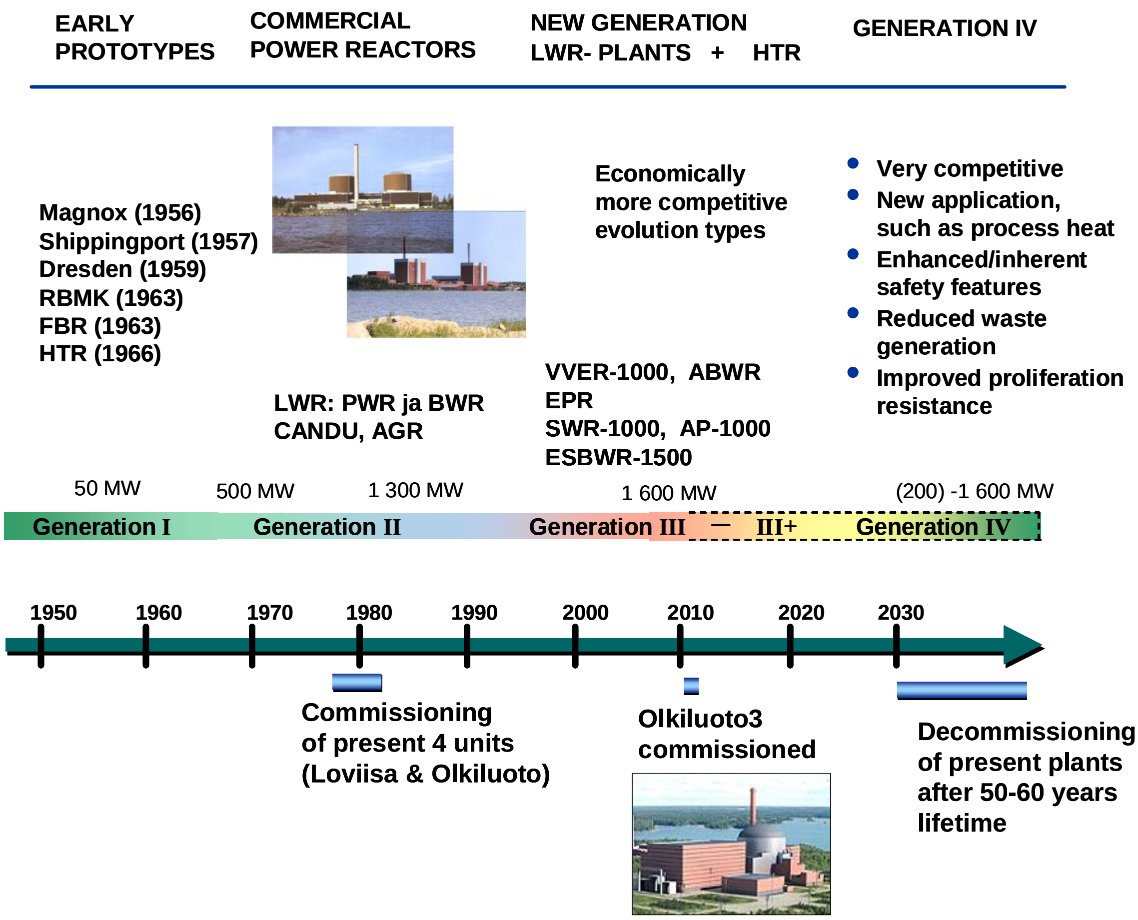
ESPOO 2008
VTT WORKING PAPERS 90



Finnish research network for generation four nuclear energy systems

GEN4FIN WORKING GROUP –
ADVISORY COMMITTEE ON NUCLEAR ENERGY
AT THE MINISTRY OF TRADE AND INDUSTRY

ISBN 978-951-38-7149-9 (URL: http://www.vtt.fi/publications/index.jsp)
ISSN 1459-7683 (URL: http://www.vtt.fi/publications/index.jsp)

JULKAISIJA – UTGIVARE – PUBLISHER

VTT, Vuorimiehentie 3, PL 1000, 02044 VTT
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Series title, number and report code of publication

VTT Working Papers 90
VTT–WORK–90

Author(s)
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Title

Finnish research network for generation four nuclear energy systems

Abstract

This report gives the reasoning for establishing a Finnish research network on future nuclear energy systems. This research network would be closely linked to the ongoing international efforts, which are also described here.

The Finnish Generation IV research network will provide especially:

– A new generation of research scientists in the field.
– Appreciated know how in the global forum on specific areas of materials engineering and science, reactor design and safety.
– Innovative and advanced research facilities and simulation programs.
– High technology industrial applications, spin-offs.
– Opportunity for Finnish safety experts to contribute to the development of safety criteria on an international level.
– Ability to assess national nuclear safety due to possible future nuclear solutions in the neighboring countries.

This report was prepared in 2005–2006, with light updating late 2007. Based on this document and a roadmap work process a research plan (NETNUC) was prepared for the Sustainable Energy (SusEn) programme of Academy of Finland. In November 2007 the Academy decided to fund NETNUC with over one million euros for the period 2008–2011.

ISBN
978-951-38-7149-9 (URL: http://www.vtt.fi/publications/index.jsp)

Series title and ISSN		Project number
VTT Working Papers 1459-7683 (URL: http://www.vtt.fi/publications/index.jsp)		16484
Date January 2008	Language English	Pages 64 s. + liitt. 46 s.
Name of project GEN4FIN koordinointi	Commissioned by MTI / Advisory committee on nuclear energy	
Keywords Generation four nuclear energy systems, Generation IV, Gen IV, GIF, INPRO	Publisher VTT Technical Research Centre of Finland P.O. Box 1000, FI-02044 VTT, Finland Phone internat. +358 20 722 4404 Fax +358 20 722 4374	

Executive summary

This report gives the reasoning for the Finnish research network (GEN4FIN) on future nuclear energy systems. This research network is closely linked to the ongoing international efforts which are also described here.

Finland is committed to nuclear energy, especially light water reactor technology, and this situation will remain unchanged for decades to come. Strong national competence has been built and maintained in areas such as safety and economic utilization of nuclear energy. Finnish achievements in terms of plant performance and power upgrades are recognized worldwide. Likewise, Finnish work on reactor safety has been highly innovative and groundbreaking, both in terms of ambitious, but realizable, safety requirements and regulatory practices, and national research & development efforts at state-of-the-art level or even beyond. This is particularly true for critical areas such as reactor dynamics, accident analyses, innovative experimental research on safety systems, severe accidents and external threats (airplane crash).Thorough knowledge in performance analysis of structural materials has made the life extension of the Finnish nuclear power plants possible. In the field of light water reactors, Finland has through decades exerted significant international influence on the development of especially reactor safety.

In recent years increased international attention has been devoted to reactor concepts that are essentially different from the existing ones and quite mature light water reactors. These new concepts, collectively known as Generation IV (Gen IV) reactors, aim to push nuclear reactor technology to completely new spheres of performance parameters (high temperatures, high process efficiency) raising many engineering challenges especially in the field of materials technologies. At the same time novel technologies are introduced for reactor fuels and fuel cycles. In order to allow Finland to benefit from these new technologies and, where appropriate, influence their evolution, it is necessary that Finland joins relevant international projects, develops domestic understanding of the critical technologies involved in the new concepts, and participates in ongoing international efforts to develop safety requirements for future reactors.

Finland has already been actively involved in research projects for new generation nuclear reactor systems. VTT has participated in the projects of the EU’s 5th and 6th framework programmes in the area of new innovative systems. One early example is the first phase of the project “High Performance Light Water Reactor (HPLWR)”. The second phase (HPLWR 2) of that project is currently underway in the 7th framework programme of EU. In addition, in the Finnish Research Programme on Nuclear Waste Management (KYT & KYT2010) there have been restricted activities in the area of advanced fuel cycle concepts – primarily the follow-up of research activities on partitioning and transmutation.

The goals of Generation IV are challenging: global sustainable development including the newly industrialized and third world countries, new safety culture, new generic technologies that can be transferred to other industries too. The two comprehensive international co-operation efforts for Generation IV nuclear systems, namely the Generation Four International Forum (GIF) and the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), have similar objectives. The key goal is sustainability through effective utilisation of the fissionable materials resources, reduced waste generation and exclusion of severe accidents by using enhanced safety features. Economic competitiveness as well as improved proliferation resistance are also aimed at. In addition new applications in addition to electricity production are foreseen, such as process heat for hydrogen production. The Sustainable Nuclear Energy Technology Platform (SNE TP) launched within EU in September 2007 has similar objectives.

Full recycling of actinides and uranium deployed in Generation IV reactors will make nuclear energy a global long term sustainable source for power production with important contribution to greenhouse gas mitigation in addition to renewable energy sources. Use of thorium as a new fission fuel will further improve the position of fission as an energy source.

The technical potential of Gen IV in power generation will be shown in a time span of 15 to 20 years as the first plants should be demonstrated. The development of Gen IV technology is revolutionary in many respects and innovative steps in plant and system features will be taken. Many basic processes seem to be fundamentally different from the NPPs in commercial use today (Gen II–III), involving, for example, new types of moderator and coolant materials and neutron energy spectra ranging from thermal to fast. Some concepts also involve continuous fuel handling, or other features that may create novel safety challenges. However, the reactor physics and thermal hydraulics methodologies and basic data needs for performance and safety analyses are in principle the same, and the increasing know-how and ability to manage these questions for either generation of reactors are largely mutually exploitable. The material performance data and models need to be upgraded and demonstrated for the more demanding operating conditions. Also the principal safety requirements are the same. The criticality safety and dynamic reactivity behavior must be in control in all situations and similar calculation methods are to be used. The safety systems will further include the shutdown systems, active and passive emergency cooling in most concepts as well as containment action. Radiation safety remains important. The development of new evolutionary or innovative safety systems for Gen IV concepts may also be utilized for the existing plants.

The primary mission of the Finnish Generation IV research network (GEN4FIN) is to improve scientific and technologic expertise in the field of nuclear energy technologies and related processes through collaboration with GIF and other global forums. The longer term mission is to create new business activities for the Finnish industry through enhanced technology transfer, innovative process development, and materials engineering.

The aim of the research network is to further support maintaining and developing national expertise and international co-operation. This effort is needed to enable timely beneficial decision making.

The activities in the research network will cover scientific, technological and industrial goals. Research & education, safety authority, manufacturing industry and power companies as well as ministries and other associated organizations are participating in the research network.

The GEN4FIN research network will provide especially:

- A new generation of research scientists in the field.
- Appreciated know-how in the global forum on specific areas of materials engineering and science, reactor design and safety.
- Innovative and advanced research facilities and simulation programs.
- High technology industrial applications, spin-offs.
- Opportunity for Finnish safety experts to contribute to the development of safety criteria on an international level.
- Ability to assess national nuclear safety due to possible future nuclear solutions in the neighbouring countries.

A further goal of GEN4FIN is also to contribute to the development of Gen IV reactors so that the facilities could possibly be deployed in Finland: to affect their acceptance and applicability. Due to the experience in utilization of nuclear energy Finland will be listened to. At least Finland should be prepared for the assessment of the national nuclear safety issues due to possible future nuclear solutions in the neighbouring countries. All proposed reactor types should be studied at some level to gather enough knowledge for their assessment.

Generation IV development is a challenging and interesting field of research and an important channel for recruiting students into the nuclear energy and technology field. Generation IV and other revolutionary fission reactors, and also fusion reactors, provide exciting challenges to new generations of nuclear professionals.

The implementation of the GEN4FIN research network will be carried out through R&D projects, education and training and international collaboration. This means that the research network should be scheduled for at least 5 years and all major actors in the

R&D field in Finland could contribute to the research network. This would correspond to the timeframe of GIF basic studies in 2005–2012, the design phase will follow in 2012–2020/2030.

This report was prepared in 2005–2006, with light updating late 2007. Based on this program document and a roadmap work process a research plan (NETNUC) was prepared for the Sustainable Energy (SusEn) research programme of Academy of Finland (see the summary in appendix H). In November 2007 the Academy decided to fund NETNUC with over one million euros for the period 2008–2011. In addition Fortum corporation will support NETNUC with a grant of 200 000 euros.

Contents

Appendices:

Terminology

ANTARES	ANTARES reactor (AREVA New Technology based on Advanced gas-cooled Reactors for Energy Supply)
BWR	Boiling Water Reactor
CANDU	"**CAN**ada **D**euterium **U**ranium". Canadian-designed power reactor of PHWR type (Pressurized Heavy Water Reactor) that uses heavy water for moderator and coolant, and natural uranium for fuel.
CHP	Combined Heat and Power
CLIMBUS	the Tekes technology programme ClimBus – Business Opportunities in Mitigating Climate Change for the period 2004–2008.
COL	combined construction and operating licence
crosscutting	involving all the Generation IV reactor concepts
DENSY	Tekes's DENSY – Distributed Energy Systems Technology Programme for the period (2003–2007)
DNB	Departure from nucleate boiling. The point at which the heat transfer from a fuel rod rapidly decreases due to the insulating effect of a steam blanket that forms on the rod surface when the temperature continues to increase.
DoE	US Department of Energy
EMWG	GIF Economics Modelling Working Group
Euratom	The European Atomic Energy Community, an international organization composed of the members of the European Union.
GEN4FIN	Finnish research network for generation four nuclear energy systems.
Generation IV (Gen IV)	fourth generation of nuclear power concepts, incl. INS
GFR	Gas Cooled Fast Reactor
GIF	Generation Four International Forum
GTK	Geological Survey of Finland
GT-MHR	Gas Turbine-Modular Helium Reactor
HPLWR	High Performance Light Water Reactor
HTR	High Temperature Reactor
IAEA	International Atomic Energy Agency
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
INS	Innovative Nuclear Energy System
KYT	Finnish Research Programme on Nuclear Waste Management for the period 2002–2005
KYT2010	Finnish Research Programme on Nuclear Waste Management for the period 2006–2010
LFR	Lead Cooled Fast Reactor

LUT	Lappeenranta University of Technology
LWR	Light Water Reactor
MICANET	Michelangelo network; competitiveness and sustainability of nuclear energy in the European Union
MSR	Molten Salt Reactor
NCS	National Climate Strategy
NEA	OECD's Nuclear Energy Agency
NGNP	Next Generation Nuclear Power Plant
OECD	Organisation for Economic Co-operation and Development
OL3	Olkiluoto 3 NPP in Finland
P&T	Partitioning and Transmutation
PBMR	Pebble Bed Modular Reactor
PESTE	PESTE-analysis. Tool to evaluate the Political, Economic, Social, Technological, and Environmental aspects.
PWR	Pressurized Water Reactor
RAPHAEL	ReActor for Process heat, Hydrogen And ELectricity generation, integrated project of the 6th framework programme of the Euratom.
RSWG	GIF Risk and Safety Working Group
SAFIR	Finnish Research Programme on Nuclear Power Plant Safety for the period 2003–2006
SAFIR2010	Finnish Research Programme on Nuclear Power Plant Safety for the period 2007–2010
SCWR	Super Critical Water Reactor
SFR	Sodium-cooled Fast Reactor
STUK	Radiation and Nuclear Safety Authority, Finland
SWOT	a strategic planning tool used to evaluate the Strengths, Weaknesses, Opportunities, and Threats involved in a project or in a business venture
Tekes	the Finnish Funding Agency for Technology and Innovation
TKK	Helsinki University of Technology
TRISO	Tristructural-isotropic fuel of micro fuel particles consisting of a fuel kernel composed of UOX (sometimes UC or UCO) in the center, coated with four layers of three isotropic materials.
TVO	Teollisuuden Voima Oy, a private electricity generation company owned by Finnish industrial and power companies, to which the company supplies electricity at cost price.
VHTR	Very High Temperature Reactor
VTT	Technical Research Centre of Finland
YEN	Advisory Committee on Nuclear Energy at the Ministry of Trade and Industry

1. Introduction

Finland is committed to nuclear energy, especially light water reactor technology, and this situation will remain unchanged for decades to come. Strong national competence has been built and maintained on areas such as safety and economic utilization of nuclear energy; Finnish achievements in terms of plant availability are recognized worldwide. Likewise, Finnish work on reactor safety has been highly innovative and groundbreaking, both in terms of ambitious, but realizable, safety requirements and regulatory practices, and national research & development efforts at state-of-the-art level or even beyond. This is particularly true to critical areas such as reactor dynamics, accident analyses, innovative experimental research on severe accidents and external threats (airplane crash). Until now, all this has pertained mainly to light water reactors, with some effort having been devoted to nuclear fusion research. In the field of light water reactors, Finland has through decades exerted significant international influence on the development of especially reactor safety. Thorough knowledge in performance analysis of structural materials has enabled the life extension of the Finnish nuclear power plants.

As Finland is committed to nuclear power at least for the next 100 years, the required knowledge and know-how should be created and maintained. In the ongoing phases of the national research programmes (SAFIR2010 and KYT2010) the target is in the safety of the current nuclear power plants and waste management. About three specialists are involved in each of the eight subfields of the SAFIR2010 programme and the entire programme creates about three to six new specialists each year. According to the national experts group on nuclear know-how about 15 new specialists would be required annually in the field. Extending the perspective to Generation IV requires a new, separate research programme.

Finland’s commitment to nuclear power:

- Olkiluoto 3 NPP will operate until 2070.
- Before that Finland shall be capable of deploying Gen IV NPP´s.
- Gen IV NPP´s should be suitable for the Finnish conditions, too.
- Safe operation of NPP´s requires local expertise.
- Government funded programmes are currently focused on research in nuclear reactor safety (SAFIR2010) and nuclear waste management (KYT2010).
- Extending the perspective to Generation IV requires a new, separate research programme.

In recent years there has been increased international attention devoted to reactor concepts that are essentially different from the existing and quite mature light water reactors. These new concepts, collectively known as Generation IV reactors, aim to push nuclear reactor technology to completely new spheres of performance parameters (high temperatures, high process efficiency), at the same time introducing novel technologies for reactor fuel, fuel cycle, and raising many engineering challenges especially in the field of materials technologies. In order to allow Finland to benefit from these new technologies and, where appropriate, influence their evolution, it is necessary that Finland joins relevant international projects, develops domestic understanding of the critical technologies involved in the new concepts, and participates in ongoing international efforts to develop safety requirements for future reactors.

This effort is needed to enable, should the technologies mature to commercial products, a serious consideration of these technologies for deployment in Finland. Whether such a move is beneficial or not remains to be decided by those who face the opportunity – but now is the time to start building a foundation on which that decision can eventually be made, based on the best possible information. Not acting now would constitute an implicit prejudgment against future technologies, and could seriously limit the range of options for the future energy solutions in Finland.

Generation IV development is a challenging and interesting field of research and an important channel for recruiting students into the nuclear energy and technology field. The goals of Generation IV are noble and challenging: global sustainable development including the newly industrialized and third world countries, new safety culture, new generic technologies that can be transferred to other industries as well. The two comprehensive international co-operation efforts for Generation IV nuclear systems, namely the Generation Four International Forum (GIF) and the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), have similar objectives listed below:

INPRO objectives [5]	**GIF objectives [1]**
Effectively unlimited fuel resources	Sustainability
Exclusion of severe accidents, Environmentally safe energy production without disturbing the natural radiation balance	Enhanced/inherent safety features
Economic competitiveness	Very competitive
Blocking the nuclear weapons proliferation pathway associated with nuclear power	Improved proliferation resistance
	New application, such as process heat
	Reduced waste generation

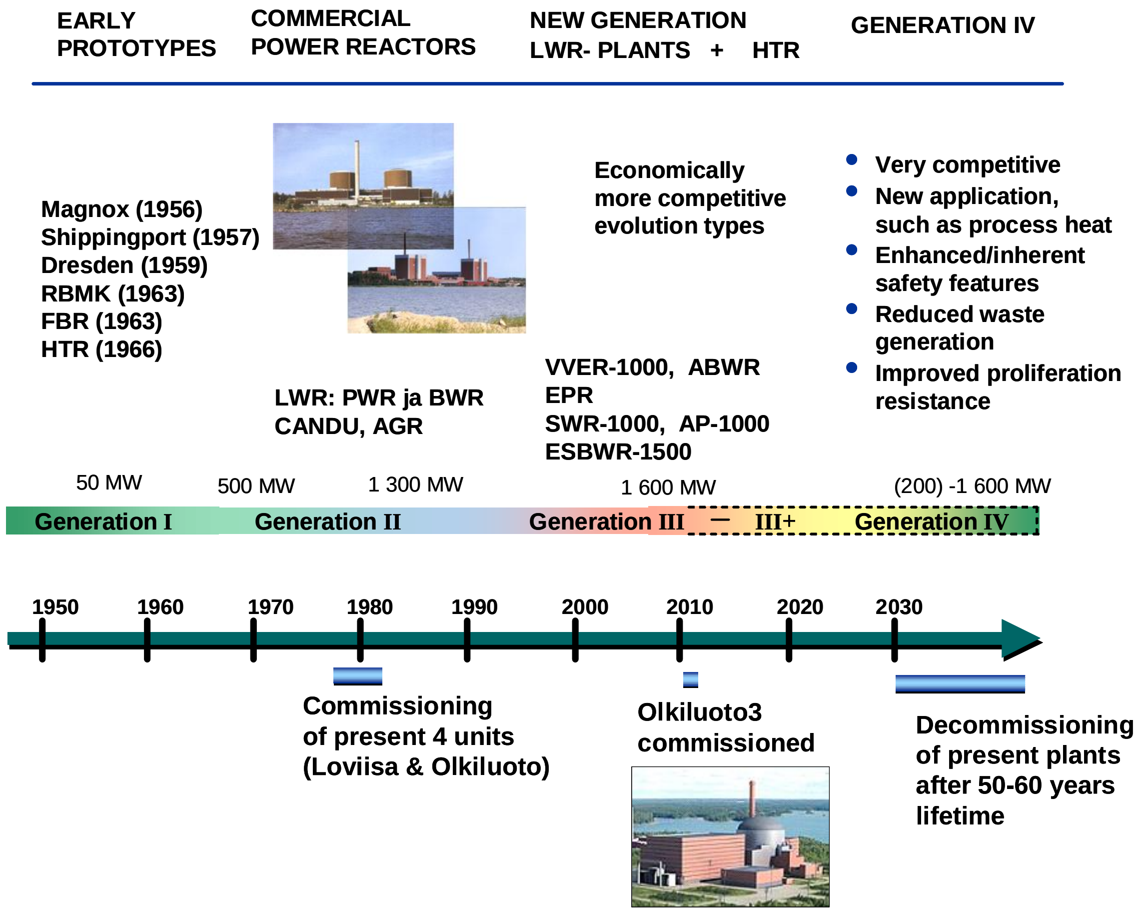


Figure 1. Evolution of nuclear power. In Finland the Loviisa and Olkiluoto 1 and 2 NPP's belong to generation II, the Olkiluoto 3 (an EPR) currently under construction belongs to generation III.

1.1 Finnish energy policy

The development of the Finnish energy system since the first oil crisis has been both economically and technically well balanced, mainly because of a successful and active energy policy as well as carefully planned responses to external forces. The production system is up-to-date, technologically advanced and diversified, supplying good quality energy with high efficiency. In Finland, industry accounts for a higher proportion of total energy consumption than in any other OECD country. The industrial structure also explains the large share of biomass, about 20% of primary energy consumption. Another specific feature of the Finnish energy system is the high overall efficiency primarily based on large share of combined heat and power production (CHP).

A major aspect of national security is a country's level of energy self-sufficiency. The introduction of nuclear power in the early 1980´s increased the self-sufficiency of Finland. The subsidiarity principle will be important in the regional self-sufficiency of energy supply. The amount and type of energy needed in the Fenno-Scandian-White sea region will depend on the future of the industry in this region. One important question is if in the future only biomass will be used as energy source in pulp and paper industry based on the sustainability criteria or if other sources of energy will be allowed. A question of the national and regional policy will be if also export of energy in form of electricity, hydrogen or other synthetic fuels (biofuels) is aimed at.

The present major challenge for energy sector is the mitigation of greenhouse gas emissions. Therefore, the governmental energy and climate change policies are closely interlinked. According to the Kyoto Protocol and the EU's internal "burden-sharing", Finland's commitment is to maintain her greenhouse gas emissions at the 1990 level at the most during the period 2008–2012. To meet this target, the first National Climate Strategy was drafted during 1999–2001. Finland's present Energy and Climate Strategy approved by the Parliament in 2006 outlines the measures that will be carried out in the energy and climate policy to meet Finland's Kyoto commitments during the period of 2008–2012. The strategy includes very concrete commitments as regards what is to be done over the next 10 years. The resources and funding have also been allocated. According to the Strategy, Finland should continue to rely on a diverse supply of energy sources, ensuring maximum self-sufficiency. All emission-free, low emission or emission-neutral production methods will be considered when decisions are being made on future capacity. In addition, Finland will utilize flexible mechanisms, defined in the Kyoto Protocol, to acquire emission units. Through the actions outlined in the strategy, Finland aims to meet the obligations set and approved for it. Without these measures, Finland's greenhouse gas emissions would exceed the target set by the Kyoto Protocol by about 15 per cent. The programme of the new government, formed in April 2007, is consistent with this strategy and states that "no form of energy production, including nuclear power, may be ruled out". The Ministry of Trade and Industry is coordinating the ongoing implementation of the Strategy.

The implementation of the strategy and its impacts are closely monitored. According to the Strategy, the programme promoting renewable energy, energy taxation and the energy conservation programme are important means when reducing greenhouse gas emissions. Power production solutions play an essential role in this. The construction of additional nuclear power capacity was the other main alternative in the Strategy of 2001, so that the decision-in-principle on the additional nuclear power capacity complied with the Strategy. Also in the future the Finnish energy policy emphasizes the role of renewable energy sources and other carbon-free options, such as nuclear power, as well as measures to improve the energy efficiency and further increased use of CHP plants. In the Finnish Energy Scenario 2100 the energy needs are covered by renewable energy sources, nuclear energy and natural gas.

Finland is thereby strongly committed to mitigation of greenhouse gas emissions. Furthermore, through the decisions in principle on spent nuclear fuel management and on the expanding of the nuclear programme by the fifth reactor unit Finland is committed to nuclear power as well, roughly for the next 100 years. Consequently, it is also important to closely follow and participate in the international co-operational efforts to develop future advanced nuclear technologies. The active participation in these efforts will at the same time benefit in maintaining high-level national expertise important for the safety of the nuclear power plants under operation or construction. Likewise, the participation in the future generation nuclear technology development efforts facilitates the follow-up of potential alternatives to the spent nuclear fuel management.

The Government is presently preparing an update of the Strategy. In addition to the climate change policy, the new National Climate and Energy Strategy will take into account the energy policy goals. The Government will draw up a long-term climate and energy strategy at the beginning of the current term. The strategy will define the principal objectives and means of Finland's climate and energy policy for the next ten years in the context of the European Union. It will also suggest measures to facilitate the adaptation to change. To steer the preparation of the strategy, a ministerial working party on climate and energy policy will be set up under the leadership of the Ministry of Trade and Industry.

The key Energy policy long-term targets of the European Union have been described in the Green Paper entitled "Toward a European strategy for the security of energy supply". The European Commission has presented a synthesis of European energy matters. An important conclusion of the Green Paper was that as much as 70% of the Union's energy requirements (as opposed to 50%, currently), would need to be covered by imported products in the next 20 to 30 years. Hence, the European Union should maintain a diversity of its sources of energy supply to avoid depending on a limited number of sources. The Green Paper also emphasizes that "the European Union must retain its leading position in the field of civil nuclear technology". The Euratom specific programme also mentions that "as the source of 35% of the electricity produced in the European Union, nuclear energy is an element of the debate on how to combat climate change and reduce the energy dependency of the European Union".

1.2 Nuclear energy in Finland

1.2.1 History

Nuclear energy has played a major role in Finnish electricity production since the beginning of the 1980s. The present proportion of nuclear electricity is about 25% of the total electricity consumption. Finland can be proud of the high load factors of her nuclear power plants, the low price of nuclear electricity and the low levels of radioactive emissions. Largely owing to nuclear electricity, Finland can also take pride in the low level of carbon dioxide emissions in the total electricity generation. The decision in principle for building the fifth nuclear reactor to Finland, Olkiluoto 3, was made in the Finnish parliament in May 2002 and the construction license was granted by the Government in early 2005. The decision to expand the Finnish nuclear power programme has markedly increased the attractiveness of nuclear energy as a career. The efforts devoted to post-graduate training have been strongly intensified and are conducted in close co-operation between the key organizations in Finland.

The increased nuclear power production is expected to play an important role in meeting the greenhouse gas emission target set for Finland in the Kyoto protocol. In addition, nuclear waste management and disposal of spent fuel are progressing according to long-term plans. The site for the spent fuel disposal facility has been approved in a Government decision-in-principle and ratified by Parliament in 2001. Furthermore, the financial arrangements for waste management are clearly defined in the legislation.

The Finnish nuclear power plants meet the constant need for base-load power. The decision to include nuclear power in the Finnish energy system was made in the late 1960s. The construction of the present nuclear power plants was decided at the turn of the 1960s and 1970s. The first unit became operational in 1977, and all four units had been taken into commercial use by the early 1980s. As a result of the good operating experiences and safety improvements, power uprating for all four units was carried out in the 1990s.

Steadily improving performance figures have been achieved, and since the mid-1980s the Finnish nuclear power plants' annual and cumulative load factors have been among the best in the world. The most important elements affecting the availability of a nuclear power plant are the duration of the annual refuelling outages and undisturbed operation. Therefore special attention is paid to the planning and technical implementation of annual refuelling outages and the reliability of plant systems.

The average annual load factor has been over 90% since 1983 almost without exception. The operation of the Finnish reactors has been undisturbed and safe. Commercial profitability has been boosted further by the extensive modernizations, including considerable upratings in the late 1990s.

1.2.2 Role of nuclear energy in GHG emission mitigation

Carbon dioxide emissions were reduced significantly in the early 1980s, when the Finnish nuclear power plants were commissioned in 1977–1982. Nuclear power replaced condensing power production, which was mainly based on coal. To curb greenhouse gas emissions, Parliament passed the National Climate Strategy (NCS) in June 2001. The NCS has focused on domestic measures as the best way to reduce the country's emissions, and includes an impressive array of programmes in all emission-producing sectors. Finland's present Energy and Climate Strategy approved by the Parliament in 2006 outlines the measures that will be carried out in the energy and climate policy to meet Finland's Kyoto commitments during the period of 2008–2012. The strategy includes very concrete commitments as regards what is to be done over the next 10 years.

The Government is presently preparing an update of the Strategy. In addition to the climate change policy, the new National Climate and Energy Strategy will take into account the energy policy goals. The Government will draw up a long-term climate and energy strategy at the beginning of the current term. The strategy will define the principal objectives and means of Finland's climate and energy policy for the next ten years in the context of the European Union. It will also suggest measures to facilitate the adaptation to change. To steer the preparation of the strategy, a ministerial working party on climate and energy policy will be set up under the leadership of the Ministry of Trade and Industry. A great deal of emissions cuts are expected to come from the new nuclear power plant, expected to be commissioned in 2011. As the commissioning of the plant has been delayed, the Finnish producers presumably need to buy some emission allowances from the EU market.

1.2.3 Research

Finnish nuclear energy research has been decentralised among several research units and groups, which operate at different State research institutes, universities, in utilities and consulting companies. The focus of nuclear R&D is on the safety and operational performance of the power plants, and on the management and disposal of waste. Publicly funded nuclear energy research provides impartial expertise in nuclear energy issues. It contributes to maintaining the necessary personnel and equipment for research and development, and it has established the framework for international collaboration.

The present national research programmes on nuclear energy are the following:

- Nuclear Power Plant Safety (SAFIR2010), 2007–2010
- Finnish Research Programme on Nuclear Waste Management (KYT2010), 2006–2010
- Euratom – Tekes Fusion Energy Cooperation, 2007–2011.

The total volume of the national research programmes on nuclear fission energy is about 50 person-years annually. Nuclear fusion research comprises about 25 person-years. At present, the total annual volume of all nuclear energy research in Finland is estimated to be some 200 person-years.

In the area of new generation nuclear reactor systems, VTT has participated in the projects of the EU's 5th and 6th framework programmes belonging to the area of new innovative systems. One early example is the first phase of the project "High Performance Light Water Reactor (HPLWR)". The second phase (HPLWR 2) of that project is currently underway in the 6^{th} framework programme of EU. In addition, in the Finnish Research Programme on Nuclear Waste Management (KYT & KYT2010) there have been restricted activities in the area of advanced fuel cycle concepts – primarily the follow-up of research activities on partitioning and transmutation as potential alternative solutions for spent fuel management and disposal.

The Nuclear Energy Act was amended in late 2003 to ensure funding for long-term nuclear safety and nuclear waste management research in Finland. The necessary finance is collected annually from the license holders to two special funds devoted to this purpose. The objective of the research funds is to ensure the high level of national safety research and to maintain the national competence in the long run.

The Finance Committee of the Finnish Parliament stated in its memorandum regarding the above changes in the Nuclear Energy Act that also in the future the Ministry of Trade and Industry should participate in the funding of basic research in the field of nuclear energy [14].

Similarly in the international evaluation of one research unit of VTT, VTT Processes in 2004 [2] the evaluation group recommended that government funding is required for nuclear energy research: VTT's activities in nuclear energy research should be maintained to support the national nuclear power programme over the entire intended life-time of the nuclear power plants in Finland. However, since there are few Finnish component manufacturers involved in the construction and operation of the nuclear power plants, the Ministry of Trade and Industry should allocate dedicated funds to VTT’s nuclear energy R&D, separate from the general basic funding.

Based on the initiative of the Advisory Group on Nuclear Energy (YEN), the planning of a possible new research programme on advanced nuclear energy systems was started in 2005. The aim of the research programme or rather a research network would be further support to maintaining and developing national expertise and international co-operation. This document is intended to describe the vision, mission objectives and framework of that planned national research network.

The role of the Gen IV in the nuclear energy production in Finland depends both on the worldwide solutions in the fuel cycle and on the new uses of nuclear energy. The issue concerning the fuel cycle is that Finland can continue to use GEN3+ LWR plants as part of an international Gen IV fuel cycle reactor fleet or if Finland for technical or political reasons should itself utilize fast Gen IV reactors to support a closed Gen IV fuel cycle. The new uses of nuclear energy like hydrogen production or other uses of process heat and district heating will require utilization of Gen IV reactors in Finland and also at new locations.

Potential new uses for nuclear energy are:

- Process heat
- Hydrogen production (hydrogen economy will require hydrogen production in Finland for economy and for reliability of supply)
- District heating.

1.2.4 Licensing

Finnish legislation contains a three-step licensing process for major nuclear facilities. In this process, the first licensing step is a Decision-in-principle, to be made at a political level and after a thorough hearing of all stakeholders, including a preliminary safety review by the Authority and agreement of prospective site(s) for the facility. Subsequent steps are the Construction License (authorization to begin building the facility) and Operating license (authorization to operate). These later steps no longer involve political/societal processing. This process has been developed into the opposite direction from e.g. the new combined construction and operating license (COL) procedure in the United States. The COL has not been tested yet by a real application, and consequential regulatory uncertainty is one of the major factors retarding new plant projects in the United States at the moment.

The Finnish licensing process has been tested in several applications, notably decisions-in-principle have been made on deep geologic disposal of spent LWR fuel, and on the construction of a fifth power reactor (Olkiluoto 3). The power reactor project has progressed already beyond the second step, Construction License having been granted in early 2005.

The Finnish licensing process is not only innovative but also demonstrably efficient: partially thanks to the staggering of work that the process demands, the Finnish authority has been able to respond to even major utility requests quite expeditiously. In contrast, countries attempting to license major facilities in one fell swoop, have repeatedly failed to accomplish the licensing within even lengthy schedules. It should not be surprising, then, that the Finnish approach – or some of its essential elements – has been gradually adopted by many European countries, such as France and Sweden.

1.3 Objectives and forums of the next generation nuclear power systems

Generation IV nuclear systems are developed in two comprehensive international co-operation efforts, namely the Generation Four International Forum (GIF) and the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO).

1.3.1 GIF

Generation IV International Forum (GIF) is a partnership of most of the world's leading nuclear technology nations to develop the next generation of nuclear energy systems. The U.S., the EU, the UK, France, Switzerland, Japan, Canada, South Korea, Brazil, Argentina, and South Africa have collaborated within this framework since 2000, with a view to exchange information and work together towards the development of the next generation of safer and more sustainable nuclear reactor systems. Euratom joined GIF in 2003 and most recently China and Russia at the end of 2006. Of the important nuclear technology nations only India is not a member in GIF.

In May 2001, the "Generation IV International Forum", or GIF, was chartered as a non-legally-binding collaborative effort among the 11 partners. Under this framework, over one hundred international experts worked together for over two years to evaluate all possible future nuclear technology concepts, and eventually produced a "technology roadmap" at the end of 2002 [1]. That document identified six system concepts that were seen as the most promising for the development of a next generation of nuclear reactors that represent substantial progress from the point of view of safety, reliability, cost, sustainability and non-proliferation. These six concepts are:

- Very high temperature reactor (VHTR).
- Supercritical-water-cooled reactor (SCWR)
- Gas-cooled fast reactor (GFR)
- Lead-cooled fast reactor (LFR)
- Sodium-cooled fast reactor (SFR) and
- Molten salt reactor (MSR).

The international Generation IV International Forum (GIF) has created a series of substantial international integrated research programmes. The research will yield vast amounts of new expertise, and it is essential that Finland will participate in the activity in order to gain access to this knowledge.

The R&D work in the global GIF forum is ongoing actively especially to study the SFR, VHTR, GFR and SCWR concepts. This forum is already attended by Finnish representatives from the research organizations and there are some ongoing activities. The Finnish activities so far are listed in Appendix 3.

The GIF technology roadmap describes the required system R&D necessary to develop each of the six selected Generation IV systems and the approximate time and cost to completion. In addition to concept-specific R&D, the roadmap recognizes that certain R&D tasks may support the advancement of multiple systems. Therefore, crosscutting R&D in the areas of fuel cycle, fuels and materials, energy products, risk and safety, economics, proliferation resistance and physical protection are also defined. Beyond the identification of promising technologies for nuclear systems (reactor, fuel and fuel cycle) one major finding of the roadmapping phase was the evidence gained about the significance of the nuclear fuel cycle for sustainability issues. This regards not only the recycling of (fissile and fertile) energetic materials but also the reduction of the volume, heat load and potential radiotoxicity of long lived waste (plutonium and minor actinides).

On February 28, 2005 a “Framework Agreement for International Collaboration on R&D of Generation IV Nuclear Energy Systems” was signed by the U.S., France, the UK, Canada and Japan in Washington. Since then also the EU, Korea and Switzerland have joined the Framework Agreement.

The GIF is led by a policy group responsible for overall policy direction and interactions with third parties. The policy group is assisted by a policy and a technical secretariat, and advised by an Experts Group on issues of R&D strategy, priorities and plans; its guidelines are implemented mainly through the six “System Steering Committees” (one per reactor concept). The U.S. currently holds the chair of the GIF policy group, supported by vice-chairs from France and Japan. Technical secretariat support for GIF is provided by the OECD's Nuclear Energy Agency (NEA). The OECD also acts as official depository of the agreement.

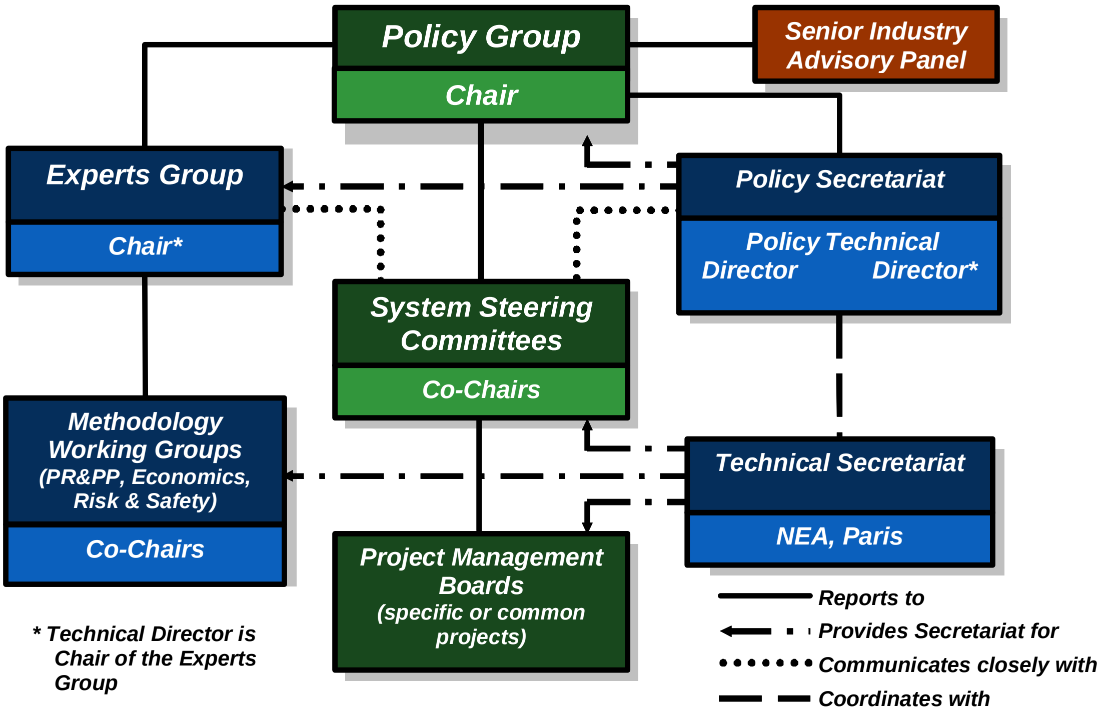
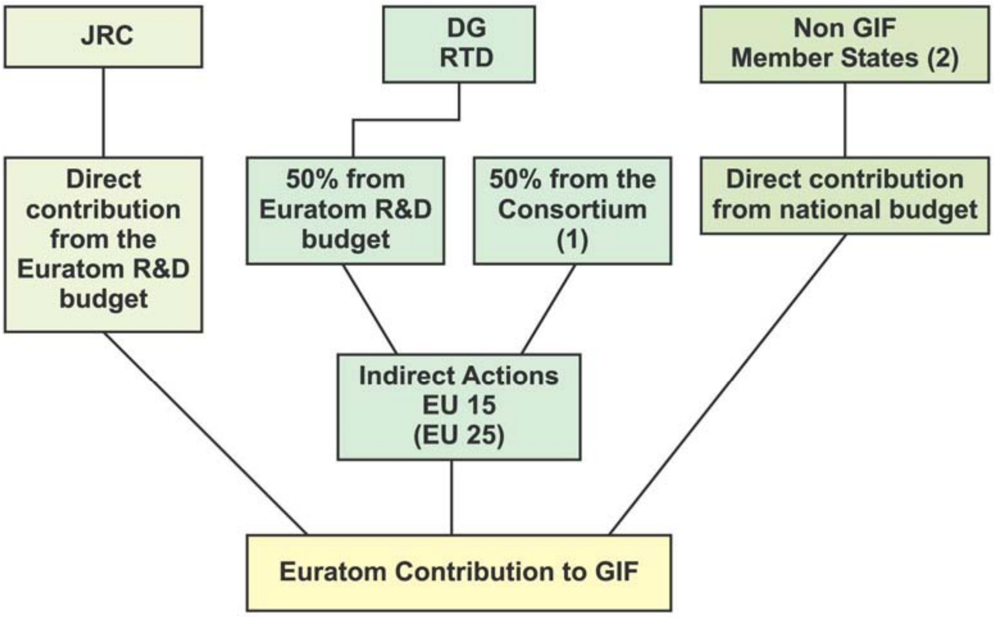


Figure 2. GIF governance structure.

Through the membership of Euratom in GIF EU will:

- make significant scientific/technical contribution to GIF (20–30 M€/year)
- play a constructive role towards achievement of GIF objectives
- provide a platform for participation from research organisations from EU member states or candidate countries not part of GIF
- align parts of European nuclear research to objectives of GIF
- have significant political impact towards future role of nuclear energy.



(1) To be selected in a call for tender launched by DG RTD, a project shall be presented a consortium of research bodies from at least 3 different Member States. In practice, The average is 6 Member States.
(2) Including presently candidates countries associated to the Euratom FP.

Figure 3. Structure of Euratom contribution to GIF.

1.3.2 INPRO

IAEA has organized an International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) [5], which is proving a forum for the coordination of research and development programmes in member states. INPRO began in 2001 on the initiative of the Russian Federation as a project that depended entirely on the political, financial and technical support of its individual member states (Argentina, Armenia, Brazil, Bulgaria, Canada, Chile, China, Czech Republic, France, Germany, India, Indonesia, Netherlands, Morocco, Republic of Korea, Pakistan, Russian Federation, South Africa, Spain, Switzerland, Turkey, Ukraine and the European Commission). The US has announced in September 2005 it will join the INPRO. The US will be the 24th member of INPRO. INPRO is expected to play a key role in supporting developing countries that want to expand or introduce nuclear energy.

1.3.2.1 INPRO's mission [5]

- To provide a forum where experts and policy makers from industrialized and developing countries can discuss technical, economical, environmental, proliferation resistance and social aspects of nuclear energy planning as well as the development and deployment of Innovative Nuclear Energy Systems (INS) in the 21st century.
- To develop the tools to analyse on a global, regional and national basis the role and structure of INS in order to meet energy demands in a sustainable manner.
- To develop the methodology for assessing INS and establish it as an IAEA set of recommendations for such assessments.
- To facilitate the coordination of international cooperation for INS development and deployment.
- To pay particular attention to the needs of developing countries interested in INS.

1.3.2.2 INPRO's Phased Schedule

In the first step, called Phase 1A, task groups established a hierarchy of Basic Principles, User Requirements and Criteria – in the areas of economics, safety, environment, waste management, proliferation resistance, and infrastructure – that must be fulfilled by an innovative nuclear energy system (INS) to meet the overall target of sustainable energy supply. The Basic Principles, User Requirements, and Criteria and the INPRO method of assessment, taken together, comprise the INPRO methodology. The INPRO methodology provides the possibility to take into account local, regional and global boundary conditions of IAEA Member States, including those of both developing and developed countries. Phase 1A was completed in June of 2003 with the publication of IAEA-TECDOC-1362, Guidance for the Evaluation of Innovative Nuclear Reactors and Fuel Cycles.

In Phase 1B INPRO arranged for some 14 case studies to be performed – by national teams or by individual experts from seven countries – to test and provide feedback on the applicability, consistency and completeness of the INPRO methodology. This feedback has lead to an improved INPRO methodology. First part of Phase-1B was completed in December 2004 with the report TECDOC 1434 "Methodology for the assessment of innovative nuclear reactors and fuel cycles".

The second part of Phase 1B of INPRO was started in January 2005 and lasted until about the middle of 2006. This phase demonstrated the capabilities of the INPRO methodology for the assessments of complete INSs. INPRO Member States have agreed on general objectives of a following phase, called Phase 2, which will build on the results achieved in the ongoing phase.

INPRO Phase 2, started in mid 2006 will organize oriented activities on R&D (e.g. Provide a forum to enable identifications and prioritizations of R&D needed under framework defined in Phase 1B); on Institutional/infrastructure (for example: Assistance for and facilitation of harmonization of licensing and industrial codes and standards, subcontracting by licensing authorities and international design certification; maintenance or development of necessary competences and experience, research facilities, etc..); on Methodology (e.g.: Further development of INPRO methodology and refinement of the assessment methodology in different INPRO areas (e.g. safety, economics, proliferation resistance, environment and waste management) in order to support the above mentioned activities.)

1.3.2.3 GIF – INPRO relationship

Concerning the relationship between the GIF and the INPRO initiative:

- INPRO is viewed as intending to refine users' requirements and methodology, in order to assess the suitability of a nuclear technology to IAEA-affiliated countries and to facilitate exchanges of public GIF information to non-GIF member countries; and
- GIF will consider the users' requirements developed by INPRO, especially with a view to enlarging the criteria to make the sustainability of nuclear power a reality.

An agreement for more extensive co-operation between INPRO and GIF has been made. From the GIF countries which are not INPRO participants Japan is acting as observer in the INPRO projects.

1.3.3 The goals and criteria for evaluation of the Generation IV concepts

In the GIF roadmap [1] the goals for Generation IV Nuclear Energy Systems have been defined as:

> **Sustainability–1** Generation IV nuclear energy systems will provide sustainable energy generation that meets clean air objectives and promotes long-term availability of systems and effective fuel utilization for worldwide energy production.
>
> **Sustainability–2** Generation IV nuclear energy systems will minimize and manage their nuclear waste and notably reduce the long-term stewardship burden, thereby improving protection for the public health and the environment.

Economics–1 Generation IV nuclear energy systems will have a clear life-cycle cost advantage over other energy sources.

Economics–2 Generation IV nuclear energy systems will have a level of financial risk comparable to other energy projects.

Safety and Reliability–1 Generation IV nuclear energy systems operations will excel in safety and reliability.

Safety and Reliability–2 Generation IV nuclear energy systems will have a very low likelihood and degree of reactor core damage.

Safety and Reliability–3 Generation IV nuclear energy systems will eliminate the need for offsite emergency response.

Proliferation Resistance and Physical Protection–1 Generation IV nuclear energy systems will increase the assurance that they are a very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism.

In the INPRO report [6] the link between the general concept of sustainability with its four dimensions and the INPRO subject areas is illustrated as in Figure 4.

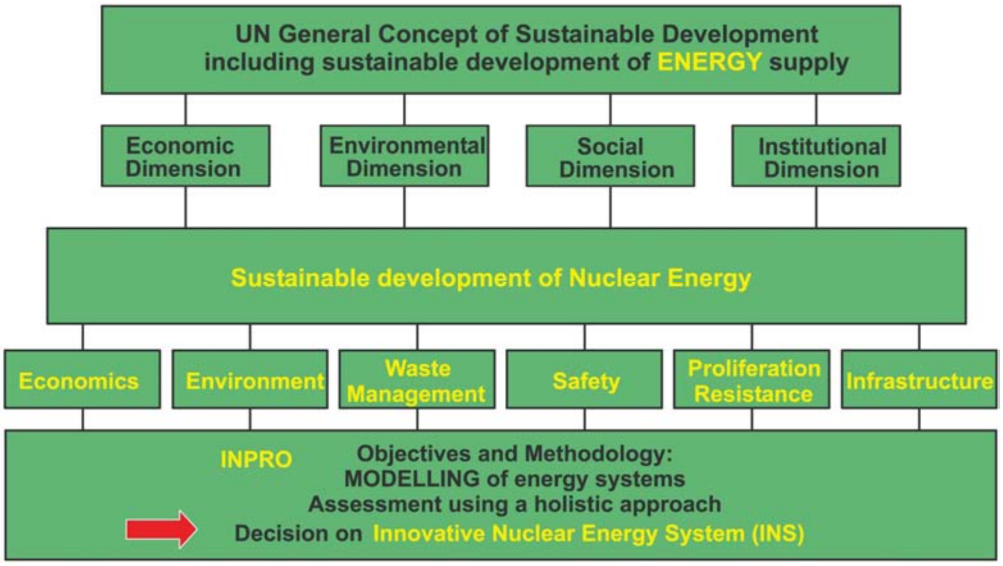


Figure 4. UN Concept of Sustainability and INPRO. [6]

1.3.4 Safety requirements for innovative reactors

The existing nuclear power plant safety requirements in most countries focus on light water reactors. Future design safety characteristics should be at least comparable to (and hopefully much better than) what has been achieved in LWRs, and safety requirements and criteria to this end are needed for practical licensing. This applies to all future technologies – passive LWRs, Gen IV concepts, and fusion – but the main challenges may differ depending on the fundamental technology. In addition to licensing requirements, for practical deployment of any technology, mature quality management methods and practices must exist.

One natural starting point for safety requirement development are the IAEA criteria. The practical safety requirements embodied IAEA safety series publications mostly pertain to LWRs (top-tier safety principles are generally considered technology-independent). There is ongoing work in the IAEA to develop technology neutral safety requirements which would be practical enough to reach with a requirement detail comparable to existing LWR guidance. However, at the moment this work relies heavily on modifying existing LWR documents by eliminating LWR technology-specific items and references. This practice overlooks the completely novel characteristics of most Gen IV concepts. Some of their salient technical features introduce new types of safety challenges that are more or less completely absent in the LWRs (e.g. potential for power excursions in fuel storage configurations, re-criticality in severe reactor accidents, risk of graphite fires; interactions between liquid metal, chemicals and coolant-water, massive amounts of low/medium level radwaste from fusion reactor inner walls and supports, etc.). It appears that there is no specific effort in the IAEA to address the quality management issues that the novel technologies raise.

The GIF has established a Risk and Safety Working Group which is to develop safety and quality goals and their evaluation methodology, in order to “assure a harmonized approach on long-term safety, risk and regulatory issues”.

Safety issues associated with fuel cycles need also to be addressed, but there the parallels between existing fuel manufacture and reprocessing facilities are closer than in the case of reactors.

Developing safety requirements and criteria is a heavily research-oriented exercise. To begin, it is necessary to understand the basic reactor system design and processes very well; then these must be simulated and various equipment / materials / components failures postulated to see how the system responds. Based on insight so gained, and taking into account estimated likelihoods of various failures, one can then develop the “safety case” (a set of plant basic features, postulated initiating events at several different frequencies of occurrence with a set of respective acceptance criteria for the process variables of main interest, and a set of plant safety features, inherent or engineered).

Finland has a long and successful track record in developing innovative safety requirements. This history starts from the construction of the Loviisa power plant in the 70’s. The original proposed design of Loviisa was modified before and during construction to meet the then state-of-the-art Western safety criteria, and many of these modifications were carried over into the subsequent plants built by the same vendor elsewhere. In the 80’s, coping with severe accidents became a central new topic in Finnish requirements. In the decision-in-principle process of early 90’s vendors had much difficulty in meeting these criteria; and shortly afterwards, in mid-90’s, new LWR designs were proposed in Europe that incorporated specific design features to address severe accidents. In the early 2000’s, external threats due to malevolence became prominent in turn, and the Olkiluoto 3 design was heavily influenced by Finnish requirement to withstand an intentional crash by a large passenger aircraft. Design features developed for Olkiluoto 3 are being adopted in other EPR projects in Europe.

Likewise, Finnish safety research has been on the cutting edge in central areas such as multidimensional reactor dynamics (alone and coupled to whole circuit thermal-hydraulic models), boron dilution, utilization of computational fluid dynamics methods (CFD), and response to operational experiences (emergency core cooling system recirculation filter clogging problem, which was identified by accident in Barsebäck in 1992 and which was resolved in Finland by determined experimental effort in 1992–1994; the problem is still worked on in several large countries such as the U.S.). Finnish computer codes have sold well, considering the size of the market. Scientific advances originating from Finland have generated prestige and respect far beyond what would be warranted by the size of the country. Such factors affect the behaviour of prospective vendors and help Finnish stakeholders to operate on the tough international markets.

1.3.5 Sustainable development in nuclear energy production

Sustainability is the ability to meet the needs of the present generation while enhancing the ability of future generations to meet society’s needs indefinitely into the future, as was described in the famous Brundtland Report [12]. In the GIF roadmap, sustainability goals are defined with focus on waste management and resource utilization. Other factors that are commonly associated with sustainability, such as economics and environment are considered separately in the technology roadmap to stress their importance. The evaluation and selection methodology applied in GIF is described in the Generation IV roadmap [1]. The approach to sustainability as applied in INPRO is described in Figure 4. The Michelangelo network for competitiveness and sustainability of nuclear energy in the European Union (MICANET) has also worked on the concept of sustainability; an adaptation of that scheme is shown in Figure 5.

Sustainable development is usually examined from three points of view: economic, environmental, and social. The NEA has described it in connection to nuclear energy in the following way (http://www.nea.fr/html/sd/welcome.html):

The analysis of nuclear energy characteristics within a sustainable development framework shows that the approach adopted within the nuclear energy sector is generally consistent with the fundamental sustainable development goal of passing on a range of assets to future generations while minimizing environmental impacts and burdens.

While existing nuclear power plants are economically competitive in most cases and perform well in deregulated electricity markets, the economic competitiveness of new nuclear power plants will remain an issue due to their high capital cost. However, nuclear power has already internalized a large part of its external costs, such as the decommissioning of the plant at the end of its life and the management and disposal of the radioactive waste produced. Such a claim cannot be made by fossil fuel technologies, all of which emit waste to the environment.

In OECD countries, nuclear energy in normal operation has a low impact on health and the environment, but in order to make a continuing contribution to sustainable development goals, nuclear energy will have to maintain its high standards of safety in spite of increasing competition in the electricity sector, ageing reactors, and the expansion of the industry to new countries and regions.

In order to meet sustainable development goals, nuclear energy will have to achieve a higher level of social acceptance than it enjoys in many countries today. The role of governments is to allow the public to put social, ethical and political issues related to nuclear energy into perspective with the issues raised by alternatives, in order to create the conditions for decision-making processes consistent with the goals of sustainable development.

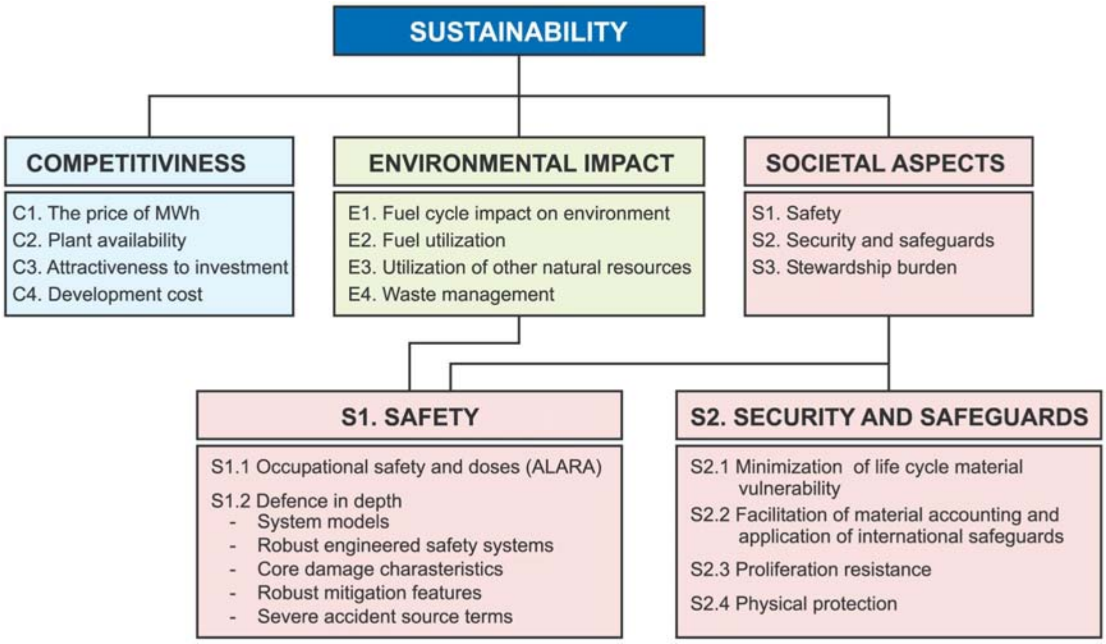


Figure 5. The criteria for the selection of nuclear technologies; adapted from the MICANET draft report [7].

1.3.6 Fuel Cycles and Sustainability

The key issue of the energy sector is the development of carbon-free or low-carbon energy technologies. In that respect already the present nuclear energy technology has a vital role. However, the long-term significance of nuclear energy in the greenhouse gas emission mitigation will greatly increase via the introduction of sustainable nuclear energy technologies (ie. closed fuel cycle and more efficient use of uranium and thorium resources by the introduction of fast reactors and Partitioning & Transmutation (P&T) -technologies to minimize the amounts, heat loads and potential toxicity of high-level nuclear wastes requiring deep geological disposal.

In the long term, the potential of nuclear power is dependent upon the available uranium resources. Reserve estimates of the uranium resource vary with assumptions for its use (Fig. 6). Used in conventional light water reactors (LWR) the identified resources of 4.7 Mt uranium, at prices up to US$130/kg, correspond to about 2400 EJ of primary energy and should be sufficient for about 100 years supply (OECD, 2006a [10]) at the 2004 level of consumption. The total conventional proven (identified) and probable (yet undiscovered) uranium resources are about 14.8 Mt (7400 EJ). There are also unconventional uranium resources such as those contained in phosphate minerals, which are recoverable for between US$ 60–100/kg (OECD, 2004 [8]).

If used in present reactor designs with a “once-through” fuel cycle, only a small percentage of the energy content is utilized from the fissile isotope U-235 (0.7% in natural uranium). With fast reactors operated in a “closed” fuel cycle by reprocessing the spent fuel and extracting the un-utilized uranium and plutonium produced, the reserves of natural uranium may be extended to several thousand years at current consumption levels, and centuries at higher levels of use. In the first recycle technology option fast reactors utilize depleted uranium and only plutonium is recycled so that the uranium resource efficiency is increased by a factor of 30 (OECD, 2001 [9]). Thereby the estimated enhanced resource availability of total conventional uranium resources corresponds to about 220 000 EJ primary energy. If advanced breeder reactors could be designed to very efficiently utilize recycled or depleted uranium and all actinides (second recycle option), then the resource utilization efficiency would be further improved by an additional factor of eight (OECD, 2006b [11]).

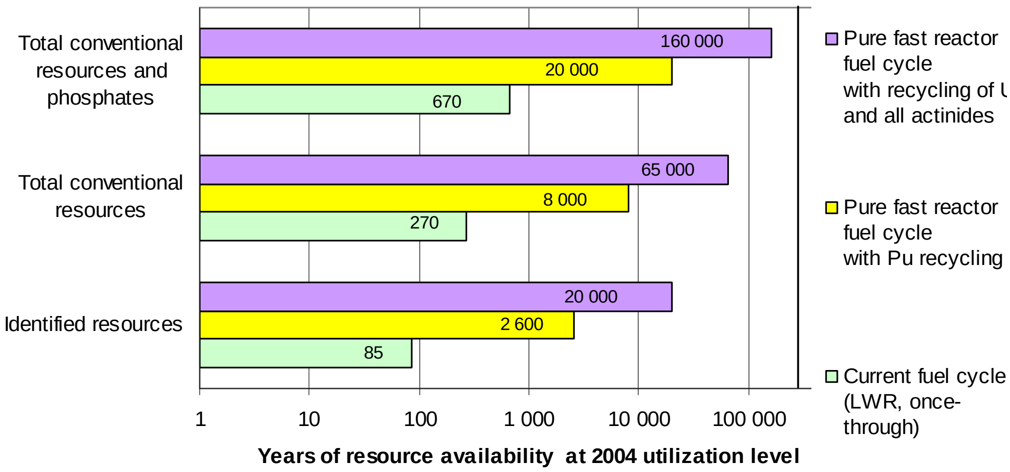


Figure 6. Years of resource availability for various nuclear technologies [11]. In 2005 the nuclear power production was 2626 TWh (29 EJ primary energy). Used in typical light water reactors the known conventional resources of 4.6 MtU correspond to about 24 000 GW(e)-years or 2400 EJ primary energy and the total conventional resources of 14.8 MtU to about 7400 EJ or 75 000 GW(e)-years.

Nuclear fuels could also be based on thorium, the proven and probable resources (OECD, 2004 [8]) being about 4.5 Mt. Thorium-based fast reactors appear capable of at least doubling the effective resource base, but the technology remains undeveloped. However, except in India (with large resources of thorium), there are not yet sufficient commercial incentives for thorium-based fuel cycle, which produces fissionable U233. Benefits of using thorium include the intrinsic proliferation resistance of thorium fuel cycle due to the presence of U232 and its strong gamma emitting daughter products. Technological development is still needed to ascertain the commercial feasibility [4].

The Generation IV roadmap concluded about the waste generation and resource use of the once-through cycle that while this fuel cycle option is the most uranium resource intensive and generates the most waste in the form of spent nuclear fuel, the amounts of waste produced are small compared to other energy technologies. In addition, the existing known and speculative economic uranium resources are sufficient to support a once-through cycle at least until mid-century. They found that the limiting factor facing an essential role for nuclear energy with the once-through cycle is the availability of repository space worldwide [see Figure 7, top]. This becomes an important issue, requiring new repository development in only a few decades (e.g., a typical repository is of the order of 100 000 tonne capacity). In the longer term, beyond 50 years, uranium resource availability also becomes a limiting factor [see Figure 7, bottom] unless breakthroughs occur in mining or extraction technologies.

Systems that employ a fully closed fuel cycle hold the promise to reduce repository space and performance requirements, although their costs must be held to acceptable levels. Closed fuel cycles permit partitioning the nuclear waste and management of each fraction with the best strategy. Advanced waste management strategies include the transmutation of selected nuclides, cost effective decay-heat management, flexible interim storage and customized waste forms for specific geologic repository environments. These strategies hold the promise to reduce the long-lived radiotoxicity of waste destined for deep geological repositories by at least an order of magnitude. This is accomplished by recovering most of the heavy long-lived radioactive elements. These reductions and the ability to optimally condition the residual wastes and manage their heat loads permit far more efficient use of limited repository capacity and enhance the overall safety of the final disposal of radioactive wastes.

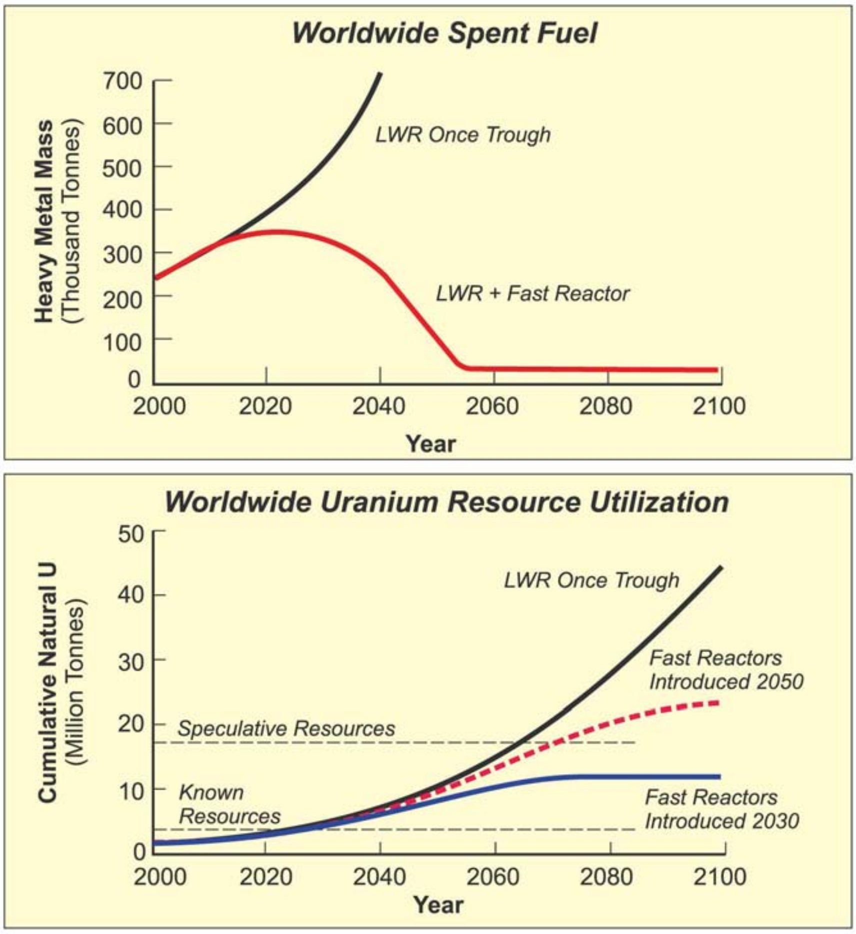


Figure 7. Worldwide spent fuel and uranium resource utilization estimates [1].

2. Feasibility and status of Gen IV

The Generation IV technology roadmap was produced at the end of 2002 in the "Generation IV International Forum", or GIF, by over one hundred international experts in over two years thorough evaluation of all possible future nuclear technology concepts. This document identified six system concepts that are seen as the most promising for the development of a next generation of nuclear reactors that represent substantial progress from the point of view of safety, reliability, cost, sustainability and non-proliferation.

2.1 Generation IV development

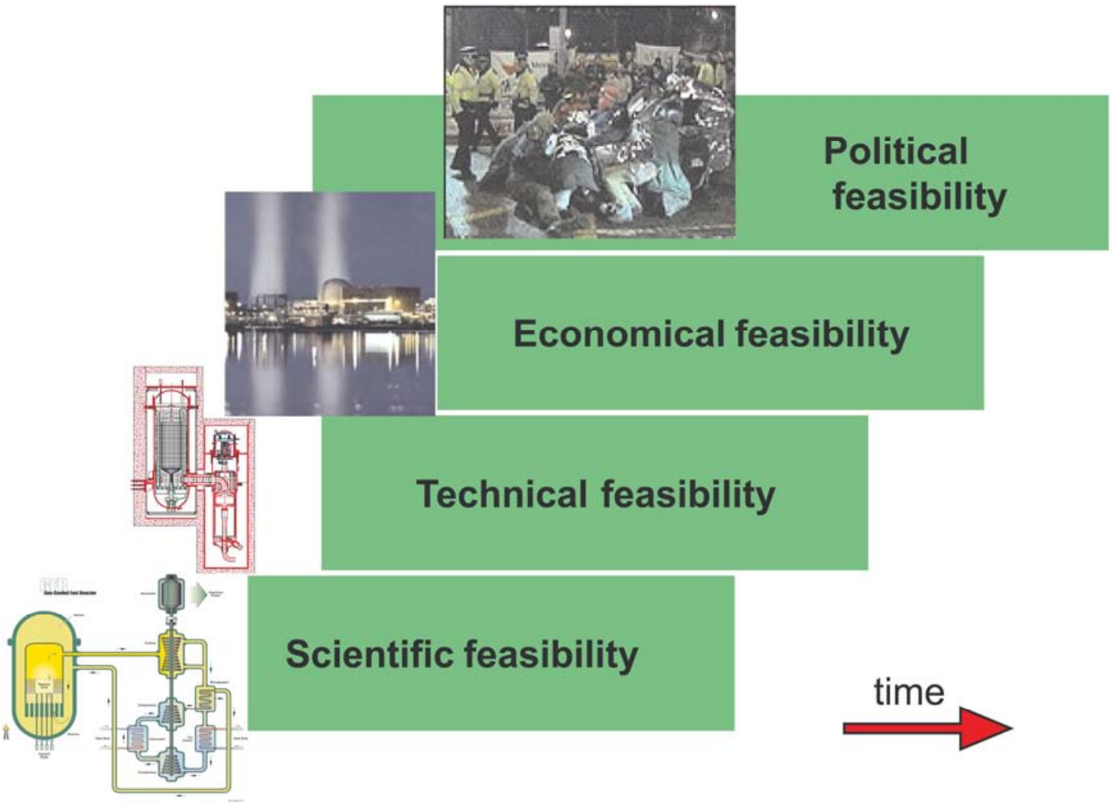


Figure 8. Evolution of the feasibility of Generation IV nuclear reactor concepts.

The scientific feasibility of the Generation IV concepts has already been achieved. Now the technical, economical and political feasibilities are studied in parallel. From the Finnish point of view the political and economical feasibility of the Gen IV will be based on the national energy strategy.

2.2 The six Generation IV nuclear reactor systems

The six Generation IV nuclear reactor systems are described in the GIF roadmap [1] as follows.

Table 1. GIF reactor systems and their main features [1].

System	**Neutron Spectrum**	**Fuel Cycle**	**Size**	**Applications**
Very High Temp.Gas Reactor (VHTR)	*Thermal*	*Open*	*Medium*	*Electricity, hydrogen production, process heat*
Supercritical Water Reactor (SCWR)	*Thermal*	*Open, Closed*	*Large*	*Electricity*
Gas-Cooled Fast Reactor (GFR)	*Fast*	*Closed*	*Medium to Large*	*Electricity, hydrogen, actinide management*
Lead-alloy Cooled Fast Reactor (LFR)	*Fast*	*Closed*	*Large to Small*	*Electricity, hydrogen production, actinide management*
Sodium Cooled Fast Reactor (SFR)	*Fast*	*Closed*	*Medium to Large*	*Electricity, actinide management*
Molten Salt Reactor(MSR)	*Thermal*	*Closed*	*Large*	*Electricity, hydrogen, actinide management*

2.2.1 VHTR – Very-High-Temperature Reactor System

The Very-High-Temperature Reactor (VHTR) system uses a thermal neutron spectrum and a once-through uranium cycle. The VHTR system is primarily aimed at relatively fast deployment of a system for high temperature process heat applications, such as coal gasification and thermochemical hydrogen production, with superior efficiency. The reference reactor concept has a 600-MWth helium cooled core based on either the prismatic block fuel of the Gas Turbine-Modular Helium Reactor (GT-MHR) or the pebble fuel of the Pebble Bed Modular Reactor (PBMR). The primary circuit is connected to a steam reformer/steam generator to deliver process heat. The VHTR system has coolant outlet temperatures above 1000°C. It is intended to be a high-efficiency system that can supply process heat to a broad spectrum of high temperature and energy-intensive, nonelectric processes. The system may incorporate electricity generation equipment to meet cogeneration needs; direct Brayton cycle with helium coolant driven turbine in the primary loop and indirect cycle conversion are under assessment. The system also has the flexibility to adopt U/Pu/Th fuel cycles and offer enhanced waste minimization. The VHTR requires significant advances in fuel performance and high temperature materials, but could benefit from many of the developments proposed for earlier prismatic or pebble bed gas-cooled reactors. Additional technology R&D for the VHTR includes high-temperature alloys, fiber-reinforced ceramics or composite materials, and zirconium-carbide fuel coatings.

The VHTR system is highly ranked in economics because of its high hydrogen production efficiency, and in safety and reliability because of the inherent safety features of the fuel and reactor. It is rated good in proliferation resistance and physical protection, and neutral in sustainability because of its open fuel cycle. It is primarily envisioned for missions in hydrogen production and other process-heat applications, although it could produce electricity as well. The VHTR system is the nearest-term hydrogen production system, estimated to be deployable by 2020.

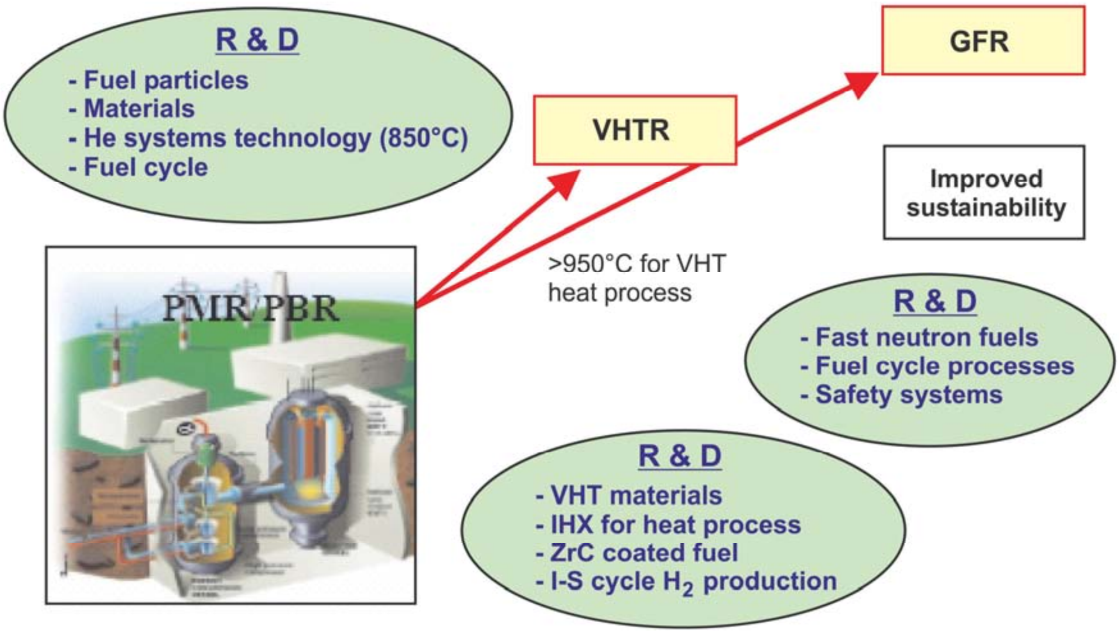


Figure 9. Evolution of the gas cooled reactor concept.

2.2.2 SCWR – Supercritical-Water-Cooled Reactor System

The Supercritical-Water-Cooled Reactor (SCWR) system features two fuel cycle options: the first is an open cycle with a thermal neutron spectrum reactor; the second is a closed cycle with a fast-neutron spectrum reactor and full actinide recycle. Both options use a high-temperature, high-pressure, water-cooled reactor that operates above the thermodynamic critical point of water (22.1 MPa, 374°C) to achieve a thermal efficiency approaching 44%. The fuel cycle for the thermal option is a once-through uranium cycle. The fast-spectrum option uses central fuel cycle facilities based on advanced aqueous processing for actinide recycle. The fast-spectrum option depends upon the materials' R&D success to support a fast-spectrum reactor. In either option, the reference plant has a 1700-MWe power level, an operating pressure of 25 MPa, and a reactor outlet temperature of 550°C. Passive safety features similar to those of the simplified boiling water reactor are incorporated. Owing to the low density of supercritical water, additional moderator is added to thermalize the core in the thermal option. The balance-of-plant is considerably simplified because the coolant does not change phase in the reactor.

The SCWR system is highly ranked in economics because of the high thermal efficiency and plant simplification. If the fast-spectrum option can be developed, the SCWR system will also be highly ranked in sustainability. The SCWR is rated good in safety, and in proliferation resistance and physical protection. The SCWR system is primarily envisioned for missions in electricity production, with an option for actinide management. Given its R&D needs in materials compatibility, the SCWR system is estimated to be deployable by 2025.

2.2.3 GFR – Gas-Cooled Fast Reactor System

The Gas-Cooled Fast Reactor (GFR) system features a fast-neutron spectrum and closed fuel cycle for efficient conversion of fertile uranium and management of actinides. A full actinide recycle fuel cycle with on-site fuel cycle facilities is envisioned. The fuel cycle facilities can minimize transportation of nuclear materials and will be based on either advanced aqueous, pyrometallurgical, or other dry processing options. The reference reactor is a 600-MWth/288-MWe, helium-cooled system operating with an outlet temperature of 850°C using a direct Brayton cycle gas turbine for high thermal efficiency. Several fuel forms are being considered for their potential to operate at very high temperatures and to ensure an excellent retention of fission products: composite ceramic fuel, advanced fuel particles, or ceramic clad elements of actinide compounds. Core configurations are being considered based on pin- or plate-based fuel assemblies or prismatic blocks.

The GFR system is top-ranked in sustainability because of its closed fuel cycle and excellent performance in actinide management. It is rated good in safety, economics, and in proliferation resistance and physical protection. It is primarily envisioned for missions in electricity production and actinide management, although it may be able to also support hydrogen production. Given its R&D needs for fuel and recycling technology development, the GFR is estimated to be deployable by 2025.

2.2.4 LFR – Lead-Cooled Fast Reactor System

The Lead-Cooled Fast Reactor (LFR) system features a fast-neutron spectrum and a closed fuel cycle for efficient conversion of fertile uranium and management of actinides. A full actinide recycle fuel cycle with central or regional fuel cycle facilities is envisioned. The system uses a lead or lead/bismuth eutectic liquid-metal cooled reactor. Options include a range of plant ratings, including a battery of 50–150 MWe that features a very long refueling interval, a modular system rated at 300–400 MWe, and a large monolithic plant option at 1200 MWe. The term battery refers to the long-life, factory fabricated core, not to any provision for electrochemical energy conversion. The fuel is metal or nitride-based, containing fertile uranium and transuranics. The most advanced of these is the Pb/Bi battery, which employs a small size core with a very long (10–30 year) core life. The reactor module is designed to be factory-fabricated and then transported to the plant site. The reactor is cooled by natural convection and sized between 120–400 MWth, with a reactor outlet coolant temperature of 550°C, possibly ranging up to 800°C, depending upon the success of the materials R&D. The system is specifically designed for distributed generation of electricity and other energy products, including hydrogen and potable water.

The LFR system is top-ranked in sustainability because a closed fuel cycle is used, and in proliferation resistance and physical protection because it employs a long-life core. It is rated good in safety and economics. The safety is enhanced by the choice of a relatively inert coolant. It is primarily envisioned for missions in electricity and hydrogen production and actinide management with good proliferation resistance. Given its R&D needs for fuel, materials, and corrosion control, the LFR system is estimated to be deployable by 2025.

2.2.5 SFR – Sodium-Cooled Fast Reactor System

The Sodium-Cooled Fast Reactor (SFR) system features a fast-neutron spectrum and a closed fuel cycle for efficient conversion of fertile uranium and management of actinides. A full actinide recycle fuel cycle is envisioned with two major options: One is an intermediate size (150 to 500 MWe) sodium-cooled reactor with a uranium-plutonium-minor-actinide-zirconium metal alloy fuel, supported by a fuel cycle based on pyrometallurgical processing in collocated facilities. The second is a medium to large (500 to 1500 MWe) sodium-cooled fast reactor with mixed uranium-plutonium oxide fuel, supported by a fuel cycle based upon advanced aqueous processing at a central location serving a number of reactors. The outlet temperature is approximately 550°C for both. The primary focus of the R&D is on the recycle technology, economics of the overall system, assurance of passive safety, and accommodation of bounding events.

The SFR system is top-ranked in sustainability because of its closed fuel cycle and excellent potential for actinide management, including resource extension. It is rated good in safety, economics, and proliferation resistance and physical protection. It is primarily envisioned for missions in electricity production and actinide management. The SFR system is the nearest term actinide management system. Based on the experience with oxide fuel, this option is estimated to be deployable by 2015.

2.2.6 MSR – Molten Salt Reactor System

The Molten Salt Reactor (MSR) system features an epithermal to thermal neutron spectrum and a closed fuel cycle tailored to the efficient utilization of plutonium and minor actinides. A full actinide recycle fuel cycle is envisioned. In the MSR system, the fuel is a circulating liquid mixture of sodium, zirconium, and uranium fluorides. The molten salt fuel flows through graphite core channels, producing a thermal spectrum. The heat generated in the molten salt is transferred to a secondary coolant system through an intermediate heat exchanger, and then through another heat exchanger to the power conversion system. Actinides and most fission products form fluorides in the liquid coolant. The homogenous liquid fuel allows addition of actinide feeds with variable composition by varying the rate of feed addition. There is no need for fuel fabrication. The reference plant has a power level of 1000 MWe. The system operates at low pressure (< 0.5 MPa) and has a coolant outlet temperature above 700°C, affording improved thermal efficiency.

The MSR system is top-ranked in sustainability because of its closed fuel cycle and excellent performance in waste burndown. It is rated good in safety, and in proliferation resistance and physical protection, and it is rated neutral in economics because of its large number of subsystems. It is primarily envisioned for missions in electricity production and waste burndown. Given its R&D needs for system development, the MSR is estimated to be deployable by 2025.

2.3 R&D Programmes for Individual Generation IV Systems

The Generation IV Roadmap facilitates the assembly of larger R&D programmes or smaller projects on which the GIF countries choose to collaborate. Entire programmes consist of all or most of the R&D needed to advance a system. Individual country projects consist of R&D on specific technologies (either system-specific or crosscutting) or on subsystems that are needed for a Generation IV system. In either case, the programme or project is focused on key technology issues and milestones. Major milestones and development needs have been identified for the collective R&D

activities. Table 2 gives the objectives and endpoint products of the R&D. The R&D activities in the Generation IV Programme Plan have been defined to support the achievement of these endpoints.

Table 2. Generation IV Objectives & Endpoints: Viability Phase.

Viability Phase Objective:
Basic concepts, technologies and processes are proven out under relevant conditions, with all potential technical *show-stoppers* identified and resolved.
Viability Phase Endpoints:
1. Preconceptual design of the entire system, with nominal interface requirements between subsystems and established pathways for disposal of all waste streams 2. Basic fuel cycle and energy conversion (if applicable) process flowsheets established through testing at appropriate scale 3. Cost analysis based on preconceptual design 4. Simplified PRA for the system 5. Definition of analytical tools 6. Preconceptual design and analysis of safety features 7. Simplified preliminary environmental impact statement for the system 8. Preliminary safeguards and physical protection strategy 9. Consultation(s) with regulatory agency on safety approach and framework issues

Table 3. Generation IV Objectives & Endpoints: Performance Phase.

Performance Phase Objective:
Engineering-scale processes, phenomena, and materials capabilities are verified and optimized under prototypical conditions
Performance Phase Endpoints:
1. Conceptual design of the entire system, sufficient for procurement specifications for construction of a prototype or demonstration plant, and with validated acceptability of disposal of all waste streams 2. Processes validated at scale sufficient for demonstration plant 3. Detailed cost evaluation for the system 4. PRA for the system 5. Validation of analytical tools 6. Demonstration of safety features through testing, analysis, or relevant experience 7. Environmental impact statement for the system 8. Safeguards and physical protection strategy for system, including cost estimate for extrinsic features 9. Pre-application meeting(s) with regulatory agency

The viability phase R&D activities examine the feasibility of key technologies. Examples of these include adequate corrosion resistance in materials in contact with lead alloys or supercritical water, fission product retention at high temperature for particle fuel in the very high-temperature, gas-cooled reactor, and acceptably high recovery fractions for actinides for systems employing actinide recycle. Periodic evaluations of the system progress relative to its goals will determine if system development is to continue.

The performance phase R&D activities undertake the development of performance data and optimization of the system (Table 3). Although general milestones were shown in the Generation IV Roadmap, specific milestones and dates will be defined based on the viability phase experience. As in the viability phase, periodic evaluations of the system progress relative to its goals will determine if the system development is to continue. The viability and performance phases will likely overlap because some of the performance R&D activities may have long lead times that require their initiation as early as possible.

Assuming the successful completion of viability and performance R&D, a demonstration phase of at least six years is anticipated for any system, requiring funding of several billion euros. This phase involves the licensing, construction, and operation of a prototype or demonstration system in partnership with industry. The detailed design and licensing of the system will be performed during this phase.

2.4 The role of Gen IV in relation to Gen III/III+ and high efficiency advanced combustion technologies

The nuclear power plant (NPP) concepts being ready for construction today are of type Gen III or Gen III+. However, the life span of the new Olkiluoto 3 EPR unit is expected to be so long that it will coexist with the more advanced fission reactors, even with fusion reactors as presented in Figure 10. This situation must be adopted and exploited in general education and R&D for the common advantage of all the various NPP species.

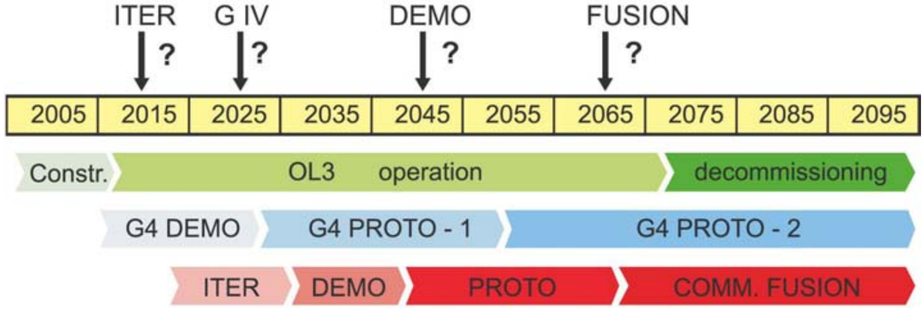


Figure 10. During the life time of the Finnish NPP unit OL3 completely new types of nuclear reactors will emerge. The actual timing is, of course, only indicative.

The technical potential of Gen IV in power generation will be shown in a time span of 15 to 20 years as the first plants should be demonstrated. The development of Gen IV technology is revolutionary in many respects and innovative steps in plant and system features will be taken. Many basic processes seem to be fundamentally different from the NPPs in commercial use today (Gen II–III), involving, for example, new types of moderator and coolant materials and neutron energy spectra ranging from thermal to fast. Some concepts also involve continuous fuel handling, or other features that may create novel safety challenges. However, the reactor physics and thermal hydraulics methodologies and basic data needs for performance and safety analysis are in principle the same, and the increasing know-how and ability to manage these questions for either generation of reactors are largely mutually exploitable. The material performance data and models need to be upgraded and demonstrated for the more demanding operating conditions. Also the principal safety requirements are the same. The criticality safety and dynamic reactivity behaviour must be in control in all situations and similar calculation methods are to be used. The safety systems will further include the shutdown systems, active and passive emergency cooling in most concepts as well as containment action. Radiation safety remains important. The development of new evolutionary or innovative safety systems for Gen IV concepts may also be utilized for the existing plants.

The increase of plant efficiency, mainly through higher operation temperatures, from the level of present Gen II/III+ plants to the targeted level of Gen IV means substantial R&D work in all aspects. This R&D work is, however, not fully Generation IV specific and it can be benefited in a shorter term to other power plant concepts. These benefits are mainly related to the materials engineering and performance studies.

In order to raise the plant efficiency, the increase of temperature of the heat transfer medium or the pressure or both of these are required. Both gas (He) and supercritical water (H_2O) fluid have been suggested in Gen IV. The entire pressure vessel, fuel assemblies and further external piping and turbines need to be designed for the enhanced process parameters (service parameters). These solutions that are relevant for the SCWR concept have been already demonstrated in commercial fossil fuel power plants that operate with a supercritical water circuit (around 250 bars and 565–590°C). The SC FFP concept is utilized in most modern boilers and a circulated fluidized bed boiler is developed in Finland. Therefore, it is assumed that the SCWR concept is the next step for the present LWRs. The VHTR reactors aim at a more specific design that is not directly derived from the present plants, therefore this concept is anticipated to need a longer term R&D compared to SCWR.

This means that for the Gen IV SCWR concept it is practically no need for the R&D of external (ex-vessel) components. However, the effects of high T, pressure, SC-water chemistry and irradiation and the pressure transients from the loading are not known enough to design the in-vessel parts. Moreover, the knowledge, data and material models (including the experimental means for these) of the combined effects are not available, although groups in the EU, Japan and USA are preparing for the laboratory facilities for this.

If innovative materials or procedures are developed in Gen IV forum (all concepts) these can be directly used in novel FFP SC-plants with a very high efficiency (CPH) and a possibility to zero emission oxyfuelling process in the future. The oxyfuelling process offers CO_2-capture possibilities but it is expected to promote the corrosion of piping from the present FFPs as it is the case in Gen IV as well.

Utilities operating nuclear reactors are dependent on the services available on international markets. In case there is a technological shift away from the LWRs while Olkiluoto 3 is operational, Finland must be ready to either invest correspondingly more to the maintenance of adequate domestic competence in LWR technology and safety, or prepare to decommission the plant prematurely.

2.5 The role of Gen IV in relation to fusion

In a long-term perspective, future power systems, nuclear fission and fusion reactors represent two evolution lines which have, on one hand, clearly different development stages and, on the other hand, much synergy of technology. Finally, these lines may separate ending up to competing energy markets, but they could also coalesce into viable fission-fusion hybrid reactors or into a symbiosis of a network of fission and fusion reactor networks. In hybrid reactors, the production of fusion neutrons would be utilized either directly as an external source for a sub-critical fission reactor core, or indirectly by producing fissile fuel. Presently, it is not timely to exclude any of the alternative paths. As a matter of fact, it is necessary to maximize collaboration between all nuclear sectors with general platforms and with various crosscutting research projects.

The first true fusion reactor, ITER will have a thermal power of about 500 MW and is aimed at demonstrating the technological feasibility of tokamaks. ITER is a full-size nuclear installation which will be licensed according to present strict safety regulations. The construction of ITER has been decided and the first plasma is expected to occur in circa 2015. None of the large prototypes of Generation IV candidates are expected any sooner although their final commercialization is anticipated much before that of fusion. The gap between the evolution phases and general attitudes are narrowing in fusion and fission.

Fusion power plants are predicted to produce base electricity with a cost being dominated by capital investments – maintenance costs might be considerable, if the first-wall components have to be changed frequently. The NPP unit size would be in the range of 1000–2000 MWe. A smaller unit would probably be too inexpensive and a bigger one be hampered by first-wall life-time problems. In principle, fusion energy could also be used for hydrogen production or generation of process heat.

Both fusion and fission sectors involve basic nuclear engineering which is needed for recruiting new professionals from commercial NPPs to basic nuclear research projects. Fusion, like Generation IV, demands attractive training, education, and R&D challenges and benefits, in general, transfer of new technology and spin offs. Procurement of ITER for superconductors, remote handling and material components are examples where industry may be interested in.

All the alternative nuclear reactors must cope with the requirements of safety and economy under possible strong and abrupt changes of the local and global conditions. Fusion and Generation IV will be facing analogous, but perhaps not one-to-one uncertainties. Fusion has an insurmountable potential for safety and sustainability. Of course, a huge amount of R&D and drastic innovations are still needed to improve its commercial feasibility. In current conceptual power plant studies of fusion, their attractiveness has increased thanks to several cross-fertilized ideas from Gen IV reactors. Fusion plant efficiency can be enhanced by the plasma performance and by the thermal cycle. Helium and LiPb have been proposed as cooling and breeding substances. High-temperature, radiation resistant materials have to be developed for both advanced fusion and fission reactors. Fusion and fission share a large number of common technologies which can be exploited for their further development: Availability of fusion plants in excess of 70–75% call for sophisticated remote handling tools having applications in many other nuclear radiation facilities. Another example is provided by the use of fission reactor safety codes for fusion reactors, which activity has the advantages of training purposes and to extension of the code validation. Also the management of activated waste and decommissioning questions are common.

Presently, Euratom R&D on fusion research has many features that Generation IV could copy. The fusion platform extends comprehensively R&D, reasonable funding has been succeeded, and excellent training and education opportunities exist. The efficiency of running the ITER-project remains to be seen.

2.6 Applications of process heat and hydrogen production

A nuclear reactor capable of producing both electricity and high-temperature heat would open additional industrial applications (see Figure 11), including the possibility of producing very efficiently industrial quantities of hydrogen based on the development of high temperature electrolysis or thermo-chemical decomposition of water (see Figure 12).

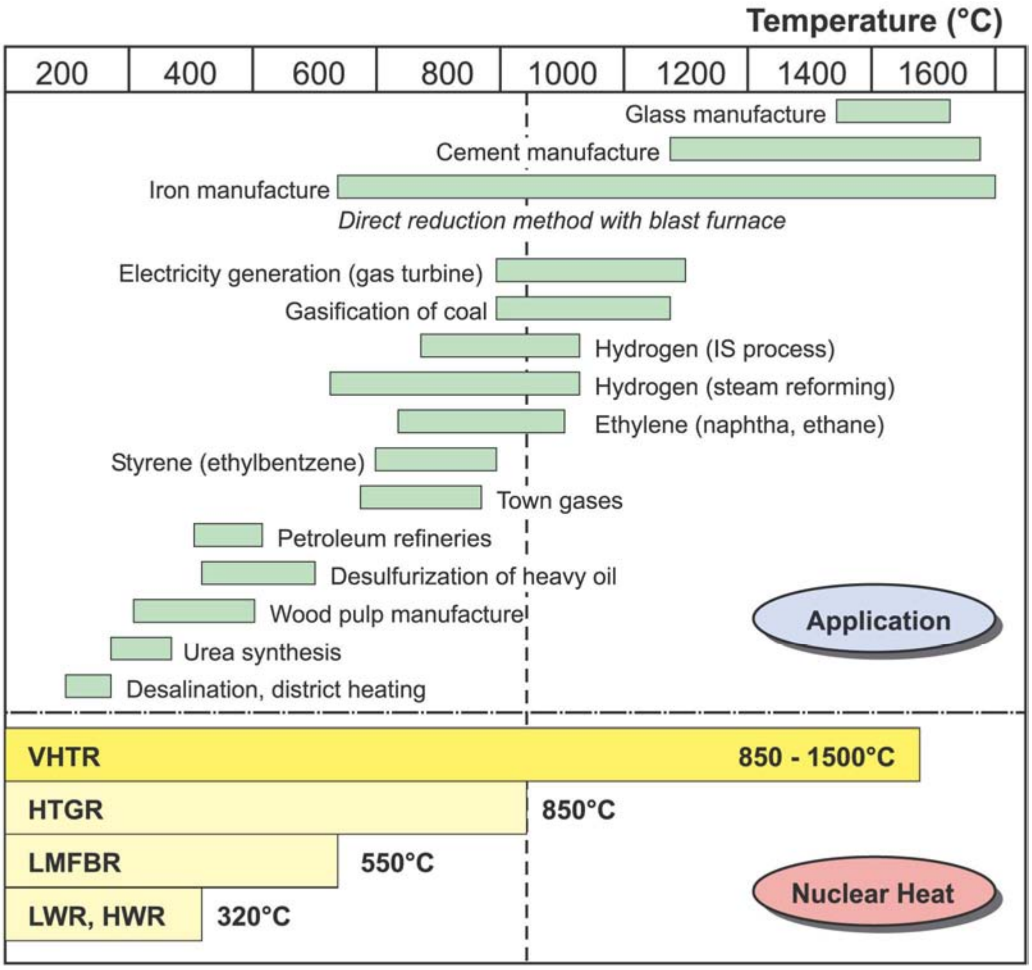


Figure 11. Process heat ranges for various industrial applications in comparison to temperatures in the different nuclear power systems. The temperature of SCWR concept is between HTGR and LMFBR.

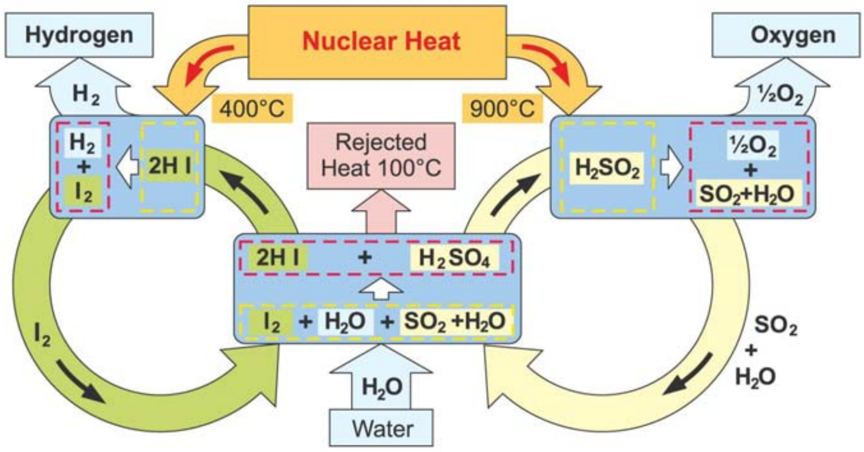


Figure 12. Nuclear energy is one of only a limited range of energy sources that can be used for the large-scale production of hydrogen while also reducing greenhouse gases.

2.6.1 Finland and hydrogen economy – potential of nuclear energy

In the scenarios for future energy economies for EU, Japan and USA hydrogen has been nominated as the second carrier of energy parallel to electricity. Hydrogen has special advantages when used as a traffic fuel. Hydrogen has been very much a political choice as it can be produced by several means and it is clean to use. Hydrogen can also be stored. Wide spread use of hydrogen as fuel requires use of fuel cells that convert hydrogen directly into electricity.

Hydrogen has the ability to act as an energy carrier in both stationary and transport applications, but particularly in the latter sector, where it offers the potential to transition from the world's current reliance on fossil fuels to increased contributions from renewable energy sources. Today in the world 50 million tons of hydrogen are produced annually, half of that by steam reformation and mainly from natural gas. In the medium- to long-term we can anticipate a general shift away from processes that emit CO_2 to the atmosphere. Future options may include CO_2-neutral paths such as hydrogen from fossil fuels with CO_2 capture, electrolysis of water using renewable electricity or nuclear energy, biomass gasification and even more long-term developments such as photochemical/biological or high temperature nuclear thermocycle pathways. An attempt to capture the technological and market readiness of these options in Figure 13.

Until now in the Finnish research work for a roadmap for hydrogen economy [13] the emphasis has been distributed energy generation and production of hydrogen containing fuel from biomass and recently also using wind power. In that roadmap it is concluded that the hydrogen and fuel cell technologies will be a growing market with large economical significance already in the 2010's.

The situation when hydrogen will be one of the main carriers of energy (hydrogen economy) will require hydrogen production in Finland for economy and for reliability of supply. Then nuclear energy might be a viable option for that also in Finland.

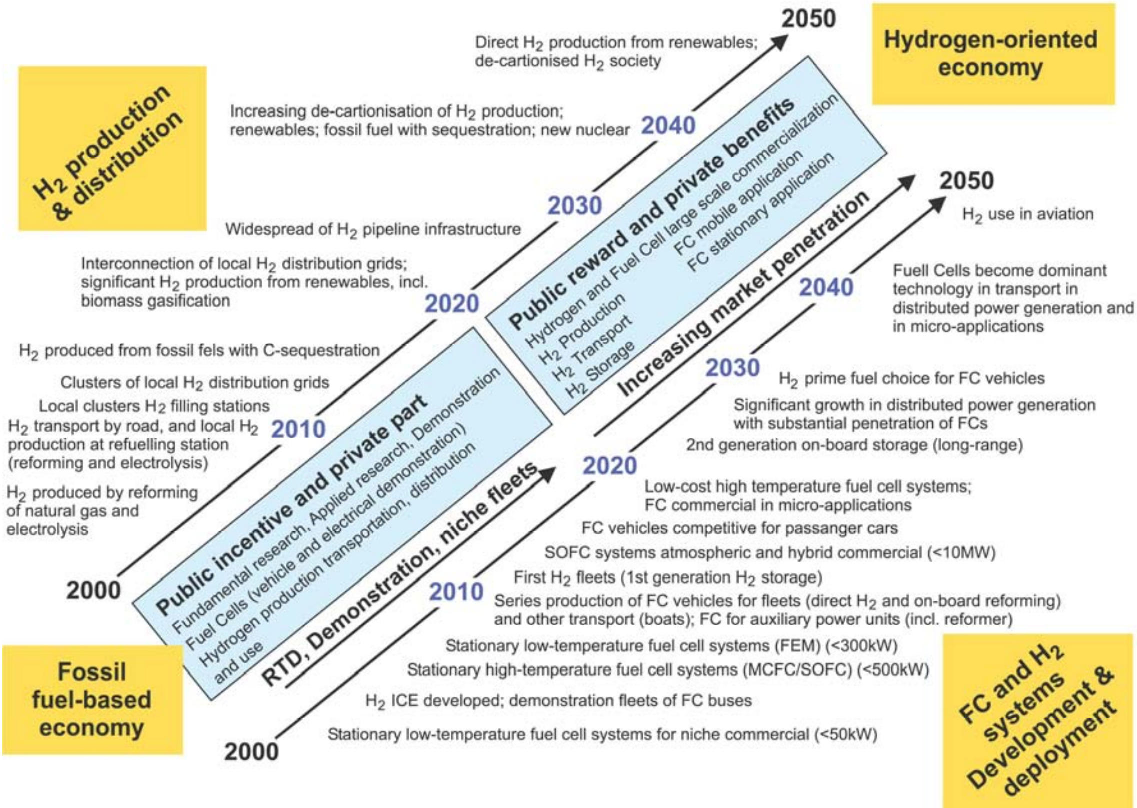


Figure 13. The European Hydrogen Economy vision [15].

3. Vision for Finnish research network for Gen IV

The vision for the Finnish research network for Generation IV is:

The Finnish actors have achieved a significant role in performing and directing scientific research and technological development for Gen IV concepts in the global forums. During the conceptual and design phases for the Gen IV demonstration plants they have actively influenced on the decisions on technological options. Finnish stakeholders have enabled indispensable and effective exploitation of the technology, and have further improved the competitiveness and development of the Finnish industry.

4. Mission – Finnish scope of activities

The main mission of the Finnish Generation IV research network is to improve scientific and technological expertise in the field of nuclear energy technologies and related processes through collaboration with GIF and other global forums. The longer term mission is to create new business activities for the Finnish industry through enhanced technology transfer, innovative process development, and materials engineering.

4.1 The scope of Finnish activities

The Finnish GEN4FIN research network will guide the strategies of the participating Finnish institutes in relation to the Generation IV issues and participation in the EU collaborations.

The participation of Finland in the development of Generation IV requires:

- increase in know-how and collaboration in different organizations: the state administration, the regulatory bodies, research and education institutes, the utility companies and other industry
- ability to integrate different disciplines and to promote innovations from science
- ability to create and participate networks in research and engineering applications
- ability to supply significant engineering expertise and products to Gen IV concepts and pilot plants
- a wider awareness in the whole society of the nuclear process possibilities for the future sustainable energy systems (mass media, politicians, citizens).

These requirements should be reflected to the SWOT for the Finnish Gen IV research network, Appendix 4. The main factors influencing the operational environment are presented in the PESTE analysis in Appendix 5.

The activities in the research network will cover scientific, technological and industrial goals. The roles of organizations participating in the research network are discussed in the following sections. These organizations are research & education, safety authority, manufacturing industry and power companies as well as ministries and other associated organizations.

4.1.1 Role of the associated organizations

The state administration will establish the research network and set the timeframes and goals. The regulatory bodies and the utility companies and other industry will participate to the board of the research network directing and commenting the research.

The role of Ministries, Tekes and Academy of Finland in management of long term nuclear knowledge in Finland should be clarified. Specific areas and interests in this research network will be sought.

4.1.2 Role of education

The nuclear renaissance in Finland has quickly turned the situation from a stagnated business-as-usual scenario into task force actions to solve the acute need of new professionals. The problem of replacement of retirees, of course, has persisted and calls for long term solutions. The positive atmosphere has increased the interest of students in nuclear education, but one has to recall that, on average, it takes a minimum of 5–10 years to educate freshmen into young experts.

The acute needs emerged by the OL3 project for manpower in the project itself and in the related organizations have been solved by efficient national collaboration. Of course, the margin of number of people in many areas is still critical, and, unfortunately, part of the expertise has only been channelled away from the research sector the long-term problems thus getting only retarded.

Long-term solutions to provide new nuclear professionals take additional efforts which involve intense participation in international education, training, and R&D networks. A looming global nuclear renaissance means, besides breathing life into present nuclear power plants, the development of novel revolutionary fission reactors, like those of Generation IV. R&D on future, revolutionary nuclear energy systems provides a way to solve the challenges to attract new talented students. In a longer perspective, these topics are well motivated also from the point of viewpoint of present NPP projects.

Generation IV offers an exiting and challenging field for students

- international, global, active exchange of scientists
- sustainable technology for the future
- new reactors for the new world
- high level academic research using front-line tools
- development of new methods and tools.

GEN4FIN research network would provide an excellent educational forum both at graduate and post-graduate level. Long term projects would make it possible to create real doctoral school positions which are totally missing in the present nuclear field in Finland.

4.1.3 Role of research organizations

The role of the research organizations in Finland is to create experts, computer programs and research facilities and to import and create knowledge. One of the main outcomes of Generation IV research networks are highly educated experts who will be hired by different organizations in the nuclear field, either after their graduation theses or later after post-graduate studies. One goal is also to increase the number of researchers in the research organizations itself.

The GEN4FIN projects are carried out in the research organizations which can be universities, research institutes or private companies. The education and R&D form a tight combination.

The present expertise in Finland covers all the classic nuclear technologies:

- Reactor physics and thermal hydraulics
- Fuel technology & fuel cycle
- Materials
- Pressure equipment.

These need to be upgraded and widened for the GIF crosscutting research areas:

- Fuel cycle
- Fuel technology
- Materials
- Risk and safety
- Economy and energy scenarios
- Energy products.

The R&D work involves

- Contributions from Finnish R&D into Gen IV development
- Technology transfer to and from Finnish industry
- Gen IV research as a platform for developing new generic technology; materials etc.
- A new, much wider scope of nuclear related R&D.

4.1.4 Role of industry

The potential role of the Finnish manufacturing industry in delivering equipment for Generation IV nuclear power plants has to be studied and planned for. Historically the industry has had a relatively strong international position in power and process plant technologies. The power companies or their supporting organizations will have opportunities in developing and providing services for the future demonstration plants.

There is synergy with the general industrial development: high temperatures, use of molten salts and metals in process industry. More than 50% of the GIF funding will be outside directly nuclear field, like in materials research. A structural alloy required for 1200°C will have application outside nuclear even before Gen IV reactors.

Finnish expertise will certainly be deployed in the international context in the large research programmes of GIF. Finnish expertise is especially appreciated in the risk & safety knowledge as well as in the economical assessment. Finnish companies might have possibilities to use their special knowledge of pulp and paper industry and the arctic environment to participate in development and production of special Generation IV facilities for this environment (like for production of electricity, process heat and district heat as well in remote locations).

4.1.5 Role of the safety authority (STUK)

The Safety Authority translates society's safety desires into practical engineering and management (etc.) terms and requirements, and oversees that these requirements are met.

For future technologies, the safety authority should

- keep itself informed of technical and technological developments
- participate in the international development for safety criteria
- develop draft domestic criteria (together with industry) to pave way for deployment of new technology (in synchrony with industry long range plans and other national priorities)
- and (for its part) ensure that national research network devotes adequate attention to the (novel) safety challenges posed by novel technologies.

National know-how is needed to support the Authority in its work; also for the case that novel nuclear technologies are deployed not in Finland but in the Finnish vicinity.

4.1.6 Role of European and global forums

Most probably within the European Union one or an integrated family of Gen IV reactors will be developed. French industry will certainly have a key role in this, but the production could be organized in the same fashion as the Airbus Industries for passenger airplanes. It would be natural for Finland and the Finnish industry to participate in this through Euratom programmes.

Finland has also the possibility to look alternative solutions and models developed in the US (DoE), Russia or Far East. This means participation to other global forums than GIF e.g. INPRO, or direct Gen IV collaboration e.g. with the USA. However, this would require a rather large critical mass of the Finnish group.

5. Implementation plan for GEN4FIN research network

The strengths of the Finnish actors are based on the ability for multidisciplinary work and fast exploitation through links and dialog with nuclear utilities and regulators. Therefore the implementation plan covers scientific, technological and industrial goals that are closely linked with each other. The experience gained in the Finnish Fusion programme confirms this approach.

The implementation of the research network will be carried out through R&D projects, education and training and international collaboration. This means that the research network should be scheduled for at least five years and all major actors in the R&D field in Finland could contribute to the research network.

5.1 Research network structure

Steps for the implementation:

1. Roadmap work for GEN4FIN activities – potential R&D project areas and ongoing activities
2. Technology transfer – participation to EU and global forums throughout the research network
3. Knowledge development and transfer by carrying out R&D projects
4. Master and doctoral level education including doctoral schools
5. Business opportunities for Finnish industry
6. Potential of key Gen IV technologies in other industries

The activities of the research network will start with:

- A R&D Roadmap work including issues presented in Table 4 and Table 5 will be combined and written out detailed R&D project initiatives.
- Finnish industry will be surveyed and activated, identification of Finnish industry working in the above mentioned fields.
- Accumulating experience from the Gen III Olkiluoto 3 construction project.
- Links to the Finnish fusion research activities and a possible hydrogen technology programme will be identified.
- A plan for the doctoral schools, seminars, summer schools etc. will be worked out,
- Participating the GIF forums and possibly EU projects.

Deep understanding and know-how of the Generation IV technologies is created only through concrete research work. Follow-up through seminars and conferences is not sufficient. Experts trained in Generation IV technologies will be internationally recognized and will certainly be invited into GIF projects. Training of such an expert will take approximately five years.

The required resources to achieve a minimum level of activity are one person year / actor in the research network. The involvement of several persons (appr. 5) is required if concrete results are pursued. The national Gen IV research network should include also a programme of national seminars on the various relevant subjects.

The training and research work in the proposed research network will gradually, in a long time span, create circumstances for innovations and industrial involvement. Therefore, it is important to be open to all the GIF concepts as after the initial research phase some of these can be discontinued. After enough expertise has been created in the new reactor concepts, Finland will be able to participate in the work of INPRO at IAEA and bilateral co-operation to USA, Japan, France etc.

A strategic plan will be prepared for the participation in the GIF working groups. For the moment Finnish members are in the working groups of the SCWR concept, in the Economic WG and in the Risk and safety WG. Through participation in the GIF working groups Finland can maximise its influence on the GIF milestone decisions.

5.2 Participation in viability assessment and in preparation of licensing requirements of Gen IV

Near term goals (up to 2012) for the R&D work and activities are:

- Participation in the GIF-projects
- Participation in EU Gen IV projects
- Bilateral collaboration to Japan, Russia, France, US will be supported.

The Finnish national research network will be planned based on the crosscutting areas and Gen IV concept studies. The crosscutting areas are:

- Fuel Cycle Crosscut
- Fuels & Materials
- Risk & Safety
- Economic and societal aspects
- Energy Products.

Participation in the development programmes will be mainly based on projects for different reactor concepts, Table 4**.**

Table 4. Main fields of required R&D for each of the Generation IV reactor systems.

System	**R&D**
Very High Temp. Gas Reactor (VHTR)	*Fuels, Materials, H_2 production*
Supercritical Water Reactor (SCWR)	*Materials, Safety*
Gas-Cooled Fast Reactor (GFR)	*Fuels, Materials, Safety*
Lead-alloy Cooled Fast Reactor (LFR)	*Fuels, Materials compatibility*
Sodium Cooled Fast Reactor (SFR)	*Advanced Recycle*
Molten Salt Reactor(MSR)	*Fuel, Fuel treatment, Materials, Safety & Reliability*

The potential Gen IV activities, status and industrial potential are listed in Table 5 (preliminary).

Table 5. Potential Generation IV activities in Finland, status and industrial potential.

Activity	**Potential R&D activities in Finland**	**Status**	**Industry**
Science			
Reactor design	Core calculational analyses	Preliminary studies of SCWR	Design tools for plant development and upgrades, license renewals Decision tools for industry
Fuel	Transient studies of fuel behavior	FRAPTRAN/GENFLO capabilities	
Safety	Experimental work on passive safety systems Whole plant simulations	Gen 3/3+ studies ongoing APROS capabilities	
Fuel cycle and waste management	Reactor physics studies	Benchmarking and validation of nuclear data	
System integration (economy, non-proliferation)	Economical comparisons: methodologies for nuclear/non-nuclear etc studies	Gen3/3+ studies	
Technology			
Materials engineering	In core materials performance and optimization Crosscutting actions for materials HT/irradiation-performance between different concepts	Gen3/3+ studies ongoing SCWR “loop” facilities developed at VTT > global level	Materials performance , novel solutions for Gen3+, fusion and other applications Monitoring devices and methods have direct potential (Gen3 and wider appl.)
Development of innovative on-line monitoring methods	Systems for test loops and reactors	Monitoring of water chemistry and corrosion	
Education	Through Universities		New generation of specialists

5.3 Schedule

The research network should have a plan at least for 5 years at a time. This would be phased to the timeframe of GIF basic studies in 2005–2012 and the design phase in 2012–2020/2030.

The work could start with a preliminary phase covering actions listed above.

5.4 Funding

Funding will be covered by national funding and extended with EU funding as acquired.

Special funding is applied for visiting scientist / scientific exchange.

The work via Finnish-DoE agreement or via co-operation with Japan will be applied from Tekes.

In the GEN4FIN research network additional resources might be accessible through collaboration with Russian and Lithuanian partners. Special EU-funds might be available for this.

6. Research network outcome

The development of Gen IV nuclear power plants will contribute to many major questions related to present energy policies. As a summary the global and Finnish benefits are listed in the following.

Gen IV technology applied in the world

- Sustainability through very long term fuel resources of the world available and improved efficiency
- Reduction in the amount and toxicity of nuclear waste
- Other industrial (hydrogen) applications will be remarkable.

Gen IV knowledge and technology applied in Finland:

- No instant need to invest in fast reactors because also in Gen IV the LWRs compose the majority of nuclear power plants (even if closed fuel cycle is achieved)
- Participation to the development benefits safety improvements of existing reactors and education of new generation of specialists
- Independent knowledge must be acquired and maintained to provide nuclear safety and ability for justifications in failure or modernisation cases
- Hydrogen needs for the Finnish industry and/or traffic may lead to high temperature reactor considerations.

The GEN4FIN research network will provide especially:

- A new generation of research scientist in the field
- Appreciated know how in the global forum on specific areas of materials engineering and science, reactor design and safety
- Innovative and advanced research facilities and simulation programs
- High technology industrial applications, spin-offs
- Opportunity for Finnish safety experts to contribute to the development of safety criteria on an international level
- Ability to assess national nuclear security due to possible future nuclear solutions in the neighbouring countries.

A further goal of GEN4FIN is also to contribute to the development of Gen IV reactors so that the facilities could possibly be deployed in Finland: to affect their acceptance and applicability. Due to the experience in utilization of nuclear energy Finland will be listened to. At least Finland should be prepared for the assessment of the national nuclear safety issues due to possible future nuclear solutions in the neighbouring countries. All proposed reactor types should be studied at some level to gather enough knowledge for their assessment.

Expertise, know-how and continuous performance improvements are necessary for excellence in both safety and economical efficiency. To obtain these goals resources are needed: money for investments and modernizations as well as education, training and R&D for excellent operation. The extremely long life of nuclear power plants means a similarly long commitment into investments in human capital, including the whole infrastructure of nuclear sector from basic engineering teaching to NPP operators.

A basic dilemma is that the characteristic evolution of energy systems lasts for several generations and can include abrupt climatic, economic or world-political changes during this century. Energy problems having lead-times of tens of years must be solved, except for the final commercial phase, by political decisions and by tax-payer money. The nuclear R&D task requires a huge commitment because the threshold for nuclear experiments is very high, their completion is long and several milestones must regularly be met to keep the interest of decision makers. Due to our rather finite national resources we have to participate actively in the international collaboration.

Generation IV and other revolutionary fission reactors, and also fusion reactors, provide exiting challenges to new generations of competent nuclear professionals. Exotic ideas and grass-root professionalism are not mutually excluding. Emerging reactor systems can form a consistent nuclear energy system able to solve a large part of global problems. A large platform for all nuclear options would benefit nuclear technology, education and training both in small and large countries.

Acknowledgements

The GEN4FIN working group acknowledges the financial support for its work from the Finnish Ministry of Trade and Industry as well as from the companies Fortum, TVO and Prizztech.

The interest shown by the European Commission and the information on GIF issues shared especially by Pierre Frigola form the JRC have been of great value for the working group.

The working group wishes also to express its gratitude to the foreign and domestic lecturers in the GEN4FIN seminars sharing their state of the art knowledge with the research community around the GEN4FIN working group.

References

1. A Technology Roadmap for Generation IV Nuclear Energy Systems, GIF-002-00, December 2002, Issued by the U.S. DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum.

2. Spitzer, J., Jernström, E. and Rahkila, P. Evaluation Report, VTT Processes, Espoo 2004.

3. GENERATION IV NUCLEAR ENERGY SYSTEMS, TEN-YEAR PROGRAM PLAN, Fiscal Year 2005, Volume I, Released March 2005, Office of Advanced Nuclear Research, DOE Office of Nuclear Energy, Science and Technology.

4. IAEA, 2005a, Thorium fuel cycle – potential benefits and challenges, International Atomic Energy Agency, Vienna 2005. http://www-pub.iaea.org/MTCD/publications/PDF/TE_1450_web.pdf.

5. INPRO Update 2005-06-08 Rev2.

6. Methodology for the assessment of innovative nuclear reactors and fuel cycles. IAEA-TECDOC 1434, IAEA December 2004.

7. Micanet Report – December 8th, 2004 Draft.

8. OECD 2004 Uranium 2003: Resources, Production and Demand, A Joint Report by the OECD Nuclear Energy Agency and the International Atomic Energy Agency, OECD 2004.

9. OECD, 2001, Trend in the nuclear fuel cycle, economic, environmental and social aspects, OECD, Paris. http://www1.oecd.org/publications/e-book/6602011e.pdf.

10. OECD, 2006a, Uranium 2005: Resources, Production and Demand, A Joint Report by the OECD Nuclear Energy Agency and the International Atomic Energy Agency, OECD/NEA. 388 p. ISBN 92-64-02425-5.

11. OECD, 2006b, Advanced nuclear fuel cycles and radioactive waste management, OECD/NEA. 248 p. ISBN 92-64-02485-9.

12. Our Common Future, BRUNDTLAND COMMISSION, World Commission on Environment and Development, Oxford University Press, Oxford (1987).

13. Rosenberg, R., Klobut, K. Naumanen, M., Reunanen, M. Sipilä, K. and Viikari, L. Suomen tiekartta vetytalouteen, Vety- ja polttokennotiekartta työryhmä, 10.9.2004. (In Finnish.)

14. Talousvaliokunnan mietintö 8/2003 vp Hallituksen esitys laiksi ydinenergialain muuttamisesta; TaVM 8/2003 vp – HE 128/2003 vp. (In Finnish.)

15. Towards a European Hydrogen Energy Roadmap, The European Hydrogen Energy Roadmap Integrated Project, Executive Report, 12 May 2004.

16. The Sustainable Nuclear Energy Technology Platform – A vision report, Special Report EUR 22842, European Communities, Directorate-General for Research, Euratom. ISBN 978-92-79-05591-1. http://www.snetp.eu/home/liblocal/docs/snetp_vision_report_eur22842_en.pdf.

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LUT	**Lappeenranta University of Technology**
Prizz Tech Oy	**A project and technology development company**
STUK	**Radiation and Nuclear Safety Authority**
Tekes	**Finnish Funding Agency for Technology and Innovation**
TKK	**Helsinki University of Technology**
TVO	**Teollisuuden Voima Oy (The Olkiluoto NP Utility company)**
VTT	**Technical Research Centre of Finland**

Appendix B: Finnish actors in Gen IV R&D

RESEARCH INSTITUTES AND UNITS

Finland has no institutes dedicated solely for nuclear research. Most research takes place at the VTT Technical Research Centre of Finland. Other major research institutes include the universities of technology in Lappeenranta and Helsinki (LUT, TKK), the Geological Survey of Finland (GTK), the Finnish Meteorological Institute and the universities of Helsinki, Kuopio, Tampere and Jyväskylä. In addition, the Radiation and Nuclear Safety Authority (STUK) and the power companies Fortum and TVO carry out internal research or finance research at the research institutes or universities. The versatile array of research subjects at the research institutes and universities promotes spin-off and spin-in relations with other industries. Spin-offs include simulation technologies, reliability engineering, fracture mechanics, and non-destructive testing, while spin-in benefits have been enjoyed in areas such as human factors, digital automation systems and computational fluid dynamics.

Appendix C: Current Finnish participation in Generation IV research programmes

- **Euratom HPLWR assessment project**
- **SCWR GIF technical management board work**
- **Euratom V/HTR project**
- **PBMR**
- **Gen IV economy modelling**
- **Advanced fuel cycle concepts (P&T)**
- **Hydrogen systems and production**
- **University seminars on Gen IV issues**

FINNISH REPRESENTATIVES IN GIF AND EURATOM PROGRAMME BODIES:

Risto Tarjanne from the Lappeenranta University of Technology is a member in the GIF Economics Modelling Working Group (EMWG).

Antti Daavittila from VTT has been since summer 2005 a member in the GIF Risk and Safety Working Group (RSWG).

Liisa Heikinheimo from VTT is a member of the GIF SCWR technical management board as the Euratom representative in material issues.

Liisa Heikinheimo from VTT is a member of the SMINS – Structural Materials for Innovative Reactor Systems, OECD NEA Special Activity Committee (SAC).

Jukka Laaksonen from the STUK Radiation and Nuclear Safety Authority is a member in the Senior Regulators' WG on the Generation IV Initiative.

Heikki Raumolin from the Fortum corporation is a member in the MICANET Policy Board and Harri Tuomisto also from the Fortum corporation is a member in the MICANET Steering Committee.

RESEARCH PROJECTS

Euratom HPLWR-project in 2000–2003 was a start and intensive effort to joint the Gen IV work VTT participating the programme co-ordinated by FZK in Germany. VTT is also a partner in the HPLWR2 project of the 7th framework programme by Euratom.

Materials performance tests and analyses were carried out at VTT as a part of a VTT Technology Theme (Clean World) in 2004–2005 and this study has been a part of a Tekes R&D project "LC power" project from 2005. The aim is to develop tools and monitoring methods for materials performance studies under SC-water conditions. The development work will provide fundamental knowledge about the oxidation kinetics and phenomenon as well. The study serves both the novel SCWR concept and the conventional supercritical boiler plant life management goals. The studies have been reported to the GIF SCWR technical management board.

In addition, in the KYT research programme there have been restricted activities in the area of advanced fuel cycle concepts – primarily the follow-up of research activities on partitioning and transmutation.

In a masters theses project production of hydrogen using nuclear power was studied. Hydrogen energy technology has also otherwise been studied at VTT and in Finland in the DENSY and CLIMBUS research programmes sponsored by Tekes.

OTHER ACTIVITIES

At the TKK and LUT there has been graduate and post-graduate student seminars on the Generation IV issues.

The GEN4FIN working group has arranged two national seminars, the first at LUT in 2006 and the second at VTT in 2007, on Generation IV issues each having around 50 participants. In the same period also two general, less formal Gen IV researchers meetings have been held in Otaniemi. For the roadmap work to workshops with a limited number of invited participants were held.

Appendix D: SWOT analysis of the situation in a Finnish perspective for selecting the targets of the Finnish research in Generation IV nuclear technologies

Strengths	**Weaknesses**
Due to its experience in utilization of nuclear energy Finland will be listened to. Strong expertise in nuclear technology. Ability for multidisciplinary work. Small country with effective networking and low hierarchy. Strong position in international networking. Long term commitment of Finland to nuclear energy Fast exploitation through links and dialog with nuclear utilities and regulators	Small country with limited resources. Short term financing policy is not favourable for future concept development and long term international programmes. Expertise will decease through retirement of present generation by 2010. No Finnish nuclear vendors.
Opportunities	**Threats**
Crucial impact on climate change mitigation Important for hydrogen infrastructure Education of next generation of nuclear energy experts for research, authorities and utility companies – attracting talented students – post graduate studies Ability to judge and apply new technologies also for non-nuclear industry Continuation in development of front edge technology Sustainable solutions for energy and process industry	Failure in political acceptance of nuclear power. Selected concepts of the Finnish Gen IV research network will fail. Low budget will not sustain knowledge development Short term goals in nuclear field compete of same limited human resources.

Appendix E: PESTE analysis: Main factors influencing the operational environment

POLITICAL / LEGAL

Awareness about risks of climate change due to green house gas emissions is increasing rapidly.

Acceptance of nuclear power is increasing.

Opposition to nuclear power still strong in Europe and in the US; especially long lived nuclear waste and proliferation of nuclear weapons are considered as unacceptable risks.

Sustainability is becoming as important as short term economic influences.

EU industrial and research policies are more and more important for Finland

Bio- and wind energies are highly accepted.

TECHNOLOGICAL

Concepts for distributed energy production are developed.

Hydrogen energy is becoming more feasible.

Concepts for clean and zero emission processes are developed

Decrease of fossil fuel resources forces the development of high efficiency mass production processes

ENVIRONMENTAL

Influences of climate change due to green house gases become increasingly apparent

Operational safety and reliability

Sustainability is becoming more and more important.

Waste management issues

Plant life management and extension

Environmental values

SOSIOCULTURAL

Big base-load plants / distributed energy production

National production technology not available > production moving to east and south

Educated employees not available > moving to better employment markets

ECONOMIC

<u>General globalisation:</u>

Global and new markets are changing make forecasts and predictability difficult

Industrial production is increasing especially in far east.

The vendors of nuclear power plants are international industrial agglomerations.

Open energy / electricity markets.

Emission trading

Prices of fossil fuels are increasing rapidly / the effect on market prices

Appendix F: Current status of Generation IV programmes

In the following the status in the development of the individual systems is described (adapted from the MICANET [7] and DOE [2] material).

VERY HIGH TEMPERATURE REACTOR (VHTR)

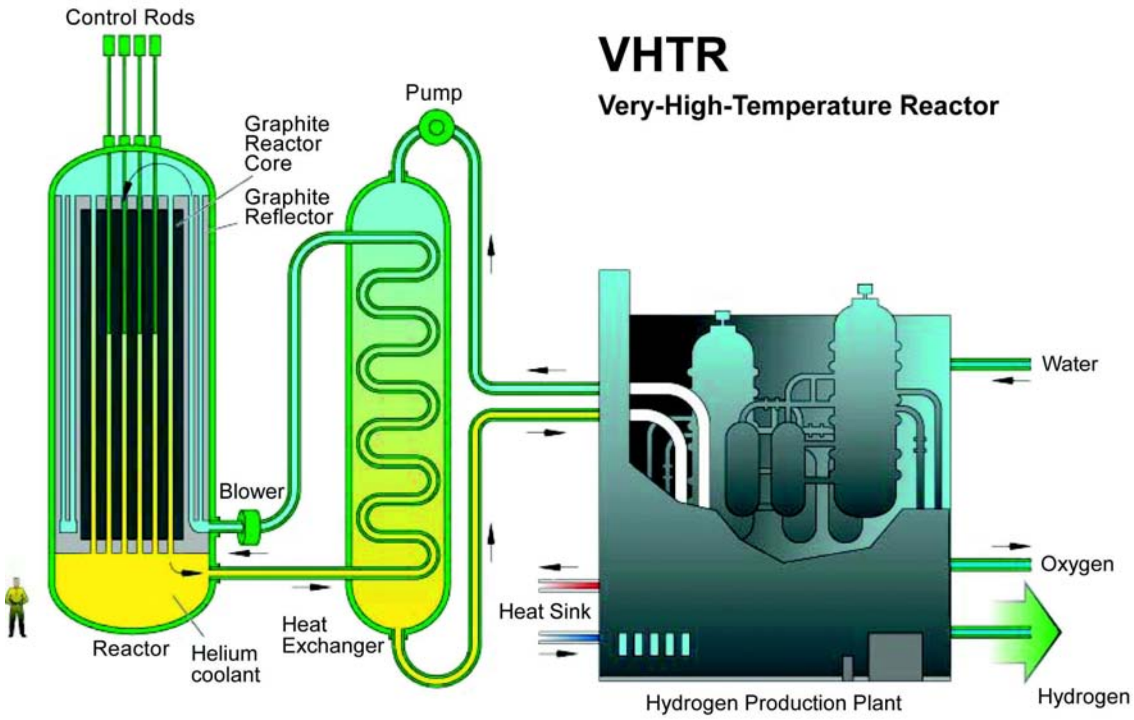


Figure F-1. Conceptual VHTR system [1].

There are good prospects for an early deployment (during the next decade) of a renewed generation of thermal neutron high temperature gas cooled reactors (HTRs) with modular design. Direct Brayton and indirect cycle conversion are under assessment. Two projects of industrial prototypes (GT-MHR and PBMR) involving large international partnerships will likely be put in operation by 2015. These modular HTRs are already making a step towards the goals of sustainable development, with their features (i.e. the TRISO particles) which prevent any severe degradation of the fuel in accident conditions. Their technology relies on the past industrial experience of HTRs and on the modern gas turbine technology. Some key feasibility issues have been and are still examined in depth.

The gas cooled reactor technology has a high potential for further developments (design optimizations, higher temperature, flexible fuel cycles of thorium, deep actinide burning, hardening of the neutron spectrum), which can improve the competitiveness of nuclear energy, open new market areas for nuclear energy (hydrogen production, industrial processes) and lead, step by step, to an improved satisfaction of the goals of sustainable development. The Very High Temperature Reactor (VHTR) is the system under development to meet these objectives.

Demonstrating the viability of the VHTR core requires meeting a number of significant technical challenges. Novel fuels and materials must be developed that: permit increasing the core-outlet temperatures from 850°C to 1000°C and preferably even higher; allow the maximum fuel temperature reached following accidents to reach 1800°C; achieve maximum fuel burnup of 150–200 GWD/MTHM; avoid power peaking and temperature gradients in the core, as well as hot streaks in the coolant gas.

The viability of producing hydrogen using thermochemical process (such as the iodinesulphur one) still requires pilot- and large-scale demonstration: whereas nuclear steam reforming of methane has already been demonstrated in a 10MW scale.

Performance issues for the VHTR include development of a high-performance helium turbine for efficient generation of electricity. Modularization of the reactor and heat utilization systems is another challenge for commercial deployment of the VHTR.

Currently most efforts both in the EU and in the USA in the Generation IV development are directed for the Very-High-Temperature Reactor Systems (VHTR). In the US the Next Generation Nuclear Power Plant (NGNP) programme for research, development, demonstration and commercial application of advanced nuclear fission reactor technologies, the VHTR concept has been chosen. The objective is to demonstrate the technical and economic feasibility of an advanced nuclear fission reactor power plant design for the commercial production of electricity and hydrogen at the US Department of Energy's (DOE) Idaho National Laboratory. The DOE hopes the NGNP could be in operation by about 2020. In Europe Euratom is developing VHTR technology in the RAPHAEL-project and Areva has its own ANTARES development programme with the goal to create a commercially competitive Advanced High Temperature Reactor.

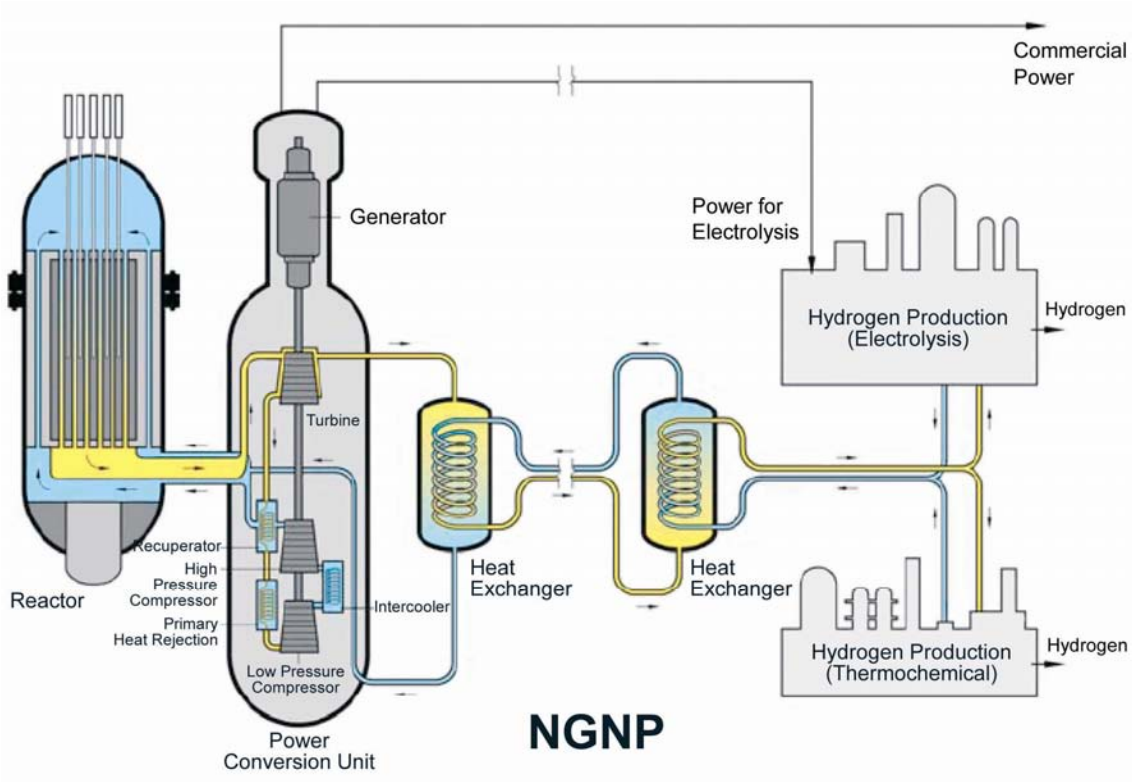


Figure F-2. NGNP configured to produce both electricity and hydrogen. [2].

SUPER CRITICAL WATER REACTOR (SCWR)

Super Critical Water Reactor (SCWR), also called High Performance Light Water Reactor (HPLWR), operates above the thermodynamic critical point of water (374°C, 22.1 MPa).

SCWR is seen as an evolutionary concept based on many existing technologies, coming from LWRs for the nuclear part and from supercritical fossil-fired plants for the conventional island. Theses systems may have a thermal or fast neutron spectrum, depending on the core design.

Even though concepts of nuclear reactor with supercritical water as coolant have been studied since the mid 50’s, there have been no prototype HPLWR ever built and tested.

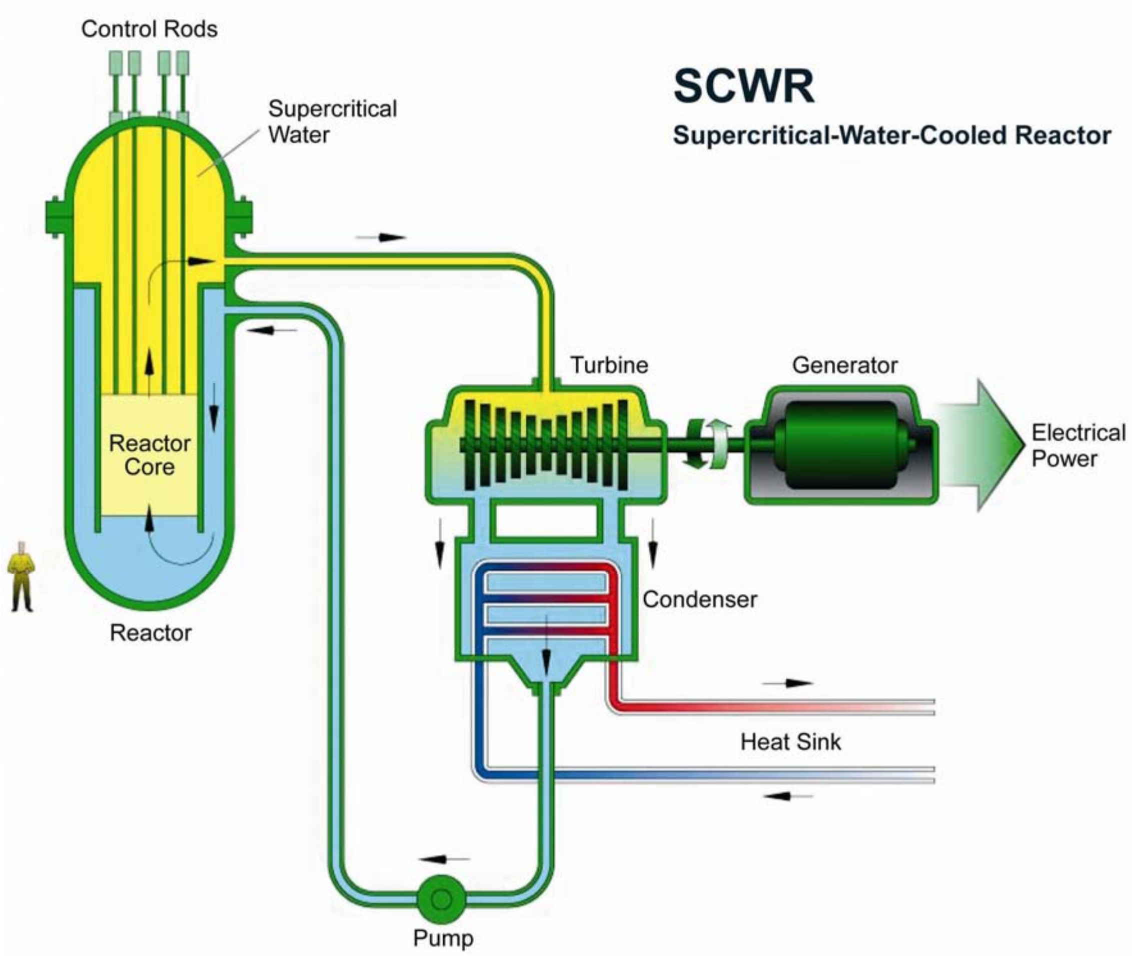


Figure F-3. Conceptual SCWR system [1].

Incentive

The SCWR is considered providing a major improvement in LWR technology in order to achieve a major reduction on cost investment for medium to large water reactor NPP. The main expected advantages of SCWR compared to present up-to-date LWR are:

- A significant increase of the thermal efficiency to about 45% (compared to 35% for LWRs) due to the high temperature of the fluid.
- The simplification of the reactor coolant system:
  - No need of steam generators nor pressurizer (with regard to PWRs)
  - No need of steam dryers and separators nor recirculation system and reduction in size of the containment building due a lower-coolant mass inventory resulting from the once-through coolant path in the vessel (with regard to BWRs)
- These specific features may also provide a benefit in the duration of the erection.

- In comparison with LWR, the reliability of SCWR may be improved because the reduction in piping, components and valves.
- A limited development work (cost and delay) to reach a commercial use, because a significant part of the technology base for the SCWR can be found in the existing LWRs and in commercial supercritical-water-cooled fossil-fired-plant.

Main technical features

The SCWR concept takes benefit of the unique thermo-physical properties of supercritical water: No boiling crisis (DNB or dry out) exists because there is no change of phase above the critical pressure, but the designer must deal with the water density that decreases drastically from the core inlet to the outlet (from 760 kg/m3 at 280°C to 90 kg/m3 at 500°C). Consequently acceptable core moderation through the core cannot be achieved with a one through flow.

A presently realistic concept is based on the Japanese developments performed in the last 15 years. The vessel is similar to a PWR vessel (although the primary coolant system is a direct cycle BWR-type system). High-pressure coolant enters the vessel at 280°C. The inlet flow splits partly to a downcomer and partly to a plenum at the top of the core to flow down through the core in special water pipes. This down flowing water has a high density and provides a good moderation in the core, even at the top.

At the bottom of the assembly, the water starts to flow upwards to remove the heat in the fuel channel. Due to the huge heat capacity of the supercritical water between the inlet and the outlet temperature, a small mass flow (about 10% of those of a PWR), is enough to cool the fuel, assuming the same core power density as for a PWR.

The fuel cladding will probably make use of stainless steel or nickel-based alloy, thus inducing the need for higher fuel enrichment (about 1%) than an equivalent LWR fuel for a given fuel discharge burnup. Hopefully the gain in plant efficiency increases the electricity output and offsets this penalty. To reach a burnup as high as in the LWR, there is a need to use enrichment higher than 5%. Then the impact on the enrichment plant, the fuel manufacturing plant and the transport system is noticeable.

Challenges and issues

For assessing SCWR viability, the main remaining key issues are:

- qualification, with regard to corrosion and stress corrosion cracking under irradiation, of materials for fuel cladding and reactor structures (the experience of fossil-fired plants provides no data on this topic), it will request in-pile testing during a sufficient amount of time
- achievement of a robust and economical design for fuel assemblies and core internals,
- mastering safety, especially power-flow stability during start-up and operation
- design of suitable safety systems with regard to LOCA and loss of feedwater flow (the small water inventory in the core has a significant impact on the reactor behaviour under accidental conditions).

There is also a need for relevant computer codes qualified for SCWR conditions; efficient coupling of neutronics-thermal hydraulics codes is needed to deal with the strong coolant density changes over the core height.

Investigation of heat-transfer at supercritical water conditions requires experiments in order to obtain a proper heat-transfer data base, thus allowing to adapt the computer codes to determine heat transfer limits and to study flow stability.

Status of development work

Since the 80’s, the major research on SCWR has mainly been performed in Japan (University of Tokyo) and Canada. There are also many US NERI funded research programmes, involving National labs, universities, and international partners, chiefly Korea and Canada.

Within the 5th European Framework Programme, a feasibility study, coordinated by FZK, has been performed on the High Performance Light Water Reactor (HPLWR). The results were first drafts of conceptual drawings, thermal-hydraulic and neutronics simulations of the core, a first approach of the safety system, a list of candidate materials for cladding and RPV internals, and an economic study. A R&D roadmap has been derived indicating the tasks to be performed until 2020, when a first prototype of the HPLWR could be constructed.

The partner countries in GIF-SCWR are the U.S.A., Canada (leader), Korea, Japan and Euratom. The Canadian make efforts to adapt the CANDU-type reactor to operate under supercritical water condition.

The Initial Gen IV SCWR goals and milestones were for a deployment of a reactor with an outlet T° of~510°C in 2025. However, this first time scale is challenged, and there are now two approaches in parallel under discussion in GIF: An accelerated schedule for a concept with an outlet T° of ~625°C with a prototype ready for operation in 2015, and a high temperature version (up to 1000°C at outlet) directed to H2 production, which could be developed with a longer term horizon. The “HPLWR Phase 2” project is supposed to be an Euratom contribution to the Generation IV International Forum.

Fast-neutron spectrum option

The SCWR may also be designed to operate with a fast neutron spectrum core. A tighter fuel lattice and no water pipe in the fuel assembly leads to a reduce water inventory in the core, this inventory may be limited to the quantity of water to that required to the fuel cooling capability. Then there is a nearly fast neutron spectrum in the core, thus allowing reaching a high conversion ratio.

However the technical issues, especially on safety (criticality hazards in case of LOCA or flooding, flow stability) and materials are more challenging and the expected breeding performances will probably not match those of other fast reactor concepts because of the “soft” fast neutron spectrum achievable. The fast SCWR is envisioned far later than the thermal SCWR. The available studies have not yet proven that a basic industrial design for the core may satisfactorily achieve both a sufficient conversion ratio and a suitable safety level.

GAS-COOLED FAST REACTOR (GFR)

During the 1960s through 1980s, gas-cooled fast reactors were being considered as an alternative to the mainstream development programme of liquid metal fast breeder reactors (LMFBR). However, GFR had poor heat transfer properties and low thermal inertia as compared to LMFBR; they could not withstand, without active safety systems, a full depressurization accident, the resulting fast temperature rise would far exceed the melting point of the typical metal cladding of the fuel rods taken into account in the design at that time. So innovative design features had to be developed to overcome shortcomings of past fast-spectrum gas cooled designs.

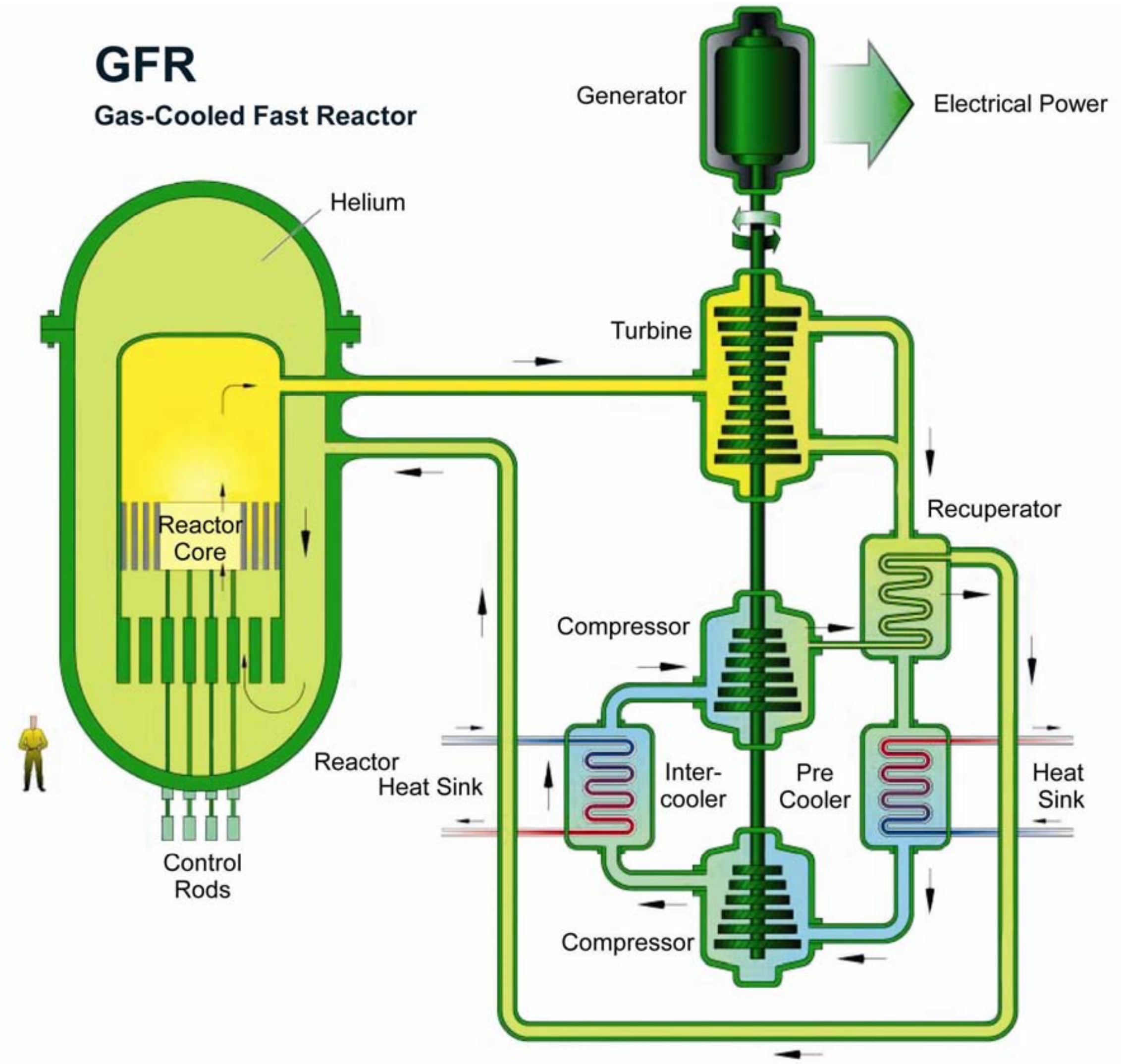


Figure F-4. Conceptual GFR system [1].

Incentive

GFRs share the sustainability attributes of fast neutron spectrum reactors:

- effective fissioning of Pu and minor actinides,
- ability to operate on wide range of fuel compositions with different fuel cycles (U, Pu), (Th, U),
- capacity for effective fuel utilization (high conversion ratio).

The helium coolant provides a small coolant void reactivity (< ßeff) and offers same advantages as for the HTR/VHTR concept:

- chemical inertness and no change of phase,
- easy in-service inspection,
- potential for very high temperature and direct cycle conversion or other applications such as high temperature electrolysis or thermochemical hydrogen production.

A significant part of the technology challenges, mostly in the scope of the primary systems and of the balance of plant, are shared by the HTR/VHTR and GFR.

Main technical features

Presently, there is still no available design of GFR. Nevertheless, the work performed thus far has allowed identifying potential fuels, materials, components and systems which may allow designing a viable GFR for power production.

To be cost attractive, the core power density must be high for a gas-cooled system (50 to 100 MWth/m3) but no fuel nor core design are yet validated for such conditions. For the core, there are several fuel design options, including both the prismatic (with fuel particles or composite fuels) and fuel pins (with actinide compound/solid solution), under evaluation. A composite ceramic-ceramic fuel (cercer) with closely packed, coated (U,Pu)C kernels or fibers is the preferred option for fuel development, but alternative options are also considered: fuel particles with large (U,Pu)C kernels and thin coatings, or ceramic-clad, solid-solution metal (cermet) fuels.

Various passive approaches need to be evaluated for the ultimate removal of decay heat in depressurization events. A high-pressure (up to 15 bars) containment building and a large pressurized gas injection safeguard system could facilitate passive decay heat removal by natural convection at a back-up pressure of 5 to 15 bars (depending on the gas).

Like HTR, GFR may utilize high-temperature helium coolant, either with a direct or an indirect power conversion cycle.

The reference concept is a 600 MWth/288 MWe, helium-cooled reactor system operating with an outlet temperature of about 850°C and using a direct Brayton cycle gas turbine. The thermal efficiency is estimated to reach 48%.

In order to achieve a high safety level, the total core power and the core power density (<100 MW/m3) will be limited to ease decay heat removal using natural convection, but these limitations may jeopardize the potential breeding ratio and power plant economics.

Challenges and issues

Some technology gaps are the same as those of the HTR/VHTR projects, therefore it is expected that they will be solved before starting GFRs industrial deployment and they are not seen as GFR main issues. The viability of GFRs is not yet demonstrated, there are still major unresolved key issues such as:

- fuel and core design,
- reactor safety,
- fuel reprocessing technology.

Fuel and Core

The fuel form and materials and the core design must meet the following requirements:

- the fuel must have a good thermal conductivity to lower the fuel temperature and must be able to withstand high temperature during abnormal condition,
- the content of heavy metal in core must be high (at least 20–25%) in order to achieve an effective conversion ratio, with a good fission product retention capability allowing to achieve high burnup.

Fuel technology

The fuel technology is not yet selected, it must be compatible with an economical process for the treatment of irradiated fuel and refabrication for recycling. For most of the candidate technology such as carbide, nitride, or oxide dispersion fuels in ceramic or metal matrices, laboratory-scale processes for treatment have been evaluated and appear technically feasible. However, the process concepts must be proven feasible for fuel treatment at production scale.

Both aqueous and pyrochemical processing methods, and combinations of the two processes, will need to be tested on the inert-matrix fuels. For waste burning, the fuel technology will have to be compatible with multiple recycling of actinides using specific chemistry and remote fuel fabrication, if needed.

Safety

Safety features must provide capability to deal with loss of coolant with a high reliability. Because of the high GFR core power density, a safety approach is required that relies on intrinsic core properties supplemented with additional safety devices and systems. A sufficient degree of passive safety will be desirable, even though the use of active safety system is openly considered. However, the cost of these systems and components must not jeopardize the feasibility of economic design.

Material

Materials for GFR core and vessel internals must be able to withstand high targeted temperature as the materials of the HTR/VHTR, and large fast fluence conditions, as in any fast neutron spectrum core.

Status of development work

Some main features of GFR are fully specific and R&D work is in progress or scheduled, aiming at assessing the viability of the GFR concept. Development is still in an early stage, this is why it is mostly driven by public funded R&D and international cooperation.

R&D actions are organized in the framework of Gen IV where the most active countries are the USA (leader) and France (CEA is performing significant R&D work on GFR), it also includes the EU, UK, Japan and to a lesser extent Korea and Switzerland.

In the 6th EU Framework Programme, GFR development action is accepted, many parties are involved: NNC (coordinator), BNFL (UK) , CEA (France), EA (Spain), PSI (Switzerland), University of Delf (Netherlands), University of Pisa (Italy), Euratom (ITU), Framatome-ANP.

The main tasks foreseen in Gen IV and in the 6th FP are quite consistent, they deal with:

- the preconceptual design of a GFR (fuel form, core design, main balance of plant),
- the safety approach (development of specific components and active and passive safety systems),
- the analysis tools and computer codes,
- the economics.

One can think that the industrial deployment of GFRs (if any) will happen only when the HTR/VHTR operation has provided confidence on the gas cooled reactor technology. However a specific Technology Demonstration Reactor would be requested in order to validate the basic technology choice, thus helping to design a prototype in a later phase.

LEAD-COOLED FAST REACTOR (LFR)

The LFRs share with the SFRs numerous design features, they also allow a fast neutron spectrum and a closed fuel cycle for an efficient conversion of fertile uranium and possibly management of actinides. Some technology and experience already exists, mainly in Russia where Alpha class submarines operated with Pb-Bi alloy-cooled reactor and LFR is promoted for civilian application such as the BREST concept.

Incentive

Some specificities of the lead cooled reactor are set out as advantages with regard to sodium:

- The low neutron absorption and slowing-down capacity of lead allows opening the fuel lattice, thus facilitating natural circulation.
- The high boiling temperature (1740°C) at atmospheric pressure provide more margins for passive safety based on thermal feedbacks; it may also ease to raise the core outlet temperature up to about 800°C, assuming that the fuel performance allows that, thus allowing hydrogen production or other process heat application.
- The lead does not strongly react with air or water, this potentially simplifies the heat transport and conversion circuit as well as the refueling approaches.

The potential on economy may be good because of the simplicity of the whole architecture and by the choice of a relatively inert coolant. On this concept, less in-depth economics optimization have been performed than for SFR; so there may be larger possibilities of improvement.

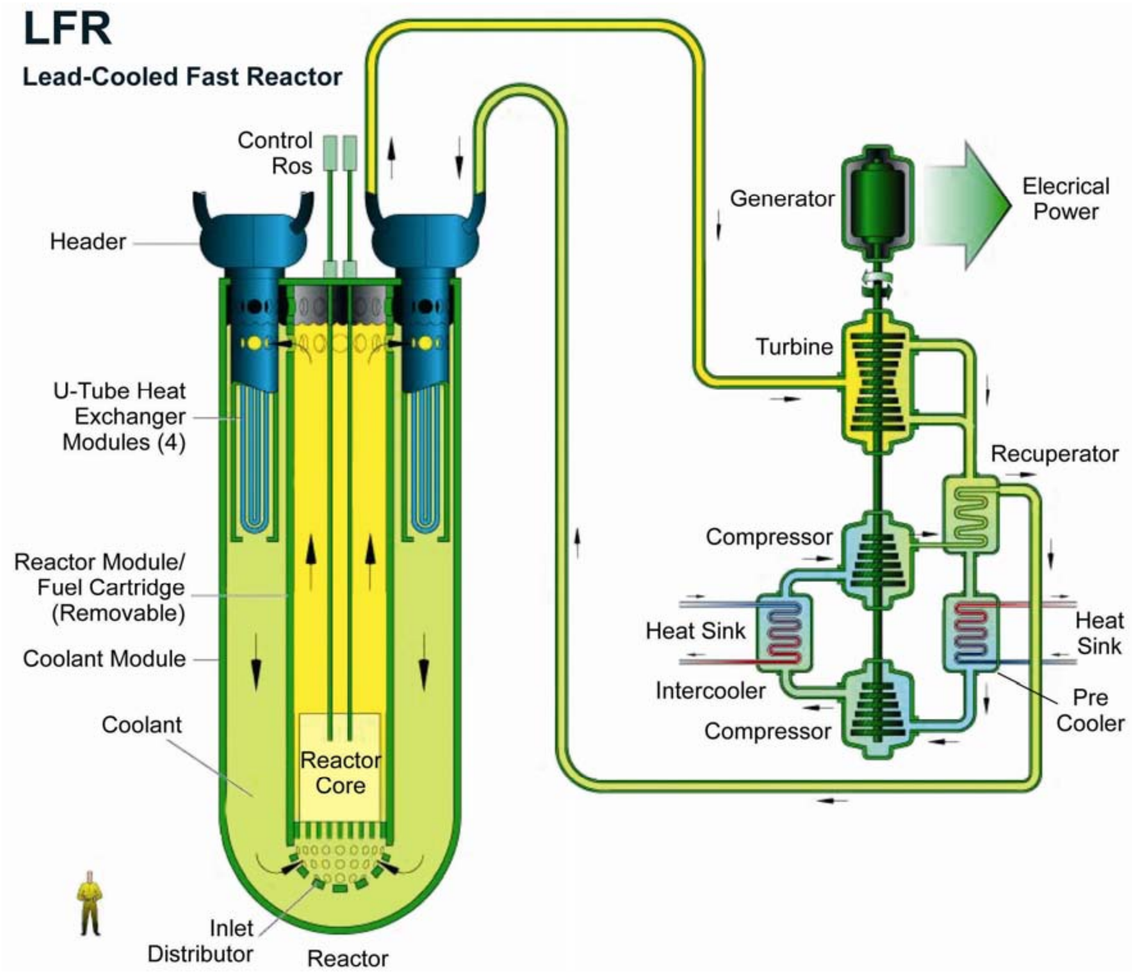


Figure F-5. Conceptual LFR system [1].

Main technical features

LFR is seen as a pool-type reactor. Lead has a low chemical reactivity, this allows a direct heat exchange between molten lead and a steam generation circuit, avoiding a secondary circuit acting as a buffer between the primary circuit and the conversion energy system.

Nitride fuel have a high potential for lead fast reactor: it is compatible with molten lead and has a high density, a high thermal conductivity to improve passive safety, and may allow operating at higher temperature than oxide fuel.

The thermal, chemical and physical properties of molten lead as coolant are seen as assets allowing simplifying the design. Therefore there is hope to achieve a cost competitive design of reactor not only for a large unit (≈1200 MWe) but also for small to medium reactor sizing. For such modules used in battery plant type, open lattice and low core power density may provide very long fuel cycle and enhance natural circulation up to full power passive safety. But, up to now there is no evidence that it is possible to meet such goals.

With regard to the whole fuel cycle, LFR concept is not very different of SFR concept as long as UO2/PuO2 fuel technology is used. Aqueous or pyroprocess recycle technology may be considered.

Nitride fuel is proposed for LFR. In this case technology for production of nitrogen highly enriched in N15 should be developed as well as reprocessing and fabrication facilities.

The lead-bismuth eutectic has a lower melting temperature (125°C) than lead (327°C); this may help simplifying the design and it is considered for the subcritical Accelerator Driven Systems (ADS). However the polonium 210 generation (Bi209 + n Po210) which is a penalizing alpha and gamma emitter, may prevent plant simplification and makes maintenance more difficult. In addition the potential supply capacity and cost of bismuth are not well known.

Challenges and issues

Some issues are similar to those of the sodium cooled systems, such as the in-service inspection and repair issues, the criticality risk due to void effect (even though LFR may have a smaller void coefficient than SFR, and lead a higher boiling temperature than sodium) and re-criticality risk following accident leading to geometry change.

The main technology gap for LFR is structural materials for primary system components: The behaviour of most of the stainless steel and nickel based alloy in molten lead is poor, due to the fact that the solubility of nickel in lead is more than thousand times higher than in sodium. Lead chemistry control requirements (i.e. amount of oxygen) should be very stringent in order to avoid corrosion of the structural materials. The recent disclosure of Russian’s extensive technology developments involving Pb-Bi eutectic coolant has brought new information, especially in the areas of corrosion protection and special alloys.

Status of development work

Russia’s MINATOM has been developing a Pb-cooled reactor (BREST), and IPPE (Obninsk) is promoting SVBR-75/100 reactor modules based on the submarine reactor design. There are some international R&D investments, such as within the DOE NERI programme and the JNC study on fast reactor commercialization, supporting concept studies for advanced reactor systems based on Pb or Pb-Bi.

Development of accelerator-driven systems (ADS) has generated significant interest in Pb-Bi as a high power spallation target material and subcritical transmutation blanket coolant. These questions were investigated in the 5th FP (programme XADS coordinated by FANP) and the work continue in the EUROTRANS action of 6th FP. In the 6th FP the LFR concept is studied in the “ELSY”: European Lead-cooled SYstem project.

SODIUM-COOLED FAST REACTOR (SFR)

Early in the nuclear industry history, SFR was seen as the easiest achievable concept allowing both electricity production and closed fuel cycle. SFRs have already been built and operated in France, Japan, Germany, the United Kingdom, Russia, the United States and India, resulting in more than 100 reactor-year of operating experience.

Among the selected Generation IV systems, SFR is the most technologically developed breeder concept, and those deployable with the shortest delay. A large part of the technology bases and infrastructure exist for further developments. However efforts are needed for investigating to what extend desirable breakthroughs may exist for the economy, safety and availability challenges.

In addition, due to the past experience (SNR 300, Super Phénix); there is a strong public acceptance issue which shall be addressed.

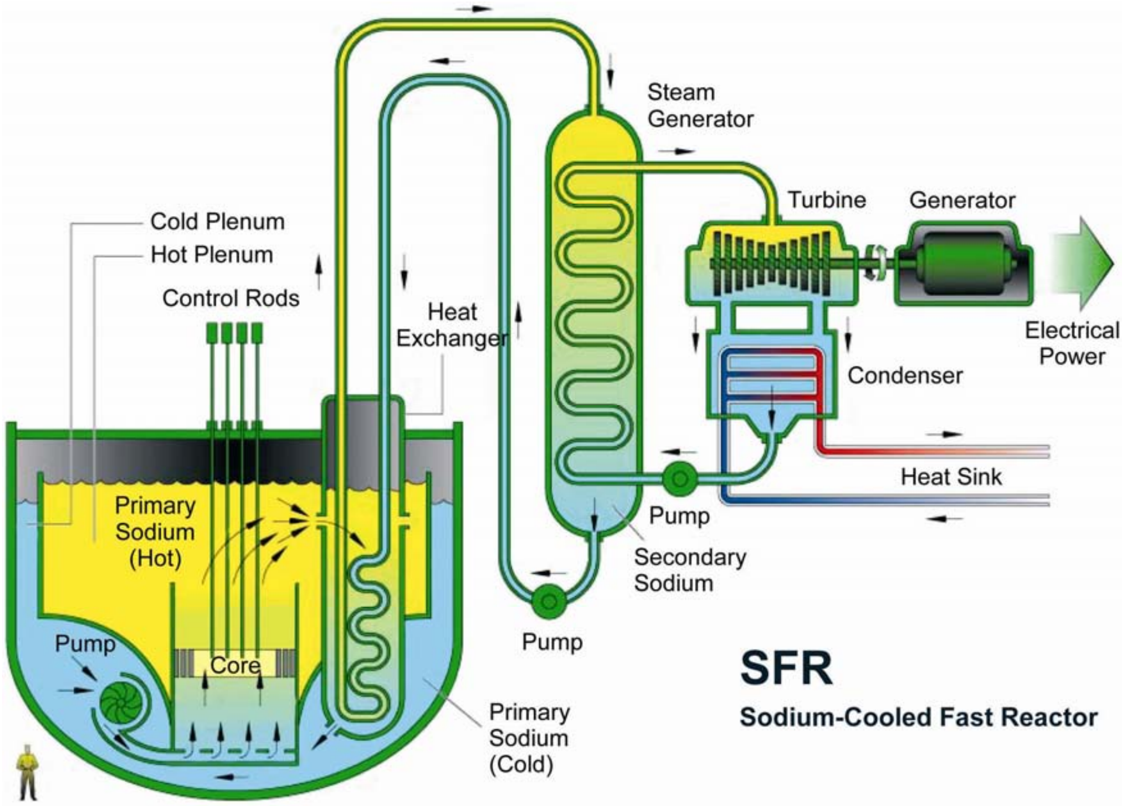


Figure F-6. Conceptual SFR system [1].

Incentive

Liquid sodium coolant allows building reactor, either of pool-type or loop-type concept with a primary circuit not pressurized. Core outlet temperature can reach the range of 500–550°C, thus providing an excellent thermal efficiency (≈ 45%)

The safety cases rely on passive responses:

- Classical ATWS events cause no fuel damage,
- Decay heat removal system needs no forced circulation,
- Thermal inertia is large in the pool-type concept,
- Operating conditions allow large margins to boiling.

The PUREX process performed well for LWR fuel reprocessing, it should at least have to be qualified for SFR fuel. Then this will allow recovering the plutonium for new fuel fabrication.

SFR should have also a good capability to burn minor actinides and is presently envisioned for managing actinides produced by LWRs. Limited tests are already performed at Phénix.

Main technical features

Sodium was chosen for coolant in most fast reactor development programmes because its density, heat transfer characteristics, and compatibility with the stainless steel materials of construction. However sodium, as a reactor coolant, has major drawbacks:

- its chemical reactivity; there have been small sodium leaks, and small fires, at essentially every sodium-cooled reactor plants operated; if the conventional island relies on a steam turbine cycle, the interface with the sodium filled system is a weak point,
- its positive void coefficient of reactivity; if sodium were to boil within the core, the nuclear reactivity introduced (the "void" reactivity) is positive over a significant fraction of a plutonium-fuelled core volume, and the maximum positive reactivity can reach several dollars;
- positive reactivity could also be inserted as a result of compaction of fuel subassembly clusters caused by mechanical effect (e.g. seismic-induced movement of the core).

The major key issue for the SFR is cost reduction to competitive levels: no SFRs based on present design would be economical to build or operate. Design studies have been done, some of them very extensively (EFR for instance), they did not provide a design with a cost comparable to or lower than those of the advanced LWRs.

The development followed for more than three decades in Europe, Russia and Japan, and the significant work performed for simplifying the plant design lead to concepts which have similarities:

- fuel made of UO2 or UO2-PuO2 pellets located in rods with stainless steel cladding, even though Na chemically reacts with UO2 in case of a clad defect,
- diversity in the reactor control systems utilizing passive mode of insertion,
- diversity and redundancy in the decay heat removal system, utilizing natural circulation.

The Sodium-Cooled Fast Reactor (SFR) is envisioned with two major options:

- a uranium-plutonium-minor-actinide-zirconium metal alloy fuel, supported by a fuel cycle based on pyrometallurgical processing in collocated facilities, this option will request more important developments than the following,

- a mixed uranium-plutonium oxide fuel, supported by a fuel cycle based upon advanced aqueous processing at a central location serving a number of reactors, this option is closer to the design already experimented.

The target discharged burnup for SFRs fuel is at least three times as large as that of LWRs. The spend fuel of SFR has higher content in plutonium, minor actinides and fission products, compared to LWR spend fuel.

Challenges and issues

Even though the extent of the technology base for SFRs is large; nevertheless some technology gaps remain in the areas of safety, reliability and economics.

It is expected that the reactor characteristics will allow a passive safe response to all design basis initiators. Issues such as positive sodium-void coefficient of reactivity, core-compaction recriticality, coolability of debris remaining in the reactor vessel must be achieved; proofs by test of the ability of the reactor to accommodate safely bounding events are expected.

Improvement of in-service inspection and repair technologies are needed to confirm the integrity of safety related structures and boundaries that are submerged in sodium, and to repair them in place. Motivated by the demand to address sodium-water reactions, it is also important to enhance the reliability of early detection systems for water leaks.

Re-optimizing the present design would probably be not enough to achieve a drastic cost reduction and some major changes may be necessary to reach this goal; specific very innovative design features may be considered, for example:

- reduced number of primary loops,
- integral pump and intermediate heat exchanger,
- development of large, highly reliable steam generators; or other fluids than sodium and/or water-steam for the secondary heat transfer system and the energy conversion system (turbine-generator plant), thus eliminating sodium-water reaction hazards (i.e. use of a supercritical CO_2 Brayton cycle could allow to remove the intermediate heat transfer system)
- use of improved materials of construction.

If minor actinide recycling is requested, then co-extraction (with Pu) or recovery after Pu separation will have to be implemented in some advanced aqueous recycle technology.

The Pyroprocess Fuel Cycle is an important challenger of the PUREX process. It has very few process steps and the facility and equipment systems are much more compact. The inability of the pyroprocess to recover pure fissile material is seen as an advantage with respect to proliferation resistance. However the pyroprocess development has never gone beyond the pilot-scale stage.

Fabrication of fuel containing minor actinides has to be developed up to an industrial scale.

Status of development work

Some effort is already foreseen on SFR within the framework of the Gen IV Initiative. The most active countries are Japan (Leader), France, Korea, the UK and the USA.

The Japanese are working to the restart of MONJU and to design the new JSFR, a concept based on the loop-type reactor of MONJU. The design accounts for cost reduction measures such as integration of IHX and primary pumps or use of 12-Cr steel as structural material, double wall steam generator tubes, as well as improved safety features which preclude recriticality accident in case of core disruptive accident.

India is launching the realization of its 500 MWe DFBR, with a pool-type design.

Russia has completed the design of the pool-type BN-800 which is basically an improved version of BN-600 that has been operating since 1980. Special effort has been made in order to reduce the positive reactivity insertion due to void effect; it aims at increasing neutron leakage in this case thus resulting in negative reactivity feedback. A seven nation team (Germany, France, UK, Italy, Japan, India and Russia) performed a comprehensive transient and accident analysis for BN-800 under the aegis of AIEA.

Europe has a large experience on liquid sodium technology, however, this experience will disappear in some years with the retirement of people having worked on these projects. Work on EFR and RNR 1500 are stopped, and the existing collaboration agreements in Europe (United Kingdom, Germany and France) are now obsolete. There is still some work performed for Phénix that CEA will continue to operate until 2009. The main action is dealing with fuel and transmutation, based on the experiments under way at Phénix.

MOLTEN SALT REACTOR (MSR)

The “non-classical” concepts analyzed by the relevant GIF technical working group featured a range of reactor designs with nuclear fuel in gaseous, liquid or solid phases, with no coolant or with non-conventional coolant, and with a variety of energy conversion system. The Molten Salt Reactor is the only “non classical concept”, among the 32 concepts analyzed, which has been kept in the final selection of the “most promising systems”.

Molten Salt Reactors were experimented in the 50s and 60s, thus there is a proof of their feasibility. Under these programmes, many issues relating to the operation of MSRs were resolved, such as the Li-Be fluoride salt behaviour under irradiation or the stability control of a fluid core.

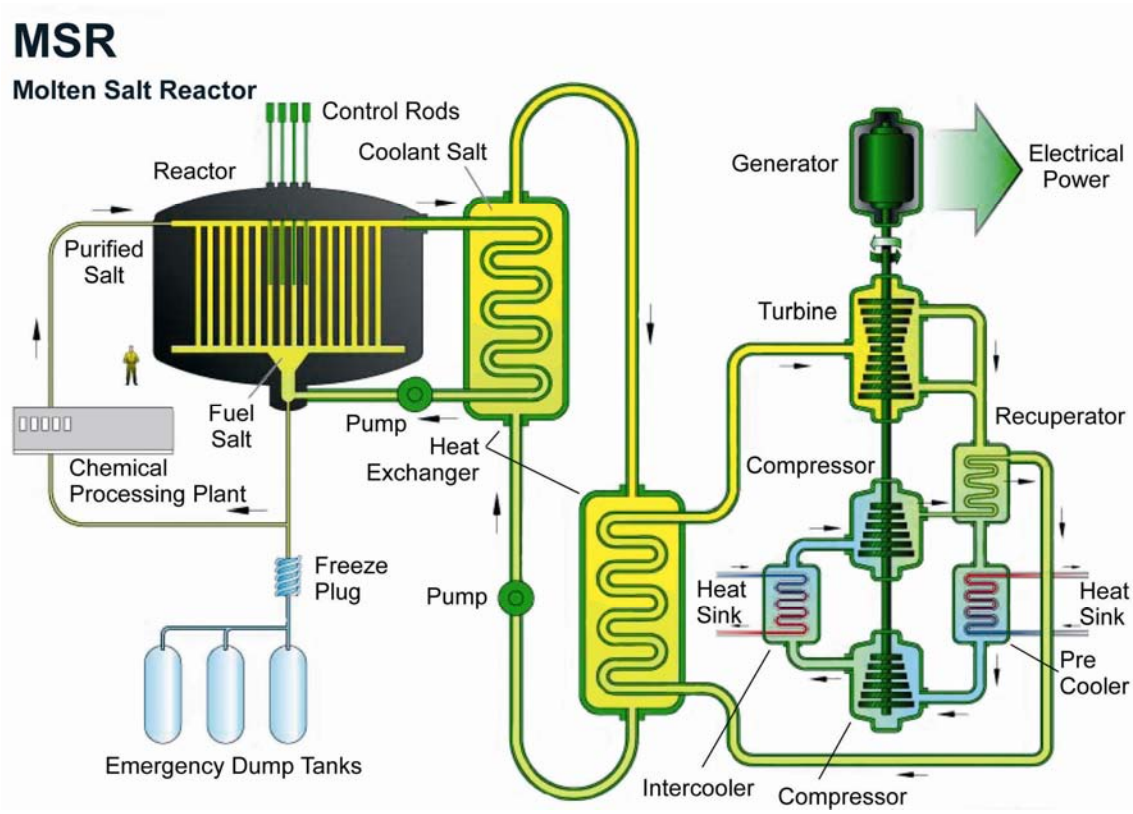


Figure F-7. Conceptual MSR system [1].

Incentive

The molten salt reactor has a good neutron economy. The MSR system is foreseen with closed fuel cycle, either U238→Pu239 or Th232→U233 cycles. This system is especially well suited for using thorium, then it may achieve an actual breeding ratio significantly higher than 1 (≈ 1.06), with a thermal neutron spectrum core. Furthermore, the thorium fuel cycle minimizes the generation of long-lived higher actinides compared with the U238 fuel cycle. MSR as also be seen as a potential actinide burner.

Safety is seen good because:

- there is no need to pressurize the core (molten salt boiling temperature is about 1400°C),
- the accident radioactive source term is low due to the continuous removal of mobile fission products from the fuel,
- the core inventory in fissile material may be kept low for a breeder reactor primarily because it operates with a neutron thermal spectrum,
- the implementation of passive safety is eased by fail-safe drainage of the fuel to cooled tanks.

Economics is not yet known. MSRs operate at relatively high temperatures (a heat source above 700°C is expected), thus allowing an efficient power conversion (> 45%), and possibly providing the potential for other energy use than electricity, such as hydrogen production. The primary system is a low-pressure system that allows reactors of very large power to be built thus getting benefit of the size effect.

The MSR has a simplified fuel cycle. There is no fuel element fabrication or recycling required and no transport of highly radioactive materials except for high-level waste after storage to reduce decay heat loads.

However, there is a major drawback: the need to implement and to operate on the reactor site, a chemical plant for online feeding and processing the core mixture and removing the fission products.

Main technical features

The fuel is a liquid mixture of alkali metal (lithium-7, beryllium, sodium…) fluorides and thorium-uranium fluoride fuel. The liquid fuel salt flows up through vertical channels into an unclad graphite core. The graphite moderates the neutron spectrum, such that criticality occurs only in the reactor core. The heat is generated directly in the molten fuel.

During operation, most fission products and all actinides form fluorides in the liquid. The fluid fuel flows out of the reactor core through a primary heat exchanger, where the heat is transferred to a secondary coolant, then the fluid fuel is pumped back to the core. The heat is dumped from the secondary system to the power cycle. The original design proposed for the MSR has a molten salt secondary loop and a high-temperature steam cycle.

There are two fluid-fuel cleanup systems.

1. A high-efficiency gas-stripping system incorporated into the primary circulation pumps removes noble gases (xenon, krypton, etc.) and tritium. The noble gases, particularly certain xenon isotopes, are strong neutron absorbers. Without the quick removal of the gases, the neutrons absorbed by these gases would prevent the reactor from being a breeder reactor.
2. A salt-cleanup system removes lanthanides and other fission products from the salt and controls the salt composition system.

MSRs can have either an intermediate or thermal neutron spectrum. The concentration of fissile materials in the salt is limited by their solubility. As a consequence, the neutron moderator characteristics of the salt are sufficient to prevent operation with a fast neutron spectrum core.

Challenges and issues

The MSR has a number of technical viability issues that need to be resolved; due to the previous experimental programmes, the R&D issues are reasonably well understood. The main topics are:

Salt Processing: Efficient process is needed to remove radionuclides from the salt to maximize the breeding ratio.

Corrosion Resistance: Long term molten salt material compatibility.

Potential long-term corrosion problems caused by the fission product tellurium were identified. Added testing, including reactor test loops, is required to have full confidence in the alloys.

The same molten salts as those considered for fission reactor are the leading candidates for cooling fusion power reactors. Thus there is a potential for synergic R&D with the MSR, unfortunately the commercial interest of such application may only be for the very long term.

Tritium Control: The 7LiF in the salt results in significantly higher tritium production than in other reactors. At the high temperatures found in an MSR, the tritium can diffuse through the heat exchangers into the secondary system. The tritium control technologies need to be fully mastered.

Off-gas System: The off-gas system must quickly immobilize captured fission products so the accident risks are not just transferred from the reactor to the off gas system but are significantly reduced.

In Service Inspection and Repair: Even though the molten salt are transparent, they melt above 400°C, thus requesting specific features for ISIR.

Current Regulatory Design: The current regulatory structure is designed for solid fuel reactors. Significant changes in design may be required to meet the intent of current regulations. Work is required with regulators to define equivalence in safety for a reactor with very different characteristics.

Non-proliferation: MSR fuel cycles are fundamentally different than once-through LWR fuel cycles and traditional closed fast reactor. Research is required to understand the issues and determine if design changes are required.

Thorium processing: Thorium has not been widely used to date, the process are not as well mastered as with the Uranium fuel cycle and there is nearly no operating experience other than at a laboratory scale.

Economics is difficult to anticipate because of its large number of subsystems, for fuel and coolant processing, which must be located on every NPP site, and because the whole industry of the fuel cycle must be developed.

If the fast breeder reactors (either liquid metal or gas cooled) succeed to be competitive, then U-Pu fuel cycle will be used for the long term, plenty of fertile fuel material is already available, and thorium may not be necessary before at least a few centuries.

Status of development work

MSRs were initially developed in the early 1950s as part of the Aircraft Nuclear Propulsion Programme in the United States. The Aircraft Reactor Experiment (ARE), a small test reactor (2.5 MWth) was operated with a core outlet temperature of 860°C.

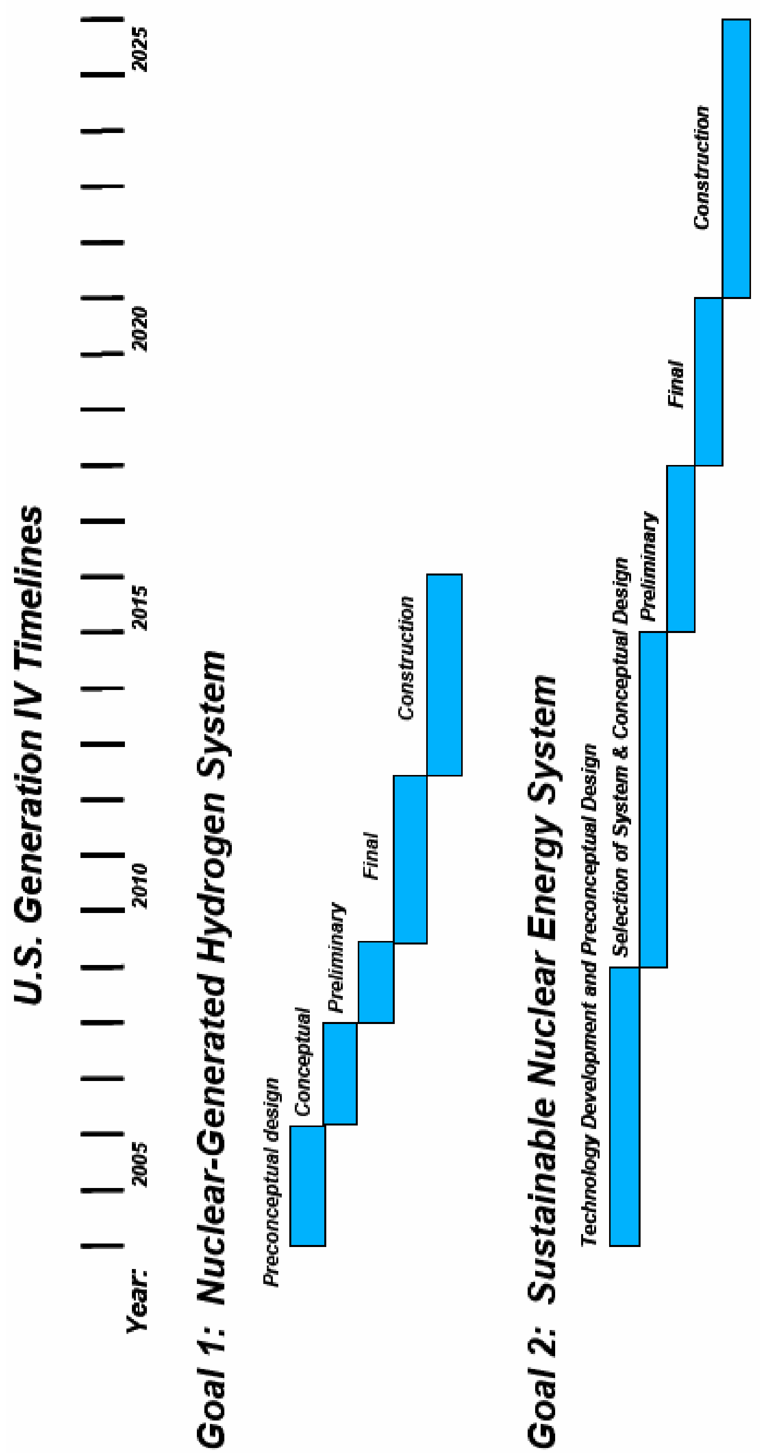
Then, the 8-MWth Molten Salt Reactor Experiment (MSRE) was successfully operated from 1965 to 1969 at Oak Ridge National Laboratory, first with U235 fuel and later with U233 fuel. The core outlet temperature of 650°C was high enough to demonstrate the concept for energy production.

The potential of the MSR concept has been confirmed by the Project MOST in the 5Th FP. Much of the recent work on MSRs has been to simplify the cleanup process. More recent proposals, have suggested using a helium gas turbine power cycle.

There is presently some work performed in Russia (Kurchatov Institute), Japan, Korea, Czech Republic, in the USA (universities, Argonne NL) and in France. EdF (with the CEA and CNRS) is examining MSRs for power production and transmutation of higher actinides in the AMSTER project (Actinide Molten Salt Transmuter).

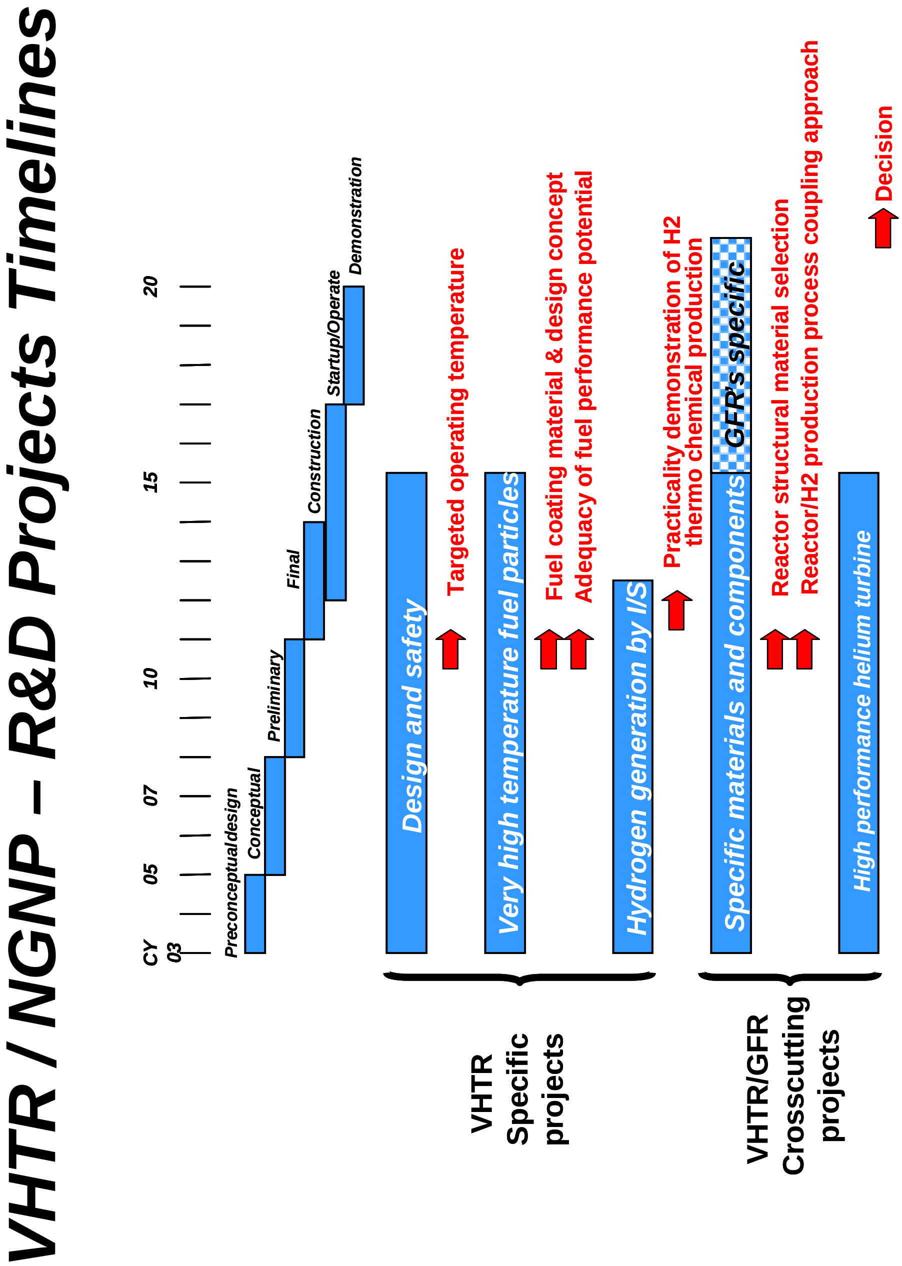
Few countries show some interest for this concept; but recently France has taken initiative to form a GIF Steering Committee for MSR and EDF supports some work on MSR.

Appendix G: Generation IV schedules



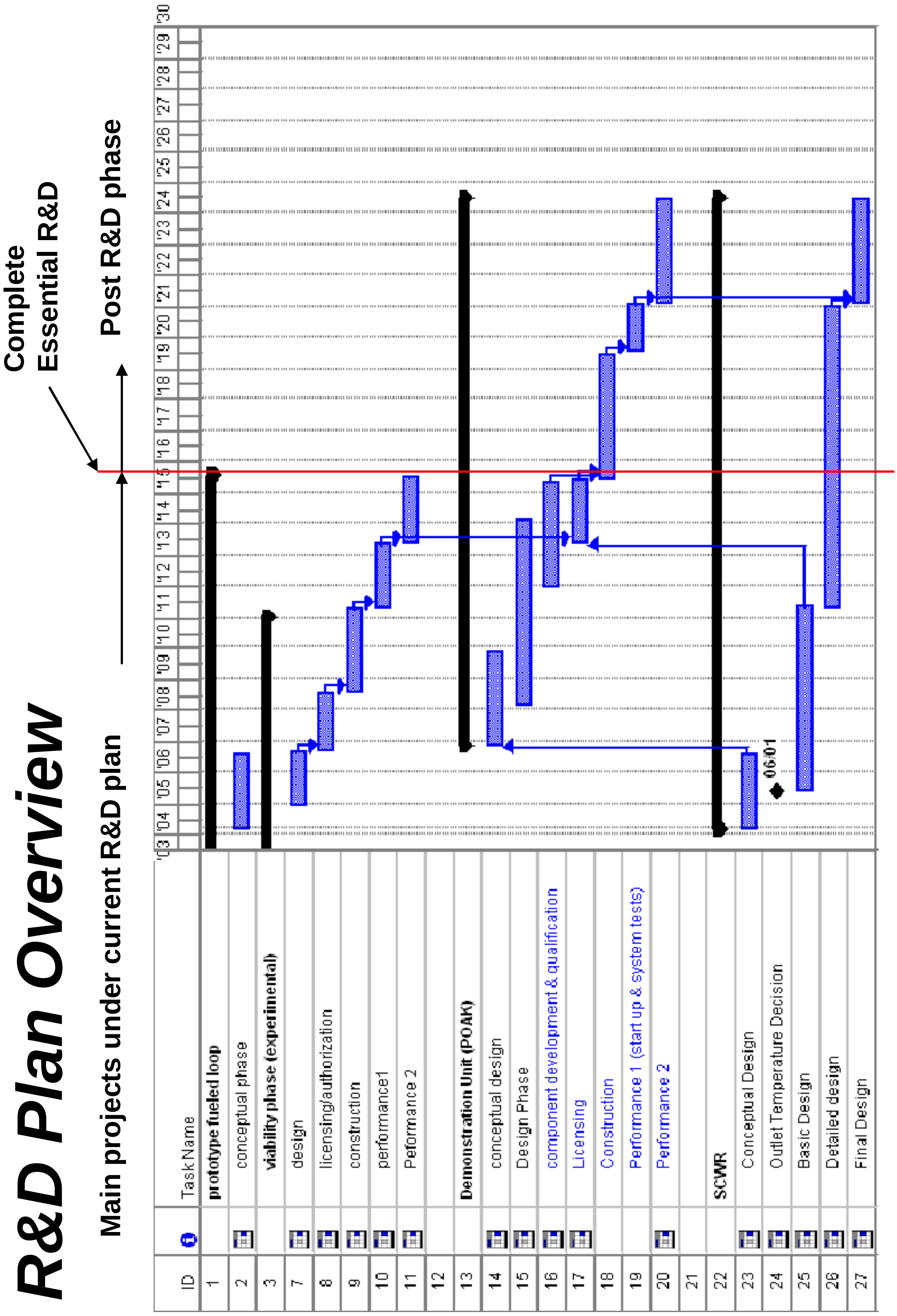
GENERATION IV NUCLEAR ENERGY SYSTEMS, TEN-YEAR PROGRAM PLAN, Fiscal Year 2005, Volume I, Released March 2005, Office of Advanced Nuclear Research, DOE Office of Nuclear Energy, Science and Technology.

System Research Plan for the Very-High-Temperature Reactor



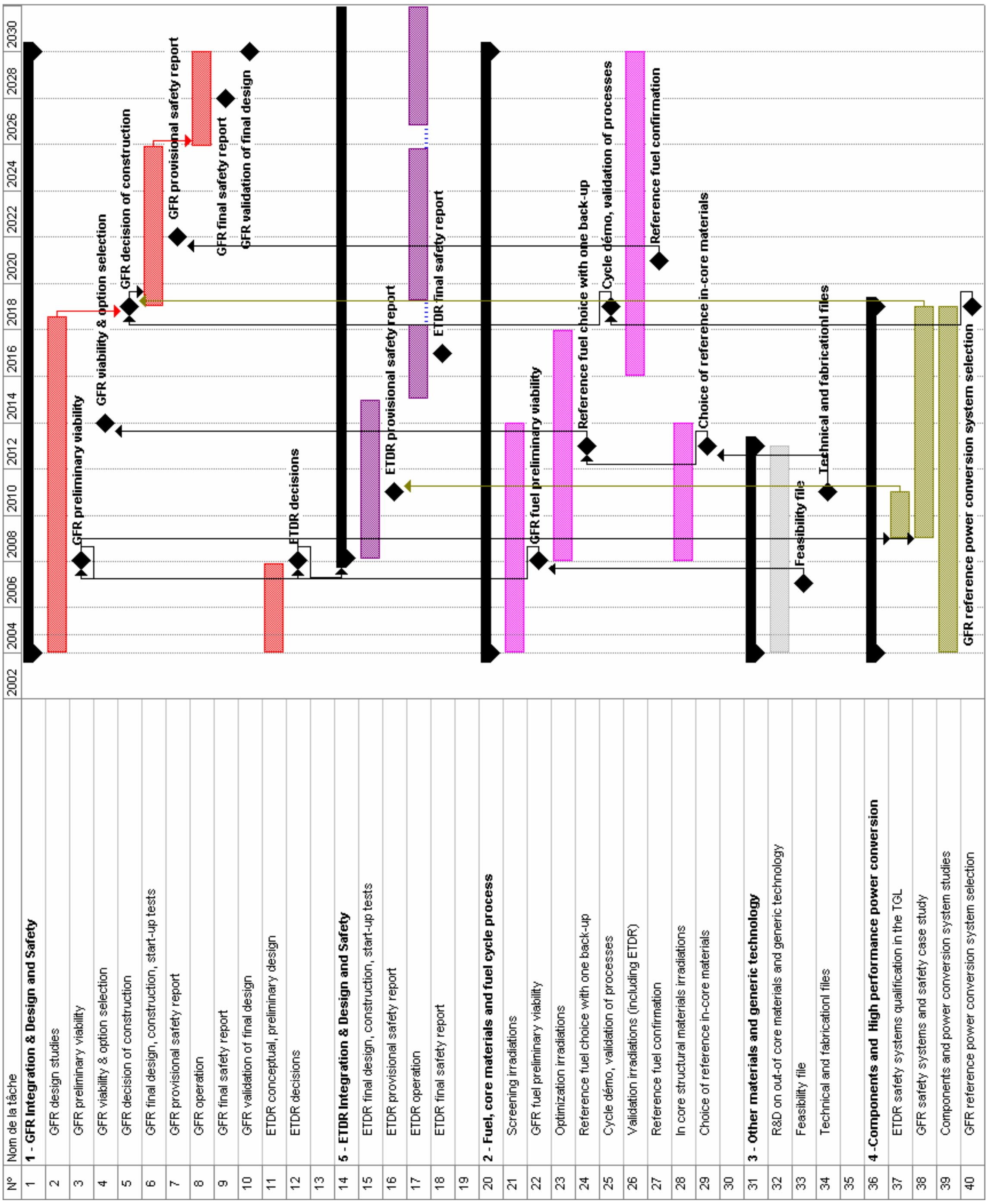
From Werner von Lensa, Forschungszentrum Juelich, Euratom Representative in the Provisional VHTR Steering Committee Meeting, presented at the Euratom GIF co-ordination meeting, Brussels 3.3.2005.

R&D Update for the Supercritical Water-Cooled Reactor (SCWR)



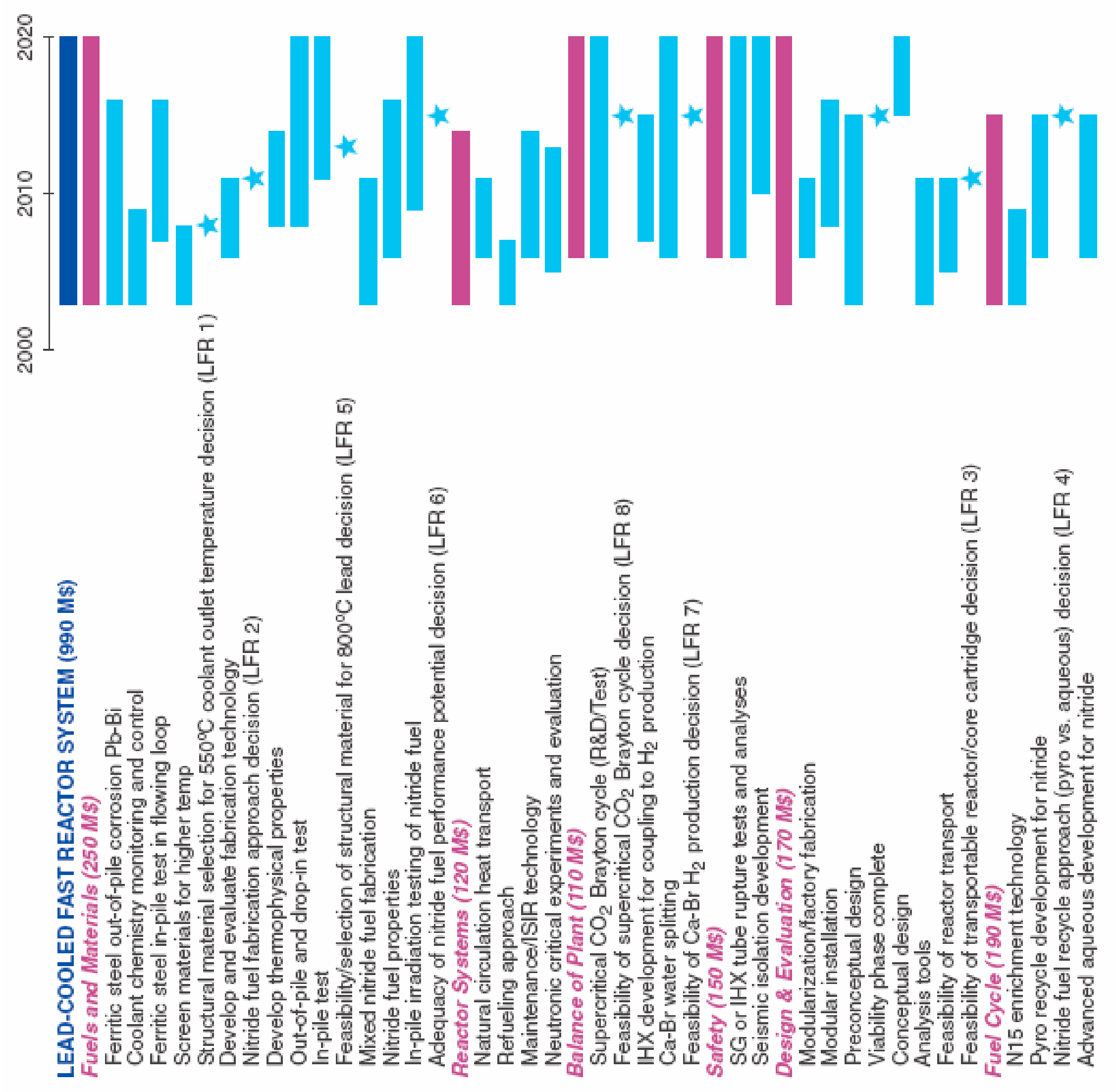
SCWR Provisional System Steering Committee, Brussels, Belgium, April 12, 2005

System Research Plan for the Gas-Cooled Fast Reactor (GFR)



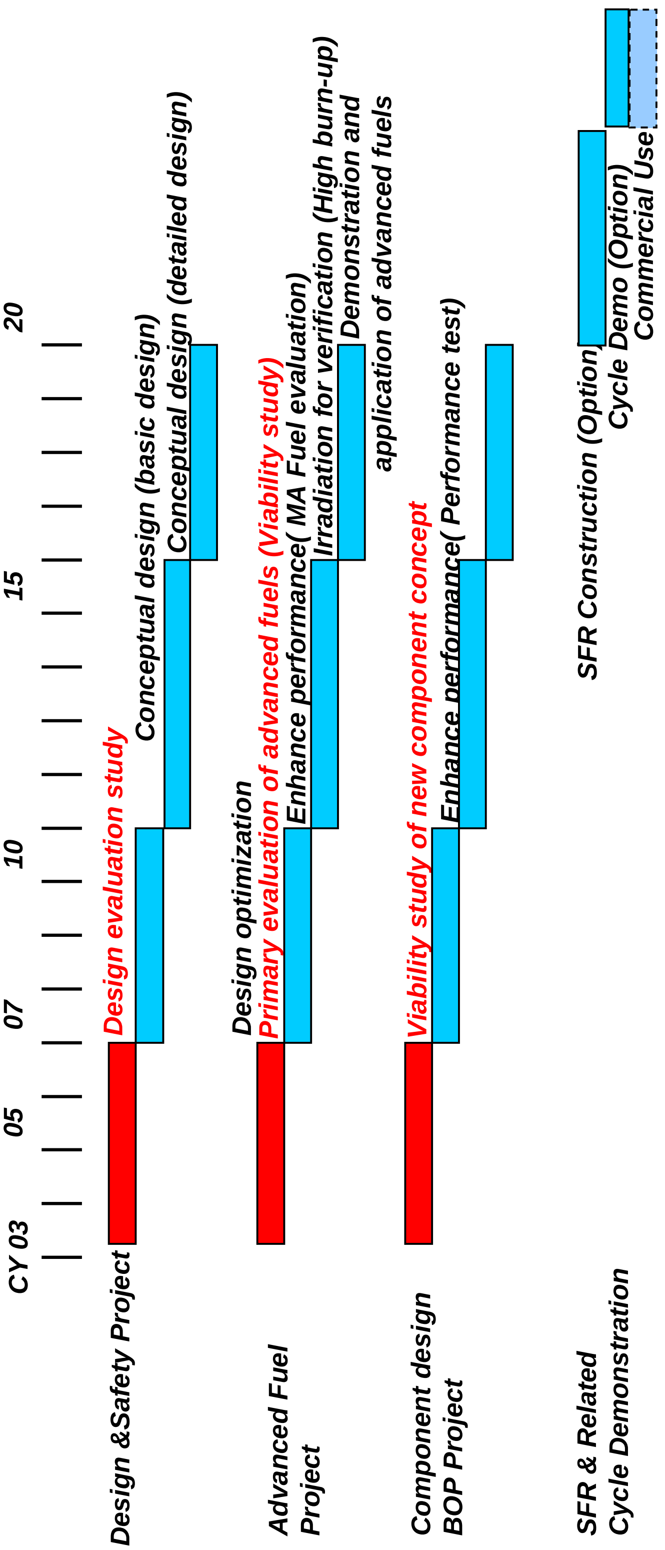
Dec 2004

Research Plan for Lead-Cooled Fast Reactor (LFR)



Reference [1]

Research Plan for Sodium-Cooled Fast Reactor (SFR)



Update on Research Plan for Sodium-Cooled Fast Reactor (SFR), Masakazu Ichimiya, co-chair, GIF Policy and Experts Group Meeting, Brussels, Belgium, April 12, 2005

Appendix H: NETNUC research plan

New Type Nuclear Reactors (NETNUC)

Summary
of the research plan presented to the Finnish Academy for funding in the Sustainable Energy research programme (SusEn) in April 2007.

NETNUC CONSORTIUM ORGANIZATION

Leader of Consortium
Prof. Riitta Kyrki-Rajamäki, Lappeenranta University of Technology
Leaders of other consortium partners
Prof. Rainer Salomaa, Helsinki University of Technology
Dr. Liisa Heikinheimo, Technical Research Centre of Finland

Name of consortium: New Type Nuclear Reactors (NETNUC)

OBJECTIVES

Today, an access to sustainable, sufficient and economically viable energy sources, mitigation of greenhouse gas emissions, and avoiding harmful environmental and health impacts are vital to growing world population. None of the presently known energy sources is able to alone solve the global energy problems: all the alternatives need to be combined to survive the future world. The new generation fission reactors can offer a remarkable contribution by extending the availability of nuclear fuel resources to thousands of years. Recycling of uranium, plutonium and minor actinides, use of thorium as an additional fission fuel, and reduction of volumes, heat loads and isolation time of remaining high-level nuclear waste requiring deep geological disposal will improve the position of nuclear fission as a long-term sustainable energy source. In addition to electricity production, new applications, process heat for industrial use, and production of hydrogen, are foreseen. Nuclear energy causes negligible greenhouse gas and fine particulate emissions. However, strict control on safety of reactors and fuel cycle facilities as well as safe and timely nuclear waste disposal and improved proliferation resistance are prerequisites of a positive net contribution to the wellbeing of the whole society. The technical potential of Gen IV in power generation will be shown in a time span of 15–20 years as the first demonstration plants are to be built (decision already made in France).

In the NETNUC project we form a multidisciplinary consortium of national and international partners to carry out basic research to generate scientific knowledge needed in the development of Gen IV fission reactors and to educate a new generation of research scientists in the field.

The research team consists of seven domestic and five international partners. Nationally the consortium joins the forces of LUT and TKK in the postgraduate level education with the research activities and opportunities by VTT for in-depth on-the-job training as well as for postgraduate theses. A critical size of the group is thus achieved, with excellent cross-fertilisation potential of the strengths of each partner. This consortium can together tackle the technical, economical, safety, environmental impact and social issues of Gen IV reactors and fuel cycles.

Research objectives

The development of Gen IV plant concepts is in many aspects revolutionary and many innovative steps in plant and system features have to be taken in the fields such as:

- integrated approach on systems and socio-economic impacts of nuclear energy taking into account the sustainability of the fuel cycle and waste management,
- assurance of high safety level and proliferation resistance,
- reactor physics and dynamics modelling and calculation system to assure control of reactivity and power production as well as inherently safe properties of reactor core in spite of new isotopes involved,
- modelling of the core and cooling circuit thermal hydraulics, and the whole energy conversion or the energy utilization process,
- advanced solutions for structural materials and fuel to achieve the more demanding operation parameters and burnup,
- renewing the energy source in biomass-based industries.

Hypotheses

The research work aims to contribute in the validation of the following hypotheses:

- Key phenomena affecting the safety of new types of reactors are understood thoroughly enabling the creation of systematic safety criteria that ensure adequate safety and security of the reactors and fuel cycle facilities (Safety).
- Advanced reactors and the associated fuel cycles can be developed that utilize more abundant natural isotopes and increase the effectiveness of the fuel resource usage and produce less high-level nuclear waste (Sustainability).
- New types of reactors can be developed in international cooperation (SCWR, VHTR, GFR, SFR) capable of producing energy effectively and economically for electricity, process heat and hydrogen yields in cogeneration processes (Efficiency).

These three hypotheses are studied in sub-projects lead by LUT, TKK and VTT, respectively. They need to be tackled within multidisciplinary research areas and the five targeted Tasks studied in these sub-projects are shown in Figure H-1.

The research field is very wide and multifaceted involving several disciplines that can be reached only via consortium networking. The efficiency and critical mass of the scattered researcher groups is further multiplied by networking. Thus a fertile environment for innovative research is created. The consortium has excellent links to other national stakeholders: end users as well as national nuclear safety research programmes SAFIR2010 & KYT2010. To obtain international impact only a consortium is presently able to provide enough resources and satisfactory networking efficiency through the existing EU-projects, GIF forums and bilateral contracts.

IMPLEMENTATION

The work of the sub-projects will be carried out grouped within five tasks and their subtasks, illustrated in Figure H-1. The work in these tasks is in most cases carried out by several of the research partners in close co-operation and the research is linked to one or more of the three hypotheses, Safety, Sustainability or Efficiency.

INTERNATIONAL COLLABORATION

There are two comprehensive international co-operation efforts for Gen IV nuclear systems, namely the Generation Four International Forum (GIF) and the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) of IAEA. Finland participates GIF through the membership of Euratom. Finnish and international members of this project consortium are represented in its committees e.g. on risk and safety, economy as well as on materials issues. The NETNUC project has active contacts to the main developers of Gen IV reactors through the international partners. The following Finnish representatives in the steering and working groups of GIF: Dr.

Liisa Heikinheimo (SG of cross-cutting materials issues), Prof. Risto Tarjanne (WG on Economics), Antti Daavittila (Risk and Safety WG).

New Type Nuclear Reactors (NETNUC)

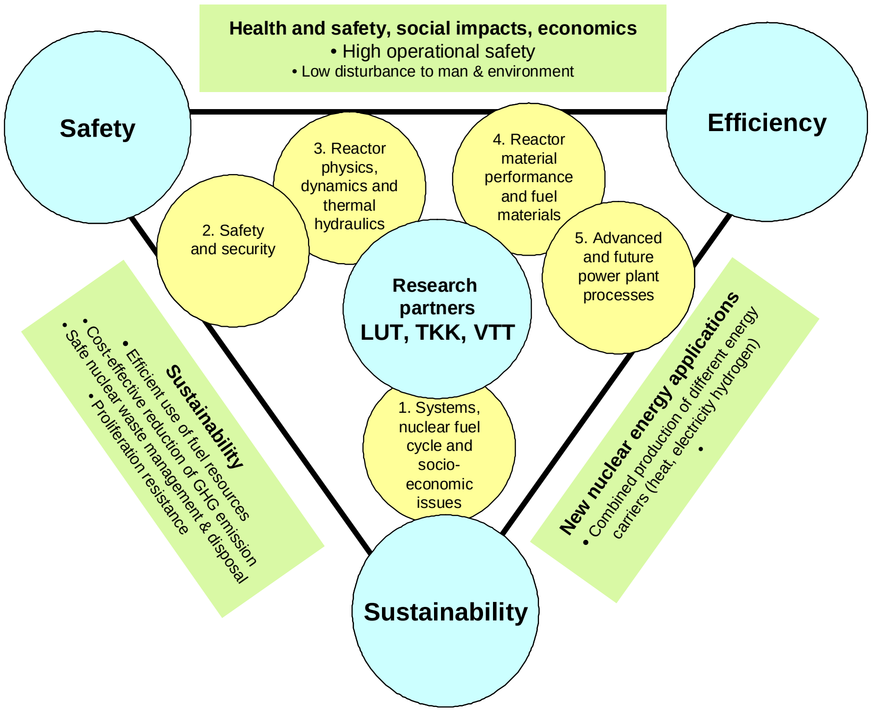


Figure H-1. Structure of NETNUC consortium project with the main hypotheses and tasks.

The Sustainable Nuclear Energy Technology Platform (SNE-TP) [16] of EU was launched in September 2007 with VTT as a partner. Its main objectives coincide with many aspects of the NETNUC proposal. Consequently NETNUC contributes to the objectives of SNE-TP, which covers both the present and advanced light-water reactor (e.g. EPR) and fast reactors with closed fuel cycle which are crucial for the long-term sustainability of nuclear fuel resources. SNE TP also covers production of other energy carriers besides electricity. Consequently, the participation of VTT in this Technology platform ensures the close networking to other European stakeholders and research organisations.

The project will be closely connected with EU projects (HPLWR2 for SCWR concept and Raphael for VHTR/GFR gas cooled concepts) and other global forums. The consortium is already actively involved in research projects of Gen IV. VTT has participated in Gen IV projects already in the previous FP5 and participates now in the project “High Performance Light Water Reactor 2”, in which Dr. Jari Tuunanen from TVO belongs to the User’s Group. Dr. Harri Tuomisto from Fortum belongs to the User’s Group and prof. Riitta Kyrki-Rajamäki to the Safety Advisory Group of the Raphael project.

RESEARCHER TRAINING AND RESEARCH CAREER

The individual MSc and Dr. research students involved in NETNUC will be supervised by their professor and the subtask supervisor(s). Besides their research work, the students will attend in the study courses organised commonly by the consortium and its collaborators. Nationally, TKK and LUT will annually give at least one Gen4 related graduate course and a regular research seminar. The students are, furthermore encouraged to participate in international topical summer courses; both TKK and LUT are full members of the Association of the European Nuclear Engineering Education Network, ENEN, which offers versatility of courses and e.g. tools for educational quality assurance. Each full-time graduate student is strongly recommended to pay a longer visit of the order of 3–12 months abroad. Students will be integrated into the GEN4FIN research network which trains them to international project activities. Both in the industry and academia, employment perspectives of new nuclear graduates appear excellent: the aging of present professionals causes a large demand of new ones.

Traditionally females have represented a minority of the field; this situation has recently improved but needs still active recruiting measures. In the project plan the share of females is 14% of the advisers and 23% of the post-graduate students.

As deliverables this project will provide several Master Theses and Doctor Dissertations on topical areas and information to decision makers and the public. Knowledge transfer will be enhanced. The consortium will create a doctoral level training programme including lecture courses and regular consortium seminars. An international part involves student participation in international activities (conferences, workshops, summer schools) and mobility visits to the partner institutes.

EXPECTED SCIENTIFIC AND SOCIAL IMPACT

The main mission of the sub-projects and tasks is to create and improve scientific and technologic expertise in the field of Gen IV reactors. This also serves the needs of nuclear energy technologies and related processes applied in Finland to-day and in future. The first future applications would be the Gen IV demonstration plants. The materials developed have a general impact on development of new materials suitable for other extreme environments, such as e.g. space applications or engines. The longer term effect of the NETNUC project is also to create new business opportunities for the Finnish industry through enhanced technology transfer, innovative process development, and materials engineering.

ISBN 978-951-38-7149-9 (URL: http://www.vtt.fi/publications/index.jsp)
ISSN 1459-7683 (URL: http://www.vtt.fi/publications/index.jsp)