties. The objectives of multi-scale physical models as well as materials tools are to develop knowledge and understanding of elementary mechanisms in real materials and their evolution (and compared with model alloys if needed) as a function of the main parameters e.g. in-service temperature, radiation damage, mechanical loading, coolant.

Constitutive equations will be developed describing the deformation and damage behaviour of the most promising materials selected for FNRs. The constitutive modelling will be based on the identification of most important hardening and ageing mechanisms and the physically motivated description of their evolutions taking into account the role of temperature and irradiation. Thereby the characterisation data produced for FNRs will be used whereas data still missing for the application and verification of the constitutive models will be generated performing appropriate supplementary experiments.

Medium term challenges:

- **physical based models microstructure and dimensional stability (including models for environmental ageing),**
- **constitutive equations for reference and irradiated materials.**

Supporting R&D for codes and design methods

For GenIV nuclear systems, the technical challenges are related to fast neutron damage, high temperature behaviour and compatibility with the coolant (corrosion, erosion, embrittlement) of the materials which will determine the lifetime of the materials and the components built from. The pre-normative research activity defined in the frame of the cross-cutting Codes and Standards programme is devoted to materials, tests definitions, destructive and non-destructive examinations, welding, fabrication, in-service inspection, mechanical design and analysis.

To capitalise in an efficient way on the R&D proposed in the chapter devoted to fast neutron systems, an on-going effort has to be performed through a mixed working group involving the Cross Cutting R&D on structural materials, the Codes and Standards programme and the designers. This group makes sure that all research programs include a standardisation goal, evaluates the observance of the initially fixed planning and defines the research results ready for the pre-normative task, with action in priority on:

A working group involving cross cutting R&D, the codes and standards programme and the designers will allow capitalising efficiently on the proposed fast neutron systems R&D.

- definition of material specifications in close collaboration with manufacturer,
- harmonisation of testing methods for the qualification of materials systems for innovative reactors,
- material data, through a mechanical properties data base,
- identify the rules missing in available Codes and Standards to cover the specific behaviour of new developed materials (e.g. cyclic softening) and their intended application conditions (e.g. lifetime up to 60 years). Formulate and conduct necessary R&D activities to resolve identified disqualifications.

Concerning the organisation, the basic research is coordinated by the material group, and the pre-normative activities needed to cover the use of the material data in the design of components by the Codes and Standards group.

Short term challenge:

building of a working group to capitalise R&D efforts for standardisation.

Knowledge management and development of expertise and knowledge

The research should be reciprocally linked to skill base refreshment, to develop and retain expertise and knowledge and it should generate European know-how in a strategic domain, disseminate knowledge and attract a young generation of materials scientists. A methodology of knowledge/expertise capture and transfer should be defined. Collaboration among R&D centres, universities and SMEs or large size companies active in the nuclear field should be promoted. A knowledge management capability would be required to ensure the maximum benefit obtained both from existing knowledge and from that generated during the future research.

Short and medium term challenge:

continuous effort to ensure a high level of knowledge management, development of expertise and practical knowledge transfer to young generation of scientists.

5.1.2 Pre-normative research, codes and standards

This chapter presents the pre-normative research activities required to convert the results of European nuclear fission research into harmonised guidelines or codes for GenII-III, GenIV and ultimately fusion nuclear power plants. The development of a European code based on the improvement of existing codes such as RCC-MR or ISDC-IC is proposed.

For GenII-III the main issue is the successful management and operation beyond the originally foreseen lifetime.

For GenIV power plants, the status and the roadmap of the different projects naturally lead to separating the pre-normative activities into three steps:

- the short term issues (2012) with pre-normative actions focusing on the tools for design and construction of 2020 SFR and VHTR prototypes, based on existing data,

- the medium term issues (2020) deal with the R&D results to answer to the technical challenges for the GenIV reactors,
- the long term issues (2040) aims to consolidate feedback from prototypes and from the development of commercial power plants.

R&D challenges for the short, medium and long term

Design and Construction Codes provide a set of essential engineering tools for the design assessment and construction of systems components. They define the common reference between prime contractors, operators, designers, engineers, manufacturers, suppliers, inspectors and safety authorities. They define the quality level of equipment necessary to meet nuclear standards.

Design and Construction Codes provide a set of essential engineering tools for the design assessment and construction of systems components.

Whenever new materials are used, application conditions extended or new tools for the assessment of components developed, research is required to advance existing codes and standards.

GenIII nuclear power plants

The successful management and operation beyond the originally foreseen lifetime of GenII and GenIII LWR is a main issue of a sustainable and economically viable nuclear energy in Europe. Two key issues have been identified:

Harmonisation of the long term operation justification methodologies is needed on safety demonstration and on ageing management. This real mid-term challenge (2020 issues) has to be focused on the needs expressed by designers and end users to improve nuclear codes and standards:

- it will concern safety requirement at the design level (on material, fabrication, examination, etc.) and defence concepts such as leak before break demonstration, break preclusion concept, defect assessment, etc.,
- probabilistic methodologies are a major point, in the frame of safety margin determination.

Ageing management implies better understanding of phenomena, in a context of optimisation of the procedures and rules:

- a better knowledge of operating conditions (feedback capitalisation and improved instrumentation),
- a better knowledge of the ageing mechanisms,
- improved monitoring through new in-service inspection procedures and considering radio-isotope in-service inspection procedures,
- development of advanced repair and replacement technologies.

The last key point for GenIII nuclear plants is the super critical water systems concept assessment: to quantify the advantages and challenges presented by the supercritical water reactor concept, it is necessary to validate existing design and construction codes with regards to new materials selection, their characterisation and rules applicability.

GenIV and fusion reactors

Mandated by the European Commission, the CEN[30] is developing European codes and technical standards for design and fabrication of pressure vessel equipment to support the entry into force of the Construction Products Directive, the Pressure Equipment Directive, the Simple Pressure Vessels Directive, and the Transportable Pressure Equipment Directive. However these European directives do not address nuclear equipment and the present European Codes and Standards are not applicable to the nuclear industry.

There is a need to reinforce European cooperation on the development of nuclear system equipment for the next generation of reactors.

There is therefore a need to reinforce European cooperation on the development of nuclear system equipment for the next generation of reactors. This can be done through pre-normative actions whose main objectives would be to capitalise R&D results on materials, structural behaviour analysis, joining, welding, fabrication and non-destructive examinations, to bring together best European practice and harmonise criteria and codes.

A sound European basis for these objectives is the RCC-MR code. Written to collect feedback from the design and construction of Superphenix, the RCC-MR was adopted by the European countries (France, Italy, Great Britain and Germany) associated in the project EFR (European Fast breeder Reactor), with the

[30] CEN European Committee for Standardization https://www.cen.eu

support of the WGCS (Working Group on Codes & Standards from the European Commission). This also benefited from the experience of the exploitation of Phenix and was used especially for the safety reassessment of this reactor between 1997 and 2003.

Today, the RCC-MR is internationally recognised since it was chosen by India for the construction of its fast breeder programme, and by ITER for the design and fabrication of the vacuum vessel and as the basis to develop ISDC-IC (ITER Structural Design Criteria – Internal Components), for the design of the TOKAMAK internal structures.

Short term issues (2012)

Although the industrial deployment of GenIV nuclear systems is planned for the long term, first operation of a SFR prototype is planned by 2020. In addition, after completion of the construction of ITER (2017) and experiments on test blanket and diverter modules, components of the first prototype of fusion power plants DEMO are planned. These very near milestones require that evaluation of different technological solutions be completed by 2012. On the same timescale, a VHTR prototype is under study in the framework of the RAPHAEL project.

With these milestones, the short term pre-normative priorities should focus on the rules for design and construction of the 2020 SFR and VHTR prototypes, as well as fusion test modules in ITER on the following topics:

- mechanical properties,
- fabrication processes,
- identification of potential damaging phenomena for new materials,
- review and critical analysis of the current RCC-MR version,
- R&D focusing on design rules for very high temperature conditions,
- assessment of design rules for defect tolerance, and associated inspection requirements.

These actions should be based on the RCC-MR and ISDC-IC codes, in order to provide design assessment and construction rules in time for the technology assessment by 2012 and the following construction contract discussion phase.

In parallel, it is necessary to develop a roadmap for a European nuclear code on the RCC-MR and ISDC-IC as a basis for GenIV Fast Systems and other nuclear fission (excluding LWR) and fusion applications. This road-map should be discussed with European stakeholders, including safety experts.

Medium term issues (2020)

Besides the SFR prototype, a V/HTR FOAK may be envisaged after 2020, for which new components and materials are investigated such as graphite for core structure or silicon carbide composite for the fuel cladding. Pre-normative actions are needed in terms of design rules, materials, fabrication (including joining technologies) and non-destructive examination techniques.

Another domain of investigation is the design of irradiated components under high dose irradiation or with significant creep deformations, where the interaction of creep and other damage mechanisms remains an open question.

The industrial deployment of GenIV reactors worldwide also calls for harmonising Design and Construction Codes. A harmonised international codification in terms of design and construction codes ought to be defined, particularly with safety experts, stakeholders of the Generation IV International Forum and participants in its Senior Industry Advisory Panel.

Long-term issues (2040)

Feedback from fission prototypes and fusion test components will necessarily lead to new development in the different domains covered by the design and construction codes:

- completion of material specifications with the support of manufacturers,
- update of codification rules for manufacturing, welding and examination processes,
- design rules would probably have to take into account new domain of working and eventually new degradations.

In parallel, research work for new materials shall be maintained and material properties shall be tabulated.

5.1.3 Modelling, simulation and methods

Modelling and simulation significantly support vendors, regulators and operators in the reactor design effort, safety assessment, licensing and issue resolution during plant operation.

Theoretical models and codes form the basis of simulations. They are inherently dependent on nuclear data and also on experimental facilities providing detailed measurements for the validation of codes. Pre- and post-processing are necessary to handle these large sets of high resolution data and enable proper visualisation of complex phenomena.

Theoretical models and codes

Theoretical models and codes span the domains of neutronics (neutrons transport in the reactor core), thermo-mechanics for nuclear fuel modelling, thermal-hydraulics (fluid flow and heat transport in the reactor systems) as well as severe accidents.

Codes in support of existing reactors have already accumulated a rich experience and must be further developed in terms of improvement of computational performance. They must incorporate new models addressing recent findings from safety research as well as new demands from the current plant operation (e.g. new fuel designs, higher resolution in energy, time and space). In the near future, this set of codes will be fruitfully extended to the application to GenIV reactor systems.

> Codes in support of existing reactors have already accumulated a rich experience and must be further developed in terms of improvement of computational performance.

Technical challenges for each area are listed below:

Neutronics

Advanced neutronics simulation methods are required by 2012 for core design and safety related analyses of future reactor designs. They should offer higher spatial resolution using neutron transport as well as increased spectral details with more energy groups, especially for modelling MOX cores.

In the medium term (2020), full time dependent solutions of stochastic and deterministic 3D neutron transport should be developed to model heterogeneous core configurations.

Time dependent Monte Carlo methods taking into consideration thermal hydraulic feedback should be developed on the long term to provide reference solutions for time dependent deterministic calculations.

In parallel with the code and model improvements, there is a need for new nuclear and physical data.

Thermal hydraulics

The objective is the development of a multi-scale approach for single- and two-phase flows. This will allow modelling turbulence at local scale and its impact on components' scale.

In the short term, the objective is to develop advanced numerical simulations for Light Water Reactors. Current system codes are used for the evaluation of transient and for demonstrating compliance with regulatory safety limits. These codes need continued development and coupling to computational fluid dynamics codes in order to better model 3D flows in case of complex phenomena such as mixing, stratification or natural circulation.

Existing codes can be efficiently adapted to GenIV systems as a first practical step towards scoping analysis.

In the medium term (2020), efficient sensitivity and uncertainty propagation methods will be developed to handle a larger amount of detailed computational data.

Advanced GenIII and GenIV reactors may feature passive systems. 3D two-phase flow in natural circulation, possibly carrying non-condensable, will need to be simulated accurately, especially for the assessment of emergency systems.

General design and analysis tools should be developed for the different GenIV systems, taking full benefit from available codes for LWR reactors.

The extension to the multi-scale approach from single- to two-phase flows is also a formidable research challenge on the medium term.

In the longer term, the development of reliable multi-scale two-phase analysis tools represents a great research challenge.

Fuels

Specific codes for advanced fuels will need to be developed in order to accompany fuels optimisation. This will help consuming less nuclear fuel, increasing safety and recycling efficiently reprocessed spent fuel.

Currently, two types of fuel codes for normal and accidental conditions in light water reactors exist. Both should further be developed on the short term (2012) for new fuel designs and international benchmarks should be extended accordingly. The current trend to move to 3D models and to develop integrated fuel codes dealing with both normal operation and accidental conditions alike should be supported.

Existing codes should be adapted by 2020 and possibly completed by new codes to simulate advanced GenIII fuels and the fuel concepts for GenIV systems. Current efforts to develop multi-time-scale simulation methodologies should be further supported.

A common platform should be developed in the long term wherein various generic material properties and models can be combined in a more straightforward manner. It would enable simulating various fuels under consideration for all reactor generations as a result of the development of multi-scale approach.

Nuclear power is a rich technical field which involves many types of physical-chemical processes at a wide range of scales.

Common code platform with multi-physics and multi-scale

Nuclear power is a rich technical field which involves many types of physical-chemical processes at a wide range of scales.

Nuclear power is a rich technical field which involves many types of physical-chemical processes at a wide range of scales. Advanced numerical simulation tools in multi-physics and multi-scale frameworks which couple existing codes are therefore of great interest and should be further developed.

Neutronics, fuel, thermal-hydraulic and structural codes should be coupled by 2012, mainly for pressurised water reactors applications. This would require adaptive modelling switching from higher to lower order based on transient evolution.

Advanced coupling schemes should be developed on the medium term (2020) for neutronic transport solution to enable pin-by-pin analysis. They should be extended to two-phase flows and adapted to GenIV systems. Coupling between thermal-hydraulic and thermo-mechanics with Monte Carlo codes is also envisaged.

In the medium to long term, a common platform where all European codes could efficiently communicate with each other and where code information could be exchanged is strongly recommended. This would greatly facilitate code development for GenIV systems while taking the invaluable experience from existing codes. As a consequence, a common communication reference would be implemented.

A specific example for multi-physics, multi-scale simulations is the prediction of material behaviour when exposed to extreme conditions, such as high neutron irradiation doses, elevated temperatures and corrosive attack by liquid metal coolants. This is mandatory for increasing the safety.

Pre- and post-processing

As a consequence of the increased level of simulation details, ever increasing data sets need to be handled efficiently. Corresponding powerful pre- and post-processing tools should therefore be developed. Advancements in this field will be of common benefit to all GenII, GenIII and GenIV reactor systems.

Research infrastructures for modelling and simulations

Experimental facilities for code validation

Simulations are symbiotic with experiments. The performance of any simulation tools must be verified and validated against an adequate set of experiments.

New test facilities and advanced measuring techniques are necessary to support the envisaged developments in nuclear engineering simulation and systematically validate models for GenIV reactors. Simulations using validated tools are expected to help using more efficiently current and future experimental facilities.

More and better quality data

Availability of accurate nuclear data (cross sections, decay constants, branching ratios, etc.) is the basis for precise reactor calculations both for current (applications to higher burn-up, plant life extension) and new generation reactors. Additional experimental measurements and their detailed analysis and interpretation are required in a broad range of neutron energies and materials. This is particularly true for fuels containing minor actinides for their transmutation in fast spectra.

New test facilities and advanced measuring techniques are necessary to support the envisaged developments in nuclear engineering simulation.

In the area of thermal-hydraulics, higher resolution data require novel measuring and imaging techniques for traditional and new physical parameters with highest possible spatial and temporal resolution.

Access to advanced computational infrastructures

Advanced simulations tools offering higher fidelity will require high-performance computing facilities. It is therefore recommended to organise easy access of nuclear simulation research to European supercomputers.

5.1.4 Fuel

The performance of fuels for GenII and III reactors is well established for current operational limits. Despite the significant knowledge base for these fuels, it is not sufficient for designing innovative fuels for GenIV systems, which will operate at more extreme conditions (temperature, burn-up, presence of minor actinides, etc.). A dedicated multidisciplinary science based programme is needed to establish fuel properties and basic understanding of fuel behaviour to develop and qualify innovative solutions, with shorter lead times, and minimising the cost and overall length of qualification programmes.

The management of actinides is a critical issue for all generations of nuclear systems.

The management of actinides, from fuel fabrication to spent fuel treatment and waste management, is a critical issue for all generations of nuclear systems.

GenII and GenIII light water reactors will continue to operate during most of the 21st century, and therefore there is a need for an improved understanding of the behaviour of their fuels in normal, incidental and accidental conditions, in order to continuously optimise their safety and economy (e.g. higher burn-up). GenIV fast neutron systems, e.g. SFR, GFR, LFR, will require innovative fuels with higher heavy metal densities, sustaining high fast neutron fluxes and higher temperatures. Sustainability will be further improved by the development of minor actinide bearing fuels and the associated treatment and recycling processes. These require major efforts in fuel science and behaviour to support the envisaged innovative designs.

R&D challenges for the short term, medium term, long term

Table 1 summarises some of the fuels and cladding materials that are either currently used or will be needed for future systems. The fuels for SFR, LFR, GFR, MSR (Molten Salt Reactor), and even the VHTR should also include minor actinides.

Basic properties of fuel materials

The reactor fuels of the future will contain minor actinides and will operate under more extreme irradiation and temperature conditions than today, necessitating substantial innovation. Thermo-chemical, thermo-physical and thermo-mechanical properties of these new materials should be known to develop behaviour model and introduce these models in fuel performance codes.

Irradiation effects for performance code development

The effect of irradiation on fuel properties is significant. Its influence can be incorporated in fuel performance codes in the medium term through integral irradiation tests. Important empirical correlations can also be determined through dedicated fuel tests, whereby information on separate parameters is sought (e.g. thermal conductivity as a function of burn up). Such tests have already been made for the thermal conductivity of UO2 and MOX, and are urgently needed for other fuel compositions (e.g. MOX, nitride, carbide, inert matrix fuel IMF) to adapt and develop phenomenological models. The development of coated particle fuel also requires

	GenII/III LWR	SCWR	SFR	LFR	ADS	GFR	VHTR	MSR
Fuel	UO2, MOX, Th-MOX	UO2, MOX, Th-MOX	OX MC/MN Targets	MOX MN	IMF	MC MN/MOX	UO2, UCO PuO2 (Zr,Y,Pu)O2	LiF-ThF4-UF4
Cladding	Zr alloy	F/M steel	AIM1 T91 ODS	T91	T91	SiC (ODS)	iPyC/SiC/oPyC	
Liner	-	-	-	-		WW/Re	Buf Carbon	Structures
Fuel form	Pellet	Pellet	Pellet Sphere pac)	Pellet (Sphere Pac)	Pellet (Sphere Pac)	Disk	Coated particle	Fluid
Coolant	Water	Water	Na	Pb	Pb or Pb/Bi	He	He	NaF-NaBF4

Table 1. Fuel and cladding materials for different reactor concepts

A major effort is needed before a full understanding of fuel behaviour through fission or radioactive decay is achieved.

similar information, for the behaviour of the kernel and encapsulating layers. Swelling and gas release are key factors in the design of many advanced fuel elements, especially carbide and nitride fuels for GFR, SFR or LFR. There is therefore a need to provide relevant experimental data on these mechanisms, to improve the understanding of basic phenomena involved and to develop models able to predict swelling and fission gas and helium transport in steady state and transient situations.

Nevertheless, a very major effort is needed before a full understanding of fuel behaviour through fission or radioactive decay is achieved. A combined multi-scale theoretical and experimental approach is needed to design correctly (and limit) the number of heavy experiments, and conversely to validate the theoretical results.

Ultimately a link between experiments and theory on isolated physical mechanisms must be transformed and incorporated into multi-scale models, and eventually into dedicated fuel performance codes, which today are largely based on empirical correlations derived from integral fuel performance experiments. UO_2 and MOX are by far the best known fuel materials, and their understanding provides a very important basis for the exploration of alternative fuel forms. Even for these fuels, major added value can be expected from a better "science-based" approach, for instance in terms of higher burn-ups, safety, and fuel behaviour in accidental situations (reactivity insertion accident, loss of coolant accident).

Priority topics for action

A. Properties of MA Fuel (2010-2012) with extension to 2020

- Fabrication of solid pellet, coated particle (nitride, carbide, oxide, fluoride) based on Th, U, Pu, MA. Determination of phases, melting point, heat capacity, thermal conductivity, and mechanical properties of those pellets or particles and viscosity for molten fuel forms.
- Experimental investigation of fuel interaction with: fission products and helium, coolant and cladding, supported by modelling for extrapolation to off–normal operating conditions.

B. Multi-purpose irradiation experiments (2010-2012) with extension to 2020

The change in properties due to irradiation shall be addressed in in-pile tests using samples to study specific effects. Scoping experiments consisting of oxide, nitride and carbide fuels irradiation at different temperatures and burn-ups will permit swelling rate and thermal conductivity correlations to be made. A similar scope should also be foreseen for VHTR fuels containing Pu/MA fuel kernels.

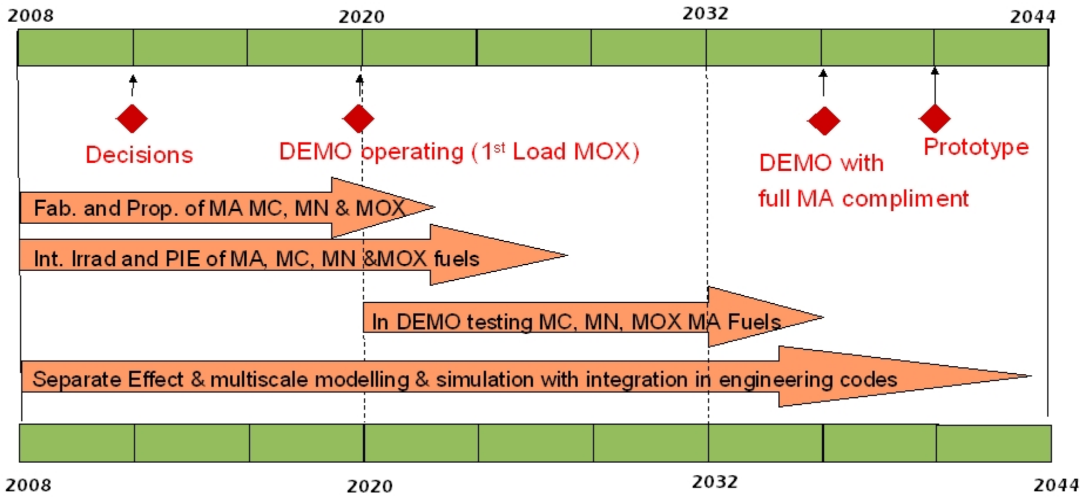

Fig. 17. Planning for the realisation of the fuel research SRA

C. Separate effects and modelling (2010-2012) with extension to 2020

Major efforts will be needed to develop and validate theoretical approaches towards the establishment of a fully integrated engineering scale approach. Specific experiments to elucidate mechanisms and define key parameters shall be performed. Inert gas behaviour in solid fuel needs experimental investigation through dedicated experiments using model systems (UO_2, UN, UC, etc…). A close interaction to design experiments and qualify theoretical models and codes is essential.

The cross cutting activities should provide the system designers with regular input data on fuel, its performance behaviour and modelling. The introduction and regular updating of a "Handbook on the properties of Advanced Nuclear Fuels" must be scheduled.

The planning for realisation of this SRA is given in Fig. 17.

5.2 Safety

Needs for safety research are identified by both regulators and operators, from their respective perspective.

Looking ahead it can happen that regulators will put in place more stringent safety criteria for the older reactors as well as those to be built. As for the operators they will strive to optimise the efficiency and availability of their plants by e.g. improving fuel utilisation, increase nominal power and prepare for an extended service time. Safety research is needed to support the licensing of these changes.

The technical safety organisations will raise within the platform the safety issues that need to be studied.

Regulators are not members of the platform but their technical safety organisations are and will raise the safety issues that need to be studied.

Selected R&D safety issues

The bulk of the safety research carried out today in Europe is performed in national programs supported by the government, regulator and operators in the respective country. The research agenda for the platform cannot integrate all these national programs but will rather select those issues that platform members agree are of highest priority. As discussed in Chapter 1, Current and Future LWRs, safety research is now needed to support long-term operation of existing LWRs in Europe.

5.2.1 Current and future LWRs

Issues in reactor physics and dynamics

The major challenge in the field should be the acquisition and the reinforcement of the fundamental knowledge, in such a way as to enable the safety assessment of current reactor improved core loadings and advanced operations, as well as of evolutionary and advanced reactors and of experimental and test facilities.

Among the main fields of interest and endeavour, we mention:

Issues in thermal-hydraulics

The main investigation and research issues in thermal-hydraulics should comprise the acquisition and the implementation of sufficient knowledge to master the following phenomena and events: passive safety features, pressurised thermal shock, inherent dilution, re-flooding on embrittled fuel, reactivity initiated accidents, main steam line break, long term coolability and thermal stratification, for which many suitable data are already available, and harmonisation and best practice development.

Issues in criticality

The objectives for the risks of criticality are less needed for current nuclear power plants for which qualified tools are worldwide shared. The remaining progress to be done consist in taking account of the burn-up credit in criticality risk evaluation. The changeover to innovative fuels and cycles will reveal new challenges for criticality safety assessment such as fuel characterisation, actinide content, new burnable poisons, innovative reprocessing methods or direct disposal of spent fuel. An active feedback from the main actors in fuel design and cycle would be required to establish the future trend in criticality safety research. The current practice being based on prevention, the main safety concern addresses the consequences of a return to criticality in the pool.

Therefore, the main actions should concern:

Issues in nuclear fuel

Research related to qualification of very high burn-up fuel under normal operation and accident conditions.

Issues in human and organisational factors

- Survey of the human and organisational practices in current reactor normal, degraded and incidental operation.
- Human and organisational factors in safety management, including operation feedback, resilience engineering, safety culture.

Issues in instrumentation and control and electrical systems

- Development of test methods to predict ageing effects on instrumentation and control components.
- The adoption of programmable digital automation components, the implementation of new technological solutions in instrumentation and control systems including the Protection Systems of current plants.

Issues in malevolent acts and natural hazards

In recent years, new threats are coming up forcing us to focus not only on internal hazards, but also on the destructive action of external agents. When assessing the safe behaviour of a system, a component or equipment, its robustness and resistance to the ageing-related phenomena and to all kind of external aggressions is to be demonstrated (including flooding, extreme whether condition, fire and seism). All these issues are widely investigated and discussed in Chapter 1 as the engines of potential extended investigation and short-term and middle-term R&D, thus here only some safety-relevant topics are mentioned, such as:

- integrity of equipment and structures,
- fire safety.

Issues in plant simulation devoted to safety

Simulators for existing plants are mainly confined to operator training and qualification for operation and accidental conditions in their qualification range, while for new generation plant, simulators should include operation outside their range of qualification to simulate internal and external hazards.

Issues in severe accidents

The work carried-out in the framework of the Severe Accident Research Network of Excellence (SARNET) concluded to a common view on the ranking of the research priorities in the field. The results were based on the outcome of the previous EURSAFE action (5th FP of the EC), the effort of benchmarking and qualification of the European Integral Severe Accident Code ASTEC, already an international reference, the results of several accident scenario calculations, and the recent research in the domain of the probabilistic safety assessment.

5.2.2 GenIV safety issues

Operating experience of current nuclear power plants can contribute significantly to identify crucial needs for further research in the fission reactor field for advanced and evolutionary systems.

Advanced and innovative reactors encompass a variety of different designs and operating modes. They span a very large set of configurations, including small and large size cores, fast-neutron and moderated spectra, gas, water and liquid metal cooling, each one matching more or less completely and comprehensively the objectives of the GenIV roadmap. Natural resource optimisation and waste minimisation are goals more likely affordable for systems with fast neutron flux, such as SFR, GFR and LFR. On the other hand, graphite moderated, gas cooled high temperature reactors such as the Very High Temperature Reactor (V/HTR) are more likely to be inherently safe; they also have the best potential for a diversified energy production (electricity, but also industrial heat and hydrogen).

> Operating experience of current nuclear power plants can contribute to identify crucial needs for further research in the fission reactor field.

In addition to the overall design, the core size and the operating modes and, in some cases, a strong coupling of neutron and temperature fields which can show-up in some large-size systems, the fuel, the materials for internals and vessel, the coolant features generate urgent needs which are incentive for specific research. Looking ahead, the research needs for future concepts are to be investigated, disclosed, and emphasised very early, so that the delivery of computation tools and the issuance of experimental results could match the design and safety-assessment schedules.

Designer, utilities, regulators and researchers are presently facing a very open landscape as regards the industrial maturity of concepts. Accordingly, the risk exists that the research effort outcomes will show up either quite poor or straightforward or false.

That is actually very challenging from the safety point of view, because, even if some common features can be found among several advanced and innovative designs (such as operation, fuel behaviour, transients and severe accidents, their consequences, and the ways to mitigate them, as it is the case for reactivity insertion accident, water or air ingress), the safety assessment is strictly tied to design features, the details of which are hardly disclosed and remain widely unknown for the most concepts at the present stage of development.

Common safety issues of GenIV systems

Several among the above mentioned concerns can be relevant to the next generation reactor safety, but their assessment remains difficult due to the limited knowledge on the design. As a common base, the "safety by design" approach can help in thinking or re-thinking the reactor designs, even at their different stages of development, by exploiting also the adoption, since the conceptual phase and during the entire development, of the deterministic and probabilistic tools, e.g. in a risk-informed approach. Moreover and similarly, "security by design" will be centred on providing intrinsic design features, which will preserve terrorist attack or sabotage, without costly additional features.

> The "safety by design" approach can help in thinking or re-thinking the reactor designs, even at their different stages of development.

Among the main safety-relevant issues, which can be seen as safety concerns for GenIV system, we mention:

- minimising the risks attached to the coolant (sodium, lead, etc.),
- practically precluding large energy release in case of extreme DBA,
- minimising the risk of severe accident,
- minimising the vulnerability to external events and aggressions,
- assessing the impact of minor actinides bearing fuels,
- diversifying the safety systems (e.g. decay heat removal),
- developing an improved instrumentation for early detection of abnormal situations,
- developing improved instrumentation and techniques for in-service inspection and repair.

The relevant R&D activity can be grouped in several main fields of endeavour:

- core physics and simulation,
- residual heat removal,
- fuel integrity,
- fission product release,
- reduction of major risk of a broad and severe damage of the core,
- in-service inspection.

All these items demand a strong R&D effort, devoted both to code development, validation and qualification, and to measurements through ad hoc mock-up experiments. In order to achieve an optimum management of the resources, a priority scaling should be established in agreement to the envisioned technological choices.

5.3 New nuclear large research infrastructures

5.3.1 Introduction

To be deployed successfully, the SRA will require new large research infrastructures. In this chapter, a synthesis of these infrastructures needed for the road maps is presented. This includes new large flexible irradiation facilities, major fuel cycle facilities as well as large supporting facilities. Modern research infrastructures are essential to remain at the forefront of nuclear fission science and technology and to support industrial innovations for nuclear reactors, fuels and fuel cycle.

Experimental and flexible testing reactors are used to support many important fields of industry and research in Europe: safety, lifetime management and operation optimisation of current nuclear power plants, development of new types of reactors with improved resources use and fuel cycle management, material development for fusion reactors and for medical applications. Nearly all European experimental reactors have been built in the 60's or 70's. With several Material Testing Reactors (BR2, Halden, HFR, LVR15, Osiris, R2, Siloe, Maria), and with experimental reactors and prototype reactors (Rapsodie, Phenix, PFR, KNK II, and AVR, THTR) for developing the sodium and gas cooled reactor technologies, Europe has gained a worldwide leadership. Some of these facilities have already been closed. The others will be more than 50 years old in the next decade and will face increasing probability of shut-down due to their obsolescence.

Modern research infrastructures are essential for Europe to remain at the forefront of nuclear fission science and technology.

Based on the present infrastructure situation and the challenge of the development of sustainable nuclear energy there is a clear need to update the large flexible irradiation infrastructures. In the roadmap of new reactor infrastructures, these large flexible irradiation facilities will complement the need for demonstration and prototype reactors in support of the development of new reactor systems. Chapter 3 describes the rationale for the need for a SFR (ASTRID) prototype, a demonstration reactor for an alternative technology to sodium, LFR (ETTP) or GFR (ALLEGRO) and an ADS demo after an assessment of the merits of industrial transmutation via ADS. These fast spectrum prototype/demonstrator reactors will also provide some experimental irradiation and minor actinide transmutation capabilities.

Fuel cycle research infrastructures are needed to support mainly recycling options for what is called "the back-end" of the nuclear fuel cycle.

To perform experiments about fuel separation processes with samples of genuine spent fuel, different hot facilities are available mainly at CEA in Marcoule, UK's National Nuclear Laboratory (NNL) at Sellafield and ITU in Karlsruhe. Some of them (such as for instance the recently commissioned shielded cells in ATALANTE and the new BTC facility in Sellafield - now known as the Central Laboratory of the NNL) enable demonstrative experiments on up to 20 kgs spent fuel. Some facilities have been satisfactorily operated to design minor actinide recycling processes in the past fifteen years.

The recycling step of advanced fuel cycle options implies experimental irradiations which require the suitable manufacturing facilities. Here again, fabrication tools do exist at laboratory scale (LEFCA in Cadarache, MA-LAB at ITU, NNL's Central Laboratory at Sellafield, ATALANTE in Marcoule). But they present actual limitations lying both in their flexibility (nature of elements and compounds) and their throughput.

In order to respond to the specific challenges posed in advanced fuel cycles (high levels of radioactivity and heat load to be handled, diverse scopes of separation processes, conditioning of the final waste, or actinide-bearing fuel fabrication) new large research infrastructures are needed, in addition to existing ones within EU.

For the "front end" of the nuclear fuel cycle, it seems that there is no obvious need for complementary large infrastructure in this area: EU competitiveness here relies today on rather well-established concepts and processes, and innovative or alternative technologies possible in a long-term perspective are rather a matter of wide survey at this step.

5.3.2 New large flexible irradiation facilities

Europe can only hold on to its leadership in the field of reactor technology if it maintains its efforts towards the realisation of a European Research Infrastructure Area. The irradiation capacity for R&D and production of medical isotopes (the medical isotopes production, including investment and operation, will be self-sustained and recovered on a commercial basis) should be based on three pillars:

To hold on to its leadership in reactor technology, Europe must maintain its efforts towards the realisation of a European Research Infrastructure Area.

1) Jules Horowitz Reactor (JHR) at Cadarache in France, of which the construction has been started in March 2007. JHR will be answering the needs for industrial applications for GenII & III in terms of structural and fuel performance improvement as well as some generic GenIV research. JHR will be also acting as back-up irradiation facility for radioisotopes production.

2) MYRRHA at Mol in Belgium, a flexible fast spectrum irradiation facility, operating as a sub-critical (accelerator driven) system, and as a critical reactor for material and fuel developments for GenIV and fusion reactors and in a back-up role for radioisotopes production. Operation as an accelerator driven system allows responding to the need expressed in Chapter 3 for an ADS demo, demonstrating the ADS concept and the efficient transmutation of high level nuclear waste (minor actinides). MYRRHA will also be able to contribute to the objectives of developing an alternative to the sodium fast rector technology due to its heavy liquid metal based coolant technology.

3) PALLAS at Petten in The Netherlands, presently under design for serving the objective of securing the radioisotopes production for medical application for Europe and as a complementary and back-up facility in support of the industrial needs for technological development for present and future reactors.

Jules Horowitz material testing reactor (JHR)

JHR will offer advanced experimental capacities, e.g. on line fission product measurements and dedicated cells to manage safety experiments with damaged fuel samples.

To meet the needs for the coming decades, JHR will be a high performance 100 MWth material testing reactor providing high fast neutron flux in an under-moderated core (10^{15} n/cm².s perturbed flux above 0.1 MeV) and high thermal neutron flux in the moderator (5×10^{14} n/cm².s). Compared to existing material testing reactors, JHR will offer advanced experimental capacities such as on line fission product measurements and dedicated cells to manage safety experiments with damaged fuel samples.

The JHR is an on-going programme with a European consortium of utilities and research organisations. The construction phase was launched in March 2007 in Cadarache (France). The qualification of JHR components and its experimental devices development and demonstration will make use of the existing material testing reactors and expertise in the field of research reactors in Europe.

MYRRHA

MYRRHA is conceived as a flexible fast spectrum facility with a power between 50 to 100 MWth. The total neutron flux levels (1×10^{15} to 5×10^{15} n/cm².s) achieved within the facility in large irradiation volumes in the core (about 20 000 cm³ in total), allow very high performance testing conditions. Especially, a very high fast neutron flux around 1×10^{15} n/cm².s for neutrons with an energy higher than 0.75 MeV can be obtained. The high flux levels, the fast spectrum and the large irradiation volumes make MYRRHA a unique tool for the study of material and fuel behaviour in support of fast spectrum technologies (SFR, LFR, GFR) and the study of fusion material behaviour. As a flexible irradiation facility MYRRHA will also be able to serve as a back-up for radioisotope production which will be the primary task of PALLAS.

Given the need in a European context for an ADS demo, as expressed in Chapter 3, MYRRHA can also address this need, since in its current design the system is able to work in subcritical and critical mode. In subcritical mode, as an Accelerator Driven System, MYRRHA is able to demonstrate ADS technology in full scale in the frame of research on transmutation of High Level Waste and demonstrate the efficient transmutation of minor actinides in an ADS.

The high flux levels, the fast spectrum and the large irradiation volumes will make MYRRHA a unique tool for the study of material and fuel behaviour in support of fast spectrum technologies.

Since MYRRHA is based on the use of an alternative coolant to the sodium namely a lead alloy, it will in this sense also be able to contribute to the development of an alternative to the sodium fast rector technology.

SCK•CEN proposes to host the MYRRHA facility on the site of Mol, Belgium.

Pallas reactor

The Petten site, in The Netherlands, integrates on the same site the reactor HFR, hot cell laboratories and medical-oriented production facilities. The Pallas project replacing HFR after 2015 will provide an innovative irradiation facility and reinforce the supply of radio-nuclides for medical application in Europe. Key elements are a flexible core and a moderate power. Like the HFR, also the Pallas reactor will act as complementary and back-up facility for material, fuel and nuclear components research.

The Pallas project will provide an innovative irradiation facility and reinforce the supply of radio-nuclides for medical application in Europe.

Nuclear medicine is important for the health of European citizens with about 10 million medical procedures per year and 15 million in vitro analyses and a back-up function from other European research reactors such as the JHR is mandatory to secure the continuous supply of the medical radioisotopes.

5.3.3 Irradiation devices for experiments

Irradiation experiments for screening, characterising, qualifying testing beyond normal conditions material and fuel are on the path of progress in water cooled reactors and even more for future technologies.

These experiments will be performed either in flexible material testing reactors or in industrial reactors or prototypes depending on the scope of the experiment, the scientific state of art, the degree of maturity of the technology to be tested, the desired irradiation conditions and cost effectiveness.

Beyond the availability of the irradiation capabilities, it is necessary to develop state-of-the-art experimental devices to go a step further beyond existing knowledge, taking into account progress in modelling, instrumentation and modern safety standards to deliver benchmarking grade experimental data.

Europe has a world-wide leading position in this field and has to keep it through intra-European synergetic developments to overcome shortage of resources and in particular in the field of reactor technology. The renaissance of nuclear energy may foster severe competition with non-European labs.

A new generation of experimental devices must be developed, in order to meet the major challenges identified in the Strategic Research Agenda.

To meet major challenges identified in the SRA, it is mandatory to develop a new generation of experimental devices with modern instrumentation and consistent to the progress of modelling. For that purpose, the European reactor technology community should go a step further in its integration by pooling its forces and know-how and sharing the development of top level experimental devices, and their implementation in existing or future irradiation facilities.

5.3.4 Fuel cycle research facilities

Besides existing facilities (ATALANTE, ITU, the new BTC facility) on which we can rely for years or decades, it is important to improve the potential in the field of experimental fuel fabrication.

A new "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 fuel (MA-bearing fuel, other than oxide fuel, etc.). Such a facility could take place in existing hot labs, in ATALANTE for instance; the goal is to get an efficient, modern and flexible tool to address the probably many and diverse experimental needs we will have.

"Pilot-scale" fabrication facilities to allow, in further steps, if necessary, demonstrative irradiation experiments at a larger scale. Such a facility is matter of study in France, considering, in connection with the fast reactor prototype, the possibility of a MA-bearing pins fabrication in La Hague (about hundreds pins per year, so about tenths of kilograms of americium). Such a facility could also be used to answer the needs of other large scale facilities, such as the ALLEGRO or MYRRHA facilities.

Another important (obvious) need is the fabrication of the fuel itself, for the core of the new experimental reactors. What is needed here could be about 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. Here too, such a facility could be a core fuel provider for others.

Concerning facilities for recycling processes, the need for new large facilities seems less urgent. Existing research large facilities (ATALANTE, ITU, BTC) offer effective potentialities at lab-scale, and should be used in the future to develop suitable processes, and to perform demonstrative runs on samples of spent fuel or on irradiated targets (at up to pin-scale).

The need for pilot-scale demonstrative facilities doesn't seem to be an urgent need for standard MOX fuel. For oxide fuels processing, MA recovery processes under development at lab-scale mainly rely on well-known and industrially mature solvent extraction technologies. The important backgrounds coming from the industrial plants feedback, or from the very important work achieved in the past decades to design modern reprocessing plants, make extraction technologies a well-mastered technology.

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

The real need for a large-scale facility will come:

- from transmutation large-scale experiments, which could involve important MA amounts to be recovered: it seems it will be necessary to assess the potentialities of existing reprocessing plants, which could be adapted to this purpose or,
- from innovative reprocessing and recycling processes, such as pyroprocesses, to recycle innovative fuels, today experimented at lab-scale; but it seems we are addressing here longer-term issues than the next decade, to several respects (time needed to develop innovative fuels, or to overcome technological gaps).

5.3.5 Other supporting facilities

The needs for supporting facilities such as dedicated liquid metal and gas loops are addressed in the relevant chapters. They are essential for components design, system development and code qualification and validation which are mandatory to sustain the safety analysis.

Also, representative zero-power nuclear facilities are needed for neutronic code validation in support of the development of new reactor concepts (SFR, LFR, GFR, ADS, VHTR) as well as in support of LWR GenII and GenIII development and operation.

The development of these facilities in Europe is strategic for the success of the deployment of the research agenda.

Fig. 18: New nuclear large research infrastructures [Source: CEA and SCK•CEN]

These major research infrastructures can be funded at EU level through private/public partnerships, involving national governments, regions, research organisations, industry and the European Commission. The research reactors fit very well in the European roadmap for large research infrastructures ESFRI[31].

[31] The European Strategy Forum on Research Infrastructures (ESFRI) roadmap is available at: http://cordis.europa.eu/esfri/roadmap.htm

Research facilities can be financed through coordinated national programmes, but they must also be supported at EU level to give confidence to private partners and to stimulate participation of Member States. Some of the facilities can also take advantage of the EU loans. The European Investment Bank has also declared itself ready to support the financing of large research infrastructures.

Research facilities can be financed through coordinated national programmes, but they must also be supported at EU level.

5.4 Education, training and knowledge management

The development of research in nuclear fission and the renewal of interest in nuclear energy both require a skilled workforce.

Like other industrial sectors, many employees who were hired in the seventies are to retire in the coming years. The competition between industrial sectors will therefore become fiercer and it will raise the issue of maintaining the knowledge base.

An important action for all industrial sectors is to raise the attractiveness of scientific studies in order to increase the number of graduate engineers and scientists. Educating more engineers is certainly the best way to diminish the pressure on human resources of all industry sectors.

It is also recommended to identify the needs for new knowledge to support the R&D for future generation reactors which is listed in the present document. This will help adapting the current courses and educate adequately the future workforce of industry and research centres which will carry out this research.

A clear picture of the stand of education at European level will be necessary in order to enable coordinating universities and take advantage of the strengths of each.

A broad picture of the different level of education from school to university and of training after graduation will help identifying best practices and recommending actions for collaboration between each stakeholder. Employers such as industry, technical safety organisations and research centres have accumulated a rich operating experience and universities are specialised in educating students. Synergies are therefore obvious.

All industrial sectors need raise the attractiveness of scientific studies in order to increase the number of graduate engineers and scientists.

Education and training is a cornerstone of international cooperation with non-EU countries, either having already a nuclear programme or developing a new one. It is recommended to establish education programmes for cooperation and mobility. It will help launching the national nuclear programmes if necessary, building a common understanding of nuclear topics, extending the contact and networks in both partners and finally opening common business perspectives.

Finally, experimental facilities are crucial for training students. The current experimental reactors which are used totally or partially for educational purposes will need upgrading and replacement. The use of existing research facilities for training engineers should also be supported as much as possible.

What next?

This Strategic Research Agenda gives a comprehensive overview of the R&D requirements needed to achieve the objectives described in SNETP's vision report. In the course of 2009 it will be complemented by a small number of appendices focusing on specific research topics (e.g. molten salt reactor and thorium cycle) and detailed roadmaps.

The next step is the issuing of the Platform's Deployment Strategy, expected to be published in the third quarter of 2009. The contributions of nuclear fission to achieving the objectives of Europe's "SET-Plan" are being structured into a European Industrial Initiative, for which preparatory work has started since the end of 2008, and a concept paper is to be issued shortly in 2009. Finally, an implementation plan will establish the procedures, priorities, timing and financing schemes for implementing the R&D programmes of the SRA. The Platform will adapt its internal organisation to best match the management and monitoring of its future activities.

Securing funding for all the proposed R&D work presents a major challenge. The funding schemes considered today are shared between private stakeholders and public funds at national and European level. These relative shares may vary as a function of the time horizon for deployment of the research results. The foreseen funding schemes are the following:

- pre-competitive R&D projects co-funded under Euratom's Framework Programme;
- joint programming between R&D organisations (mainly suited for basic studies and cross-cutting topics);
- national R&D programmes co-ordinated for example by Research Councils;
- EU Structural Funding allocated according to national and local priorities;
- projects supported by loans from the European Investment Bank;
- the nuclear European Industrial Initiative, with precise funding schemes to be defined shortly;
- private funding by the final user (utilities) for short & medium term R&D programmes in support of technologies presently in operation.

SNETP's Strategic Research Agenda will be periodically reviewed and updated.

Glossary & Contributors

Glossary

- ADS — Accelerator Driven System
- ALLEGRO — GFR demonstration plant
- ASTRID — SFR prototype plant
- DGR — Deep underground Geological Repository
- DS — Deployment Strategy
- EFIT — European Facility for Industrial Transmutation
- ENEF — European Nuclear Energy Forum
- ESFRI — European Strategy Forum of Research Infrastructures
- ETP — European Technology Platform
- ETPP — European Technology Pilot Plant
- FNR — Fast Neutron Reactor
- FOAK — First Of A Kind (reactor)
- GFR — Gas-cooled Fast Reactor
- GIF — Generation IV International Forum
- HLW — High Level Waste
- HTR — High Temperature Reactor
- IGD-TP — Implementing Geological Disposal Technology Platform
- IHX — Intermediate Heat Exchanger
- ILW — Intermediate level waste
- IMF — Inert Matrix Fuel
- LFR — Lead-cooled Fast Reactor
- LLW — Low level waste
- LWR — Light Water Reactor
- MA — Minor Actinide
- MOX — Mixed Oxide fuel
- MSR — Molten Salt Reactor
- MYRRHA — Multi-purpose hybrid Research Reactor for High-tech Applications
- NFC — Nuclear Fuel Cycle
- NW — Nuclear Waste
- ODS — Oxide Dispersion Strengthened material
- R&D — Research and Development
- SCWR — Super-Critical Water Reactor
- SET — Strategic Energy Technology
- SFR — Sodium-cooled Fast Reactor
- SNETP — Sustainable Nuclear Energy Technology Platform
- SRA — Strategic Research Agenda
- SSC — Structures, systems and components
- VHTR — Very High Temperature Reactor

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