GEN IV International Forum℠

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GIF R&D Outlook for Generation IV Nuclear Energy Systems

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ACRONYMS

AHTR	advanced high-temperature reactor
AVR	Arbeitsgemeinschaft Versuchsreacktor
ELSY	European lead-cooled system
EMWG	Economics Methodology Working Group
ETDR	experimental technology demonstration reactor
GFR	gas-cooled fast reactor
GIF	Generation IV International Forum
GTHTR	gas turbine high-temperature reactor (Japan)
GT-MHR	gas turbine modular helium reactor
HTR	high-temperature reactor
HTR-PM	high-temperature reactor–pebble bed module
HTTR	high-temperature engineering test reactor
IAEA	International Atomic Energy Agency
LFR	lead-cooled fast reactor
LWR	light water reactor
MA	minor actinide
MSR	molten salt reactor
NGNP	Next-Generation Nuclear Plan
NHDD	nuclear hydrogen development and demonstration
O&M	Operations & Maintenance
PBMR	pebble bed modular reactor
QMS	quality management system
R&D	research and development
SCWR	supercritical water-cooled reactor
SFR	sodium-cooled fast reactor
SSTAR	small secure transportable autonomous reactor
THTR	thorium hochtemperature reaktor (Germany)
VHTR	very high-temperature reactor

GIF R&D OUTLOOK FOR GENERATION IV NUCLEAR ENERGY SYSTEMS

1. AN ESSENTIAL ROLE FOR NUCLEAR ENERGY

The world's population is expected to expand from 6.7 billion people today to over 9 billion people by the year 2050, all striving for a better quality of life. As the earth's population grows, so does the demand for energy and the benefits that it brings: improved standards of living, better health and longer life expectancy, improved literacy and opportunity, and many others. Simply expanding the use of energy along the same mix of today's production options, however, does not satisfactorily address concerns over climate change and depletion of fossil resources. For the earth to support its population while ensuring the sustainability of humanity's development ,we must increase the use of energy supplies that are clean, safe, cost effective, and which could serve for both basic electricity production and other primary energy needs. Prominent among these supplies is nuclear energy.

There is currently 370 GWe of nuclear power capacity in operation around the world, producing 3000 TWh each year—15% of the world's electricity—the largest share provided by any non-greenhouse-gas-emitting source. This reduces significantly the environmental impact of today's electricity generation and affords a greater diversity of electricity generation that enhances energy security.

The importance of reducing greenhouse gas emissions is now universally recognized, and numerous strategies and scenarios are proposed in order to achieve more sustainable future energy supplies. In the majority of these, the prospects are good for nuclear energy's growth. For example, the 2008 World Energy Outlook forecasts an additional 250 GWe of nuclear capacity by 2030 in a scenario that would stabilize the atmosphere at 450 ppm CO_2 and thereby limit global warming to 2°C above pre-industrial levels. Of course, if other forms of clean energy cannot be deployed in sufficient amounts, nuclear must be ready to do more to complement them well into the future.

Many of the world's nations, both industrialized and developing, are driving the growth of nuclear energy. Some 43 new units are under construction in 11 countries, and more are preparing to move forward. They are confident that nuclear energy is a valuable option for their energy security in the future. However, challenges still exist to further large-scale use of nuclear energy: (1) nuclear energy must be sustainable from the standpoint of its utilization of nuclear fuel resources as well as the management and disposal of nuclear waste, (2) the units must operate reliably and be economically competitive, (3) safety must remain of paramount importance, (4) deployment must be undertaken in a manner that will reduce the risk nuclear weapons proliferation, (5) new technologies should help meet anticipated future needs for a broader range of energy products beyond electricity, and (6) governments need to support the revitalization of their nuclear R&D infrastructures. The first four are the major goals of Generation IV; the latter two have become increasingly important in recent years.

1.1 Meeting the Challenges of Nuclear Energy's Essential Role

To meet these challenges and develop future nuclear energy systems, the Generation IV International Forum (GIF) is undertaking necessary R&D to develop the next generation of innovative nuclear energy systems that can supplement today's nuclear plants and transition nuclear energy into the long term. Generation IV nuclear energy systems comprise the nuclear reactor and its energy conversion systems, as well as the necessary facilities for the entire fuel cycle from ore extraction to final waste disposal. Generation IV systems can be broadly divided into fast and thermal reactors that address the above challenges with differing emphasis and technology (Section 2).

Today, most countries use the once-through fuel cycle, whereas a few close the fuel cycle by partial recycling. Recycling (using either single or multiple passes) recovers uranium, plutonium, and other transuranics from the spent fuel and uses it to make new fuel, thereby producing more energy and reducing the need for enrichment and mining. Recycling in a manner that does not produce separated plutonium can further avoid proliferation risks. However, the once-through fuel cycle is still often viewed as the most competitive given the existing supplies of uranium, though it is expected that views will change as supplies become scarcer and the cost of maintaining an open cycle exceeds that of a closed cycle. With recycling, other benefits are realized: the high-level radioactive residues occupy a much-reduced volume, and their long-term burden can be significantly reduced (decay heat and radiotoxic inventory). Furthermore, they can be processed into a resistant and durable waste form for disposal. Of course, recycling the long-lived elements, especially the higher actinides that can be transmuted in fast reactors, achieves maximum reduction.

Even before the cost of CO_2 is taken into account (for example, through emissions trading schemes), the cost of nuclear power generation in many countries is competitive with the cost of producing electricity from CO_2-emitting coal or natural gas. On the other hand, advanced nuclear energy systems must address the escalating construction costs associated with new nuclear plants. Once again, a major R&D effort is needed to develop advanced designs that reduce capital costs and construction times.

Overall, the safety and environmental record of present-day nuclear plants is excellent. Nevertheless, the safety of nuclear power will be increased; that of advanced systems will be addressed through a clear and transparent safety approach that arises from a comprehensive and rigorous R&D program.

Fissile materials within civilian nuclear power programs are well safeguarded against exploitation by their host states because of an effective international system of controls and monitoring. Nevertheless, it is desirable for safeguards regimes and intrinsic nuclear design characteristics for future nuclear fuel cycles and nuclear materials to achieve an even higher degree of protection from the diversion or covert production of nuclear materials. Current-generation plants have robust designs and added precautions against sub-national, non-host-state threats of sabotage and nuclear material theft, including acts of terrorism. Future nuclear energy systems will provide even greater physical protection against such threats.

Most Generation IV systems are aimed at R&D advances that enable high operating temperatures. This will allow greenhouse-gas-free nuclear energy to be more broadly substituted for fossil fuels in the production of hydrogen and process heat.

Finally, with regard to the challenge of maintaining the R&D infrastructure, the Forum strongly supports the coordinated revitalization of nuclear R&D infrastructure worldwide to a level that would once again move a new generation forward quickly.

Generation IV nuclear energy systems will take another two to three decades to advance towards our ambitious goals. This *Generation IV R&D Outlook* provides a view of what the GIF members hope to achieve collectively in the next five years. As always, each Forum member is free to choose the systems that they will advance. The various sections introduce the systems that we are advancing and the goals that we are working towards. They also describe the horizontal work we do in support of all our technologies, highlighting vital areas such as quality management, system integration and assessment, and collaborations around the world.

Our resolve is to promote future nuclear energy systems that enable the safe and sustainable worldwide growth of nuclear energy well into the future. The Forum is excited about the prospects for nuclear energy and believes our plans can make a considerable contribution to its long-term success.

2. FINDINGS OF THE ROADMAP

2.1 Generation IV Nuclear Energy Systems

The *Generation IV Roadmap* exercise culminated in the selection of six Generation IV systems.[1] The basis for the selection of six systems was to:

- Identify systems that make significant advances toward the technology goals
- Ensure that the important missions of electricity generation, hydrogen and process heat production, and actinide management may be adequately addressed by Generation IV systems
- Provide some overlapping coverage of capabilities, because not all of the systems may ultimately be viable or attain their performance objectives and attract commercial deployment
- Accommodate the range of national priorities and interests of the Forum.

The effort today in Generation IV follows through on this basis, with the aim of developing and delivering viable, high-performance systems in a few decades. The six systems are outlined in Table 1. They are described below after a short introduction of the nuclear fuel cycle and followed by summaries regarding fuel cycles and overall sustainability, missions and economic outlook, the approach to safety and reliability, and proliferation resistance and physical protection.

Table 1. Overview of the six Generation IV systems.

System	Neutron Spectrum	Coolant	Temperature °C	Fuel Cycle	Size (MWe)
VHTR (very-high-temperature reactor)	Thermal	Helium	900-1000	Open	250–300
SFR (sodium-cooled fast reactor)	Fast	Sodium	550	Closed	30–150, 300–1500, 1000–2000
SCWR (supercritical water-cooled reactor)	Thermal/fast	Water	510–625	Open/ closed	300-700 1000–1500
GFR (gas-cooled fast reactor)	Fast	Helium	850	Closed	1200
LFR (lead-cooled fast reactor)	Fast	Lead	480–800	Closed	20–180 300–1200 600–1000
MSR (molten salt reactor)	Fast/thermal	Fluoride salts	700–800	Closed	1000

2.2 Fuel Cycles and Sustainability

The choice of nuclear fuel cycle has a large impact on the long-term sustainability of the nuclear energy option. A once-through cycle is the most uranium resource-intensive and generates the most waste in the form of used nuclear fuel, as only ½% of the fuel is converted into energy. However, the amounts of waste arisings or emissions (including CO_2) are small compared to other energy technologies such as fossil fuels. In addition, the existing known and estimated additional economic uranium resources are sufficient to support a once-through cycle at least until late century, according to the most recent Red Book analysis.[2] In the longer term, beyond the latter part of this century, uranium resource availability also becomes a limiting factor unless breakthroughs occur in mining or extraction technologies.

Systems that employ a fully closed fuel cycle will reduce repository space and performance requirements, provided their costs are 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 will reduce the long-lived radiotoxicity and decay heat of waste destined for geological repositories by several orders 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.

Because closed fuel cycles require the partitioning of spent fuel, they have been perceived as increasing the risk of nuclear proliferation. The advanced separations technologies for Generation IV systems are designed to avoid the separation of plutonium and incorporate other features to enhance proliferation resistance and provide effective safeguards. In particular, all Generation IV systems employing recycle avoid separation of plutonium from other actinides and incorporate additional features to reduce the accessibility and weapons attractiveness of materials at every stage of the fuel cycle.

In the most advanced fuel cycles using fast-spectrum reactors and extensive recycling, it may be possible to reduce the radiotoxicity of all wastes such that the isolation requirements can be reduced by several orders of magnitude (e.g., for a time as low as 1000 years) after discharge from the reactor. This would have a beneficial impact on the design of future repositories and disposal facilities worldwide. However, this scenario can only be established through considerable R&D on fuel recycling technology.

2.3 Descriptions of the Generation IV Systems

In the following descriptions, *viability* refers to examining the feasibility, integration, and scale up of key technologies (not just their proof of principle), and *performance* refers to undertaking the development of performance data and optimization of the system. These phases are then followed by *demonstration* that involves licensing and construction of a prototype or demonstration system in partnership with industry and other countries.

2.3.1 VHTR – Very-High-Temperature Reactor

The VHTR is the next generation in the development of high-temperature reactors and is primarily dedicated to the cogeneration of electricity, hydrogen, and process heat for industry. Hydrogen can be extracted from water by using thermo-chemical, electro-chemical, or hybrid processes. The reactor is cooled by helium gas and moderated by graphite with a core outlet temperature greater than 900°C (with an ultimate goal of 1000°C) to support the efficient production of hydrogen by thermo-chemical processes. The high outlet temperature also makes it attractive for the chemical, oil, and iron industries.

The VHTR has potential for high burnup (150–200 GWd/tHM), passive safety, low operation and maintenance costs, and modular construction.

Two baseline options are available for the VHTR core: the pebble bed type and the prismatic block type. The fuel cycle will initially be once-through with low-enriched uranium fuel and very high fuel burnup. The system has the flexibility to adopt closed fuel cycles and offer burning of transuranics. Initially, the VHTR will be developed to manage the back end of an open fuel cycle. Ultimately, the potential for a closed fuel cycle will be assessed.

The electric power conversion may employ either a direct (helium gas turbine) or indirect (gas mixture turbine) Brayton cycle. In the near term, the VHTR will be developed using existing materials, whereas its long-term development will require new and advanced materials.

The basic technology for the VHTR has been established in former high-temperature gas reactors such as the U.S. Peach Bottom and Fort Saint-Vrain plants as well as the German Arbeitsgemeinschaft Versuchsreacktor (AVR) and thorium hochtemperature reaktor (THTR) prototypes. The technology is being advanced through near- and medium-term projects, such as the pebble bed modular reactor (PBMR), the high-temperature reactor–pebble bed module (HTR-PM), the gas turbine high-temperature reactor (GTHTR 300C), ANTARES, nuclear hydrogen development and demonstration (NHDD), the gas turbine modular helium reactor (GT-MHR) and the Next-Generation Nuclear Plant (NGNP), led by several plant vendors and national laboratories respectively in the Republic of South Africa, the People's Republic of China, Japan, France, the Republic of Korea, and the United States. Experimental reactors such as the high-temperature engineering test reactor (HTTR) (Japan, 30 MWth) and HTR-10 (China, 10 MWth) support this advanced reactor concept development, together with the cogeneration of electricity and hydrogen, and other nuclear heat applications.

2.3.2 SFR – Sodium-Cooled Fast Reactor

The sodium-cooled fast reactor (SFR) uses liquid sodium as the reactor coolant, allowing high power density with low coolant volume fraction. While the oxygen-free environment prevents corrosion, sodium reacts chemically with air and water and requires a sealed coolant system.

Plant size options under consideration range from small, 50 to 300 MWe modular reactors to larger plants up to 1500 MWe. The outlet temperature range is 500–550°C for the options, which affords the use of the materials developed and proven in prior fast reactor programs.

The SFR closed fuel cycle enables regeneration of fissile fuel and facilitates management of high-level waste—in particular, plutonium and minor actinides. However, this requires that recycle fuels be developed and qualified for use. Important safety features of the Generation IV system include a long thermal response time, a reasonable margin to coolant boiling, a primary system that operates near atmospheric pressure, and an intermediate sodium system between the radioactive sodium in the primary system and the power conversion system. Water/steam and supercritical carbon dioxide are considered working fluids for the power conversion system to achieve high performance in terms of thermal efficiency, safety, and reliability. With innovations to reduce capital cost, the SFR will be economically competitive in future electricity markets. In addition, the fast neutron spectrum greatly extends the uranium resources compared to thermal reactors. The SFR is considered to be the nearest-term deployable system for actinide management.

Much of the basic technology for the SFR has been established in former fast reactor programs and is being confirmed by the upcoming Phenix end-of-life tests in France, the restart of Monju in Japan, the lifetime extension of BN-600 and startup of BN-800 in Russia, and the startup of the China Experimental Fast Reactor scheduled in 2009.

2.3.3 SCWR – Supercritical Water-Cooled Reactor

The SCWR is a high-temperature, high-pressure water-cooled reactor that operates above the thermodynamic critical point of water (374°C, 22.1 MPa). Two design options—pressure vessel and pressure tube—exist for the SCWR. The system needs to assess the technical feasibility of issues (e.g., materials, chemistry, and operating conditions) common to both.

The reference plant has a 1500-MWe power level, an operating pressure of 25 MPa, and a reactor outlet temperature of up to 625°C. Due to the low density of supercritical water, a moderator other than the coolant must be added to thermalize the core. The SCWR balance-of-plant is considerably simplified because the coolant does not change phase (boil) in the reactor. However, safety features similar to those of advanced boiling water reactors are incorporated.

The main advantage of the SCWR is improved economics because of the higher thermodynamic efficiency (up to about 50% versus 34% for light water reactors today) and the potential for plant simplification. Improvements in the areas of safety, sustainability, and proliferation resistance and physical protection are being pursued by considering several options for designs using thermal as well as fast-neutron spectra and the use of a closed fuel cycle, including thorium.

2.3.4 GFR – Gas-Cooled Fast Reactor

The GFR is a high-temperature, helium-cooled fast reactor with a closed fuel cycle. It combines the advantages of fast-spectrum systems with those of high-temperature systems. The fast spectrum affords more sustainable use of uranium resources and waste minimization through fuel recycling and burning of long-lived actinides, and the high temperature affords high-thermal-cycle efficiency and industrial use of the generated heat, e.g., for hydrogen production. The reference reactor is a 2400-MWth/1100-MWe, helium-cooled system operating with an outlet temperature of 850°C using three indirect power conversion systems with a combined cycle. Direct Brayton cycle gas turbines can be considered in a second stage.

The GFR adopts some of the fuel recycling processes of the SFR and the reactor technology of the VHTR. The reactor development approach relies as far as possible on the structures, materials, components and power conversion system developed for the VHTR. However, R&D beyond the work on the VHTR is needed, mainly on core design and safety approach. Core configuration options are based on pin- or plate-based hexagonal fuel assemblies or prismatic blocks. Since graphite-bearing fuel and core materials are not appropriate for a fast reactor, several new fuel forms are being considered: composite ceramic clad mixed actinide carbide fuel, or advanced fuel particles.

2.3.5 LFR – Lead-Cooled Fast Reactor

The LFR features a fast-neutron spectrum and a closed fuel cycle for efficient conversion of fertile uranium. It can also be used as a burner of actinides from spent fuel and as a burner/breeder with thorium matrices. An important feature of the LFR is the enhanced safety that results from the choice of a relatively inert coolant provided that issues of the weight and corrosive nature of lead can be overcome. It has the potential to meet the electricity needs of remote sites as well as for large grid-connected power stations.

The designs that are currently proposed as options are two pool-type reactors, the small secure transportable autonomous reactor (SSTAR) and the European lead-cooled system (ELSY).

The reference design for the SSTAR is a 20-MWe natural circulation reactor in a transportable reactor vessel. The LFR features molten lead coolant, a nitride fuel containing transuranic elements, a fast spectrum core, and a small size. These combine to provide a unique approach to proliferation resistance by enabling a long core life, autonomous load following, simplicity of operation, reliability, transportability, and a high degree of passive safety. Conversion of the core thermal power into electricity at high efficiency (44%) is accomplished by a supercritical carbon dioxide Brayton cycle.

The ELSY reference design is a 600-MWe reactor with molten lead coolant. This concept has been under development within the 6th Euratom Framework Programme. ELSY aims to demonstrate the possibility of designing a competitive and safe fast critical reactor using simple engineered technical features while providing for minor actinide burning.

2.3.6 MSR – Molten Salt Reactor

The MSR fuel is unique in that it is dissolved in the fluoride salt coolant. Compared with solid-fueled fast reactors, thermal-spectrum MSRs have lower fissile inventories, no radiation damage constraint on fuel burnup, no fabrication of fuel forms, no spent nuclear fuel assemblies, and a homogeneous isotopic composition of fuel in the reactor. These and other characteristics may enable MSRs to gain unique capabilities and competitive economics for actinide burning and extending fuel resources. The technology was partly developed in the 1950s and 1960s, when earlier MSRs were mainly thermal-neutron-spectrum concepts.

Other new aspects include the use of a Brayton power cycle (rather than a steam cycle) that eliminates many of the historical challenges in building MSRs as well as the conceptual development of fast spectrum cores for the MSR that have large negative temperature and void reactivity coefficients—a unique safety characteristic not found in solid-fuel fast reactors. In addition, the development of higher temperature salts as coolants would open the MSR to new nuclear and non-nuclear applications. These salts are being considered for intermediate heat transport loops within all types of high-temperature reactor systems (helium and salt cooled) and for hydrogen production concepts, oil refineries and shale oil processing facilities, among other applications. For most of these applications, the heat would have to be transported up to a kilometer or more.

An alternative concept under consideration in this system is the advanced high-temperature reactor (AHTR). The AHTR uses liquid salts as a coolant but has the graphite core structures and coated fuel particles of the VHTR. The superior heat transport characteristics of salts compared with helium could enable power densities 4 to 6 times higher and power levels up to 4000 MWth with passive safety.

2.4 Missions for Generation IV Systems

While the evaluations of systems for their potential to meet all goals were a central focus of the roadmap participants, it was recognized that countries would have various perspectives on their priority uses, or missions, for Generation IV systems. The following summary of missions resulted from a number of discussions by the Forum and the roadmap participants. The summary defines three major mission interests for Generation IV: electricity, hydrogen or process heat, and actinide management. All six systems have electricity applications. The higher temperature systems (VHTR, GFR, LFR and MSR) have potential applications in hydrogen production or industrial process heat for such chemical processing facilities as petroleum refineries. The three fast reactor systems and the MSR have the capability to transmute actinides for effective waste management.

2.4.1 Electricity Generation

The traditional mission for civilian nuclear systems has been generation of electricity, and several evolutionary systems with improved economics and safety are likely in the near future to continue fulfilling this mission. It is expected that Generation IV systems designed for the electricity mission will yield innovative improvements in economics and be cost competitive in a number of market environments, while seeking further advances in safety, proliferation resistance and physical protection, and sustainability. These Generation IV systems may operate with either an open or closed fuel cycle that improves the use of nuclear fuel and reduces high-level waste volume and mass. Further, it may be beneficial to deploy these nearer- and longer-term systems symbiotically to optimize the economics and sustainability of the ensemble. Within the electricity mission, two specializations are needed:

- *Mature Infrastructure, Deregulated Market.* These options within Generation IV systems are designed to compete effectively with other means of electricity production in market environments with larger, stable distribution grids; well-developed and experienced nuclear supply, service, and regulatory entities; and a variety of market conditions, including highly competitive deregulated or reformed markets.
- *Limited Nuclear Infrastructure.* This option within Generation IV systems is designed to be attractive in electricity market environments characterized by small, sometimes isolated, grids and a limited nuclear regulatory and supply/service infrastructure. These environments might lack the capability to manufacture their own fuel or to provide more than temporary storage of used fuel.

2.4.2 Hydrogen Production, Cogeneration, and other Non-electricity Missions

This emerging mission requires nuclear systems that are designed to deliver other energy products based on the fission heat source or that may deliver a combination of process heat and electricity. The process heat is delivered at sufficiently high temperatures (likely needed to be greater than 700°C) to support steam-reforming, steam electrolysis, or thermochemical production of hydrogen, as well as other chemical production processes. Application to desalination for potable water production may be an important use for the rejected heat.

In the case of cogeneration systems, the reactor provides all thermal and electrical needs of the production park. The distinguishing characteristic for this mission is the high temperature at which the heat is delivered. Besides being economically competitive, the systems designed for this mission would need to satisfy stringent standards of safety, proliferation resistance, physical protection, and product quality.

For this mission, systems may again be designed to employ either an open or closed fuel cycle, and they may ultimately be symbiotically deployed to optimize economics and sustainability.

2.4.3 Actinide Management

Actinide management is a mission with significant societal benefits—nuclear waste consumption and long-term assurance of fuel availability. This mission overlaps an area that is typically a national responsibility, namely the disposition of spent nuclear fuel and high-level waste. Although Generation IV systems for actinide management aim to generate electricity economically, the market environment for these systems is not yet well defined, and their required economic performance in the near term will likely be determined by the governments that deploy them. Most Generation IV systems are aimed at actinide management, with the exception of the VHTR. Note that the SCWR begins with a thermal neutron spectrum and once-through fuel cycle, but may ultimately be able to achieve a fast spectrum with recycle.

The mid-term (30–50 year) actinide management mission consists primarily of limiting or reversing the buildup of the inventory of spent nuclear fuel from current and near-term nuclear plants. By extracting actinides from spent fuel for irradiation and multiple recycle in a closed fuel cycle, heavy long-lived radiotoxic constituents in the spent fuel are transmuted into much shorter-lived or stable nuclides. Also, the intermediate-lived actinides that dominate repository heat management are transmuted.

In the longer term, the actinide management mission can beneficially produce excess fissile material for use in systems optimized for other energy missions. Because of their ability to use recycled fuel and generate needed fissile materials, systems fulfilling this mission could be very naturally deployed in concert with systems for other missions. With closed fuel cycles, a large expansion of global uranium enrichment is avoided.

2.5 Generation IV Deployment

The objective for Generation IV nuclear energy systems is to have them available for wide-scale deployment before the year 2030. The deployment dates anticipated for the six Generation IV systems in the *Roadmap* assumed that considerable resources would be applied to their R&D. This has proven to be difficult, but a good start has been made by the Forum as described in the most recent *2008 Annual Report*. Also challenging was the three-year period needed to finalize the legally binding agreements covering multilateral R&D contracts.

The Generation IV program will continually monitor industry- and industry/government-sponsored R&D plans and progress in order to benefit from them and not create duplicate efforts. Cases where industrial developments are halted or merged may signal needed changes in the Generation IV R&D plans. Likewise, early Generation IV R&D is likely to hold significant advances for current systems.

3. CURRENT OUTLOOK FOR THE GENERATION IV SYSTEMS

In the following sections, each system is updated with respect to its current status and outlook. While all are now engaged in research, this has been refined in steps in the early years as the systems have begun to more fully understand and address the R&D needed for their development.

3.1 VHTR

The VHTR has a long-term vision for high-temperature reactors that requires its development in several important technical directions. At the same time, the VHTR benefits from a large number of national programs that are aimed at nearer-term development and construction of prototype gas-cooled reactors. The overall plan for the VHTR within Generation IV is to complete its viability phase by 2010, and to be well underway with the optimization of its design features and operating parameters within the next five years.

3.1.1 VHTR Mission and Overview

The VHTR is dedicated to the cogeneration of electricity and hydrogen and to serving process heat applications. The VHTR is an attractive energy source for large industrial complexes, such as refineries and petrochemical industries, because it would supply large amounts of process heat and generate hydrogen for upgrading heavy and sour crude oil or for other uses. If deployed widely, the VHTR can greatly reduce the intensity of industrial CO_2 emissions.

The VHTR has two established baselines—employing pebble bed or prismatic block fuel elements in the core (see Figure 1). The higher core outlet temperatures of these fuels enable high efficiencies for electricity and hydrogen production and offer process heat to meet industrial applications ranging between 500–900°C. Hydrogen production is achieved by splitting water with either high-temperature electrolysis or thermo-chemical cycles such as the sulphur-iodine or hybrid sulfur processes.

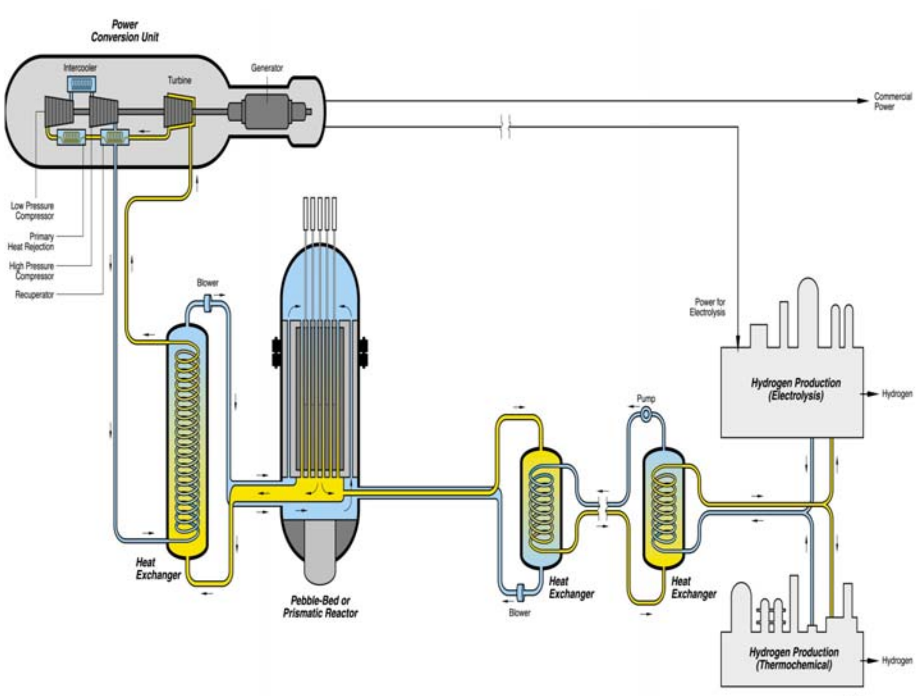

Figure 1. VHTR with electricity and hydrogen production alternatives.

Electricity may be generated by either a direct or indirect Brayton cycle; the direct cycle would require a helium gas turbine, the latter could employ a gas mixture (likely helium/nitrogen) instead of pure helium. Regardless of the choice of electric power cycle, the supply of process heat will require an intermediate heat exchanger connected to the primary circuit. Near term concepts for this are being developed using existing materials, and more advanced concepts are stimulating the development of new materials. The intermediate heat exchanger will also serve the hydrogen production process and may use a working fluid such as helium, a gas mixture, or a molten salt.

3.1.2 Fuel Cycle and Fuel

The fuel cycle will initially be a once-through fuel cycle specified for high burnup (150–200 GWd/tHM) using low enriched uranium. The operation with a closed fuel cycle will be assessed and solutions to better manage the fuel cycle back end will be developed.

Despite the alternate (pebble or prismatic) fuel designs, the two baselines have many technologies in common that allow for a unified R&D approach. The well-known UO_2 TRISO-coated particle fuel (with a UO_2 kernel and SiC/PyC coating) may be used in either, or it may be enhanced with a UCO fuel kernel or an advanced ZrC coating through additional research. The possible use of thorium as a fuel will be studied conceptually.

The primary emphasis in fuel development is on its performance at high burnup, power density, and temperature. The R&D broadly addresses its manufacture and characterization, irradiation performance and accident behavior. Irradiation tests will provide data on coated particle fuel and fuel element performance under irradiation as necessary to support fabrication process development, to qualify the fuel design, and to support development and validation of models and computer codes on fission product transport. They will also provide irradiated fuel and materials samples for post-irradiation and safety testing. The performance expected for the fuel must be verified for all normal, transient, or accident conditions as well as certain severe accident conditions (beyond design basis). A key claim of the fuel is its ability to retain fission products in the fuel particles under a range of postulated accidents with temperatures up to 1600°C.

A strategy for waste minimization and waste management will be established that considers sustainability criteria, economics, and proliferation issues. Different approaches for spent fuel management are being considered:

- Direct disposal of coated particles and graphite moderator
- Separation of coated particles and moderator, and treatment of both fractions
- Separation of kernels from coatings and reprocessing of kernels for recycling in VHTR systems (or other reactors).

3.1.3 Advanced Components and Materials

There are several unique components needed for the VHTR, including the reactor pressure vessel, intermediate heat exchangers, and Brayton cycle turbomachinery. The pressure vessels are unique due their size and thickness being larger than modern boiling water reactor vessels. Their development includes welding and fabrication methods, as well as means to assure the thermal emissivity of the outer vessel walls.

The intermediate heat exchanger must be a highly reliable boundary between the primary and the secondary coolants, compact, and thermally efficient. However, operating under very high-temperature conditions makes its development difficult. Printed circuit heat exchangers or plate-fin type compact heat exchangers are favored because of their size and high efficiency, but new materials are needed; the development of the intermediate heat exchanger exceeds all existing metallic materials normally considered.

The electric power conversion will employ a Brayton cycle system that includes the turbine as well as a recuperator and precooler/intercooler components. Again, the high operating temperatures magnify the issues in choice of materials, seals, and fabrication methods. Other components in the plant such as valves, blowers, piping and thermal insulation share these issues.

For core outlet temperatures up to about 900°C, existing materials can be used; however, temperatures above this, including safe operation during off-normal conditions, require the development and qualification of new materials. The research is focused on (1) graphite for the reactor core and internals; (2) high-temperature metallic materials for internals, piping, valves, high-temperature heat exchangers, and gas turbine components; and (3) ceramics and composites for control rod cladding and other core internals as well as for high-temperature heat exchangers and gas turbine components.

3.1.4 Special Issues and Technology

Within the Generation IV systems, the VHTR leads the way on the development of hydrogen production process development. As mentioned above, the main alternatives are high-temperature electrolysis (using both electricity and high-temperature process heat) or thermo-chemical and hybrid cycles (using only high temperature process heat). The two alternatives require much development, and the research covers the viability of the basic processes, materials for fuel cells or reaction vessels, and scale-up and control of large processes. Most of the development in the next five years is planned at bench scale, with limited integration of sub-process elements into full systems, or laboratory scale, with integrated elements at less than full scale and for limited duration. In about five years, a pilot-scale test might range up to about 0.5 MW of thermal power from a non-nuclear heat source.

Beyond the process equipment, research is ongoing into the coupling of a nuclear reactor with the hydrogen production process. This involves the thorough analysis of safe and reliable control and operation, including the hazards or upsets that each system might pose to the other. It also branches out into the conceptual design and economics of systems for various petrochemical and other applications.

3.2 SFR

The SFR has a long-term vision for highly sustainable reactors that requires its development in several important technical directions. At the same time, the SFR benefits from the operational experience worldwide with sodium-cooled reactors as well as a number of national programs that are aimed at nearer-term restart, development, and construction of prototype Generation IV reactors. The overall plan for the SFR within Generation IV is to be well underway with the optimization of its design features and operating parameters within the next five years and to complete its performance phase by 2015.

3.2.1 SFR Mission and Overview

The SFR is dedicated to actinide management, and also the production of electricity and heat if enhanced economics for the system can be realized. The SFR is an attractive energy source for nations that desire to make the best use of limited nuclear fuel resources and manage nuclear waste by closing the fuel cycle. If deployed widely, the SFR can reduce the intensity of CO_2 emissions.

Fast reactors hold a unique role in the actinide management mission because they operate with high-energy neutrons that are more effective at fissioning transuranic actinides. The main characteristics of the SFR for actinide management mission are:

- Consumption of transuranics in a closed fuel cycle, thus reducing the radiotoxicity and heat load which facilitates waste disposal and geologic isolation
- Enhanced utilization of uranium resources through efficient management of fissile materials and multi-recycle
- High level of safety achieved through inherent and passive means that accommodate transients and bounding events with significant safety margins.

The SFR system uses liquid sodium as the reactor coolant, allowing high power density with low coolant volume fraction. While the oxygen-free environment prevents corrosion, sodium reacts chemically with air and water and requires a sealed coolant system. The reactor unit can be arranged in a pool layout or a compact loop layout. Three options are considered: (1) a large size (600 to 1500 MWe) loop-type reactor with mixed uranium-plutonium oxide fuel and potentially minor actinides, supported by a fuel cycle based upon advanced aqueous processing at a central location serving a number of reactors; (2) an intermediate-to-large size (300 to 1500 MWe) pool-type reactor with oxide or metal fuel; and (3) a small size (50 to 150 MWe) modular-type reactor with uranium-plutonium-minor-actinide-zirconium metal alloy fuel, supported by a fuel cycle based on pyrometallurgical processing in facilities integrated with the reactor. The two primary fuel recycle technology options are (1) advanced aqueous and (2) pyrometallurgical processing. A variety of fuel options are being considered for the SFR, with mixed oxide the lead candidate for advanced aqueous recycle and mixed metal alloy the lead candidate for pyrometallurgical processing. Figure 2 shows two of the larger plant alternatives.

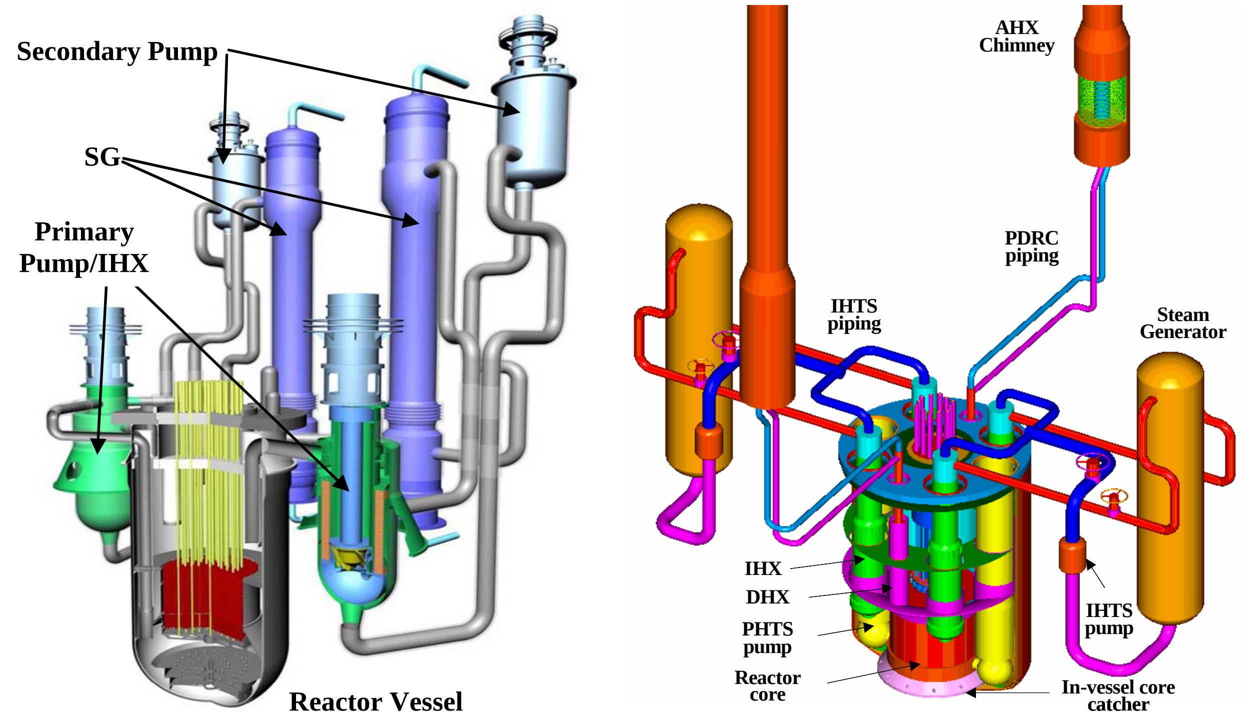

Figure 2. Loop-type JSFR (1500 MWe) left and pool-type KALIMER (600 MWe) right.

Although the sodium-cooled fast reactor technology is the most mature of the GIF systems, the capital cost of the first reactors has been high compared to commercial LWRs. Recent cost studies estimate that the capital cost of current designs may be 25% greater than conventional LWRs. Much of this difference is due to LWR cost reductions achieved from optimizing their designs based on building hundreds of commercial LWRs worldwide; there is no equivalent fast reactor experience. Since it is important to achieve a level of economic competitiveness for SFRs that enables commercial deployment, the SFR design options incorporate significant technology innovations to reduce the SFR capital costs by a combination of configuration simplifications, advanced fuels and materials, and refined safety systems. In addition, design for improved safety and proliferation resistance is also underway.

3.2.2 Fuel Cycle and Fuel

Fast reactors can operate in three distinct fuel cycle roles. A conversion ratio less than 1 ("transmuter") converts transuranics into shorter-lived isotopes to reduce long-term waste management burdens. A conversion ratio near 1 ("converter") provides a balance of transuranic production and consumption. This mode results in low reactivity loss rates with associated control benefits. A conversion ratio greater than 1 ("breeder") affords a net creation of fissile materials, but requires the recycle of more uranium in the reactor and fuel cycle. An appropriately designed fast reactor has flexibility to shift between these operating modes; the desired actinide management strategy will depend on a balance of waste management and resource extension considerations.

In conjunction with the actinide management goal, research plans will consider means to reduce the waste generation by features such as improved thermal efficiency, the greater utilization of fuel resources, and the development of superior waste forms for the SFR closed fuel cycle. Efforts will also be made for achieving reductions in the amount of waste generated from the operations and maintenance and the decommissioning of system facilities, and the amount of waste migrating to the environment.

An advanced fuels development effort will proceed with the three objectively defined phases: preliminary evaluation, minor-actinide (MA) fuels behavior evaluation, and high-burnup fuel behavior evaluation. Preliminary evaluation of advanced fuels entails comparison among oxide fuel, metal fuel, carbide fuel, and nitride fuel with respect to the fuel fabrication process and fuel irradiation behavior, including an initial evaluation of MA-bearing fuels. R&D efforts will be focused on the MA fuels evaluation with respect to fabrication process feasibility and irradiation behavior. At the end of 2010, preliminary selection of advanced fuel(s) will be made based on MA fuel evaluation. After that, high-burnup capability will be evaluated. This leads to the final selection of advanced fuel at the end of 2015.

3.2.3 Advanced Components and Materials

The main objective of this R&D is improved system performance through the design of advanced components and technologies to enhance the economic competitiveness of the plant, and by researching the use of alternative energy conversion systems, notably the use of a supercritical CO_2 energy conversion cycle in the plant that could allow further cost improvements. The supercritical CO_2 cycle offers the potential for surpassing 40% efficiency in energy conversion, even at the 550°C sodium coolant outlet temperature of the reference SFR designs.

Several R&D elements are of particular interest for the economic competitiveness of the SFR, including development of advanced in-service inspection and repair technologies and assessment procedures for dissimilar welds and leak-before-break, and advanced steam generators with improved reliability.

3.2.4 Special Issues and Technology

Regarding economics, the reduction of the plant capital costs is crucial. A number of innovative SFR design features have been proposed:

- *Configuration simplifications*. These include a reduced number of coolant loops by improving the individual loop power rating, improved containment design, refined (and potentially integrated) component design, and possibly elimination of the intermediate coolant loop.
- *Improved Operations & Maintenance (O&M) technology*. Innovative ideas are being considered for in-service inspection and repair. Remote handling and sensor technology for use under sodium are being developed, including ultrasonic techniques. In addition, increased reliability for sodium-water steam generators (e.g., by using double tube configuration with leak detection) is being pursued by advanced detection and diagnostic techniques.
- *Advanced reactor materials*. The development of advanced structural materials may allow further design simplification and/or improved reliability (e.g., low thermal expansion structures and greater resistance to fatigue cracking). These new structural materials need to be qualified, and the potential for higher temperature operation evaluated.
- *Advanced energy conversion systems*. The use of a supercritical CO_2 Brayton cycle power-generating system offers the potential for surpassing 40% efficiency; a more compact design may also be possible. Cost and safety implications must be compared to conventional Rankine steam cycle balance-of-plant design.
- *Fuel Handling.* Techniques and components employed in previous fast reactors were reliable, but very complicated and expensive. Recent design innovations may simplify the fuel handling system but require the development and demonstration of specialized in-vessel handling and detection equipment.

The total cost of electricity also includes the plant operation cost. This can be reduced by enhancing the plant load factor by making the reactor cycle length longer and capacity factor higher (e.g., by robust materials and improved system reliability). The fuel cycle cost can also be reduced by increasing fuel burnup. For this purpose, advanced cladding materials together with high-burnup transuranic fuel will be crucial.

With regard to reactor safety, technology gaps center around two general areas: assurance of passive safety response and techniques for evaluation of bounding events. The advanced SFR designs exploit passive safety measures to increase reliability. The system behavior will vary depending on system size, design features, and fuel type. R&D for passive safety will investigate phenomena such as axial fuel expansion and radial core expansion, and design features such as self-actuated shutdown systems and passive decay heat removal systems. The ability to measure and verify these passive features must be demonstrated. Associated R&D will be required to identify bounding events for specific designs and investigate the fundamental phenomena to mitigate severe accidents.

Finally, the development of SFR technology provides the opportunity to design modern safeguards directly into the planning and building of new nuclear energy systems and fuel cycle facilities. Incorporating safeguards into the design phase for new facilities will facilitate nuclear inspections conducted by the International Atomic Energy Agency (IAEA). The goal of this oversight is to always have an accurate grasp of the current inventory through the utilization of advanced technologies to verify the characteristics of the security system (accountancy, detectability, and promptness) and the physical protection characteristics (physical protection measures, the monitoring level, and security measures) and for ensuring robust design to guarantee these characteristics. It is also necessary to maintain transparency and openness in terms of information to more effectively and efficiently monitor and verify nuclear material inventories.

3.3 SCWR

The SCWR has a long-term vision for light water reactors that requires significant development in a number of technical areas. At the same time, the SCWR benefits from the resurgence of interest worldwide in light water reactors (LWRs) as well as an established technology for supercritical water power cycle equipment in the coal power industry. The overall plan for the SCWR within Generation IV is to complete its viability phase research by about 2010 and operation of a prototypical fueled loop test by about 2015, thereby preparing it for construction of a prototype sometime after 2020.

3.3.1 SCWR Mission and Overview

The SCWR is dedicated to advancing the next generation of baseload electricity. The SCWR is an attractive energy source for electric utilities because it offers considerable plant thermal efficiency increase and capital cost reduction while using a coolant that the industry has decades of experience with. If deployed widely, the SCWR can reduce the intensity of CO_2 emissions from electricity generation based on fossil fuels.

The SCWR has two established baselines—employing either pressure vessel or pressure tube boundaries for the supercritical water in the core (see Figure 3). The higher 625°C outlet temperature of the reactor affords a thermal efficiency approaching 50% (versus the 34% efficiency of today's LWRs), and the high-pressure single-phase coolant avoids the need for steam generators and enables use of an off-the-shelf advanced power turbine. These could potentially result in a capital cost reduction of up to 40%.

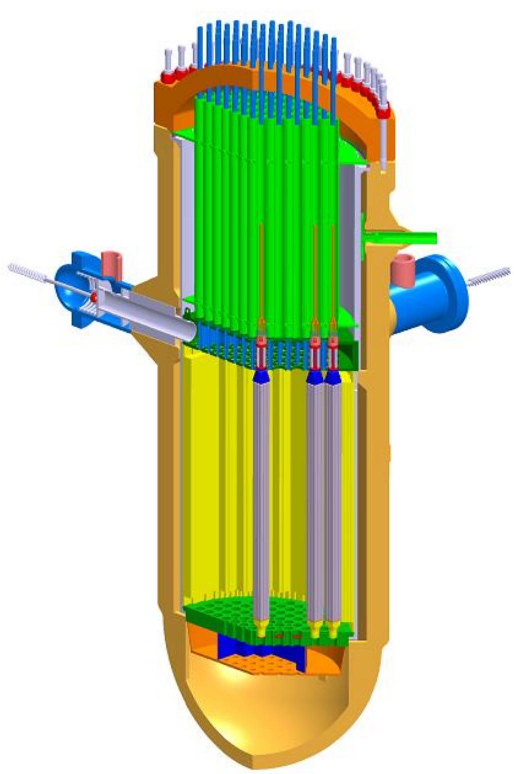

Figure 3. SCWR pressure vessel baseline alternative.[3]

The fuel cycle will initially be a once-through fuel cycle based on proven light or heavy water reactor UO_2 fuel. The operation with a core that is modified to be a fast spectrum reactor with a closed fuel cycle will be assessed based on proven aqueous fuel reprocessing technologies. In addition, thorium fuel will be investigated for the pressure-tube SCWR baseline.

3.3.2 Fuel Cycle and Fuel

The ability to use proven UO_2 fuel greatly simplifies the application of fuel and fuel cycle technology to the SCWR. However, the supercritical water is known to challenge the corrosion/erosion performance of current cladding technology, and R&D is focused on advanced cladding materials. This is discussed in the next section with other materials development needs.

3.3.3 Advanced Components and Materials

There are several unique components needed for the SCWR, including the reactor pressure vessel or pressure tubes and its internal structural components, moderator channels, control rods and drives, the condenser and high-pressure pumps, valves, and seals. The reactor pressure boundary must operate above the high pressure (22.1 MPa) of supercritical water. This may be addressed with thicker sections, and thermal stresses can be avoided with a thermal sleeve for the outlet nozzle.

Zirconium-based alloys, common in water-cooled reactors, may not be a viable material without thermal and/or corrosion-resistant barriers. Based on available data for other alloy classes, there is no single alloy that has received enough study to unequivocally ensure its performance in an SCWR. Another key need of this system will be an enhanced understanding of the chemistry of supercritical water. Water above its critical point is accompanied by dramatic changes in chemical properties. Its behavior and degradation of materials is further accelerated by in-core radiolysis, which preliminary studies suggest is markedly different than what would have been predicted by simplistic extrapolations from conventional reactors.

The approach to development of materials and components will build on (1) evaluation of candidate materials with regard to corrosion and stress corrosion cracking, strength, embrittlement and creep resistance, and dimensional and micro-structural stability; (2) the potential for water chemistry control to minimize impacts as well as rates of deposition on fuel cladding and turbine blades; and (3) measurement of performance data in an in-pile loop. All of these are critical to establishing viability of the SCWR.

3.3.4 Special Issues and Technology

As discussed above, the SCWR leads the way among Generation IV systems in the development of advanced materials for water coolant. In fact, the diffusion of this technology into current generation light and heavy water reactors seems assured.

However, much remains to be done: the thermal-hydraulic performance during normal and off-normal operation, as well as postulated accidents, needs to be addressed both with advances in the design and safety approach as well as the analysis tools. Issues to be addressed include (1) the basic thermal-hydraulic phenomenon of heat transfer and fluid flow of supercritical water in various geometries, (2) critical flow measurements, (3) the strong coupling of neutronic and thermal-hydraulic behavior, leading to concerns about flow stability and transient behavior, (4) validation of computer codes that reflect these phenomena, and (5) definition of the safety and licensing approach as distinct from current water reactors, including the spectrum of postulated accidents.

3.4 GFR

The GFR has a long-term vision for highly sustainable reactors that requires significant development in a number of technical areas. Unlike the SFR, the GFR does not have the benefits from operational experience worldwide and will require more time to develop. Like the VHTR, however, the GFR does use helium coolant and refractory materials to access high temperatures, allowing it to provide process heat. The overall plan for the GFR within Generation IV is to be well underway with the viability research within the next few years and to hopefully complete its viability phase by 2012.

3.4.1 GFR Mission and Overview

The GFR is dedicated to actinide management, and also the production of electricity and heat. The GFR is an attractive energy source for nations that desire to make the best use of limited nuclear fuel resources and manage nuclear waste by closing the fuel cycle. If deployed widely, the GFR can greatly reduce the intensity of CO_2 emissions.

Fast reactors hold a unique role in the actinide management mission because they operate with high-energy neutrons that are more effective at fissioning transuranic actinides. The main characteristics of the GFR for actinide management mission are:

- A fast neutron spectrum core with neutral or positive breeding gain
- Very limited or no use of blankets
- Limited plutonium core inventory to reduce materials needed for deployment.

The GFR requires the development of a robust refractory fuel element and appropriate safety architecture. A preliminary baseline is a 1200-MWe unit in Figure 4, employing dense carbide or nitride fuel that results in good performance for plutonium breeding and minor actinide burning.

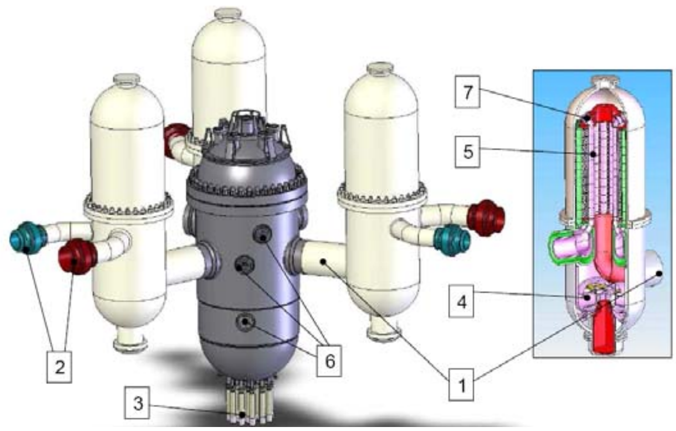

Figure 4. 1200-MWe GFR primary system and reactor cutaway.

Neither experimental reactors nor prototypes of the GFR system have been licensed or built, therefore, the construction and operation of a first experimental reactor—the experimental technology demonstration reactor (ETDR)—is proposed with an extended performance phase to qualify key technologies. A technology demonstration reactor would qualify key technologies and could be put into operation by 2020.

3.4.2 Fuel Cycle and Fuel

Spent fuel treatment for the GFR can be accomplished with aqueous processes similar to those of the SFR but qualified for the unique GFR fuel form. At least two fuel forms have the potential to satisfy the GFR requirements: a ceramic plate-type fuel element and a ceramic pin-type fuel element. The reference material for the structure is reinforced ceramic comprising a silicon carbide composite matrix ceramic. The fuel compound is made of pellets of mixed uranium-plutonium-minor actinide carbide. A leak-tight barrier made of a refractory metal or of Si-based multilayer ceramics is added to prevent fission products diffusion through the clad.

3.4.3 Advanced Components and Materials

Unlike the VHTR, which uses its considerable thermal mass to limit the rise of core temperature during transients, the GFR requires the development of a number of unique subsystems to provide defense in depth for its considerably higher power density core. These include a robust decay heat removal system with added provisions for natural circulation heat removal, such as a low-pressure-drop core. The secondary circuit uses a He-N_2 gas mixture with an indirect combined (Brayton and bottoming steam) power cycle to achieve a 45% thermal efficiency.

A gas-tight envelope acting as additional guard containment is provided to maintain a backup pressure in case of large gas leak from the primary system. It is a metallic vessel, initially filled with nitrogen slightly over the atmospheric pressure to reduce air ingress potential. This unique component limits the consequence of coincident first and second safety barrier rupture (i.e., the fuel cladding and the primary system). Dedicated loops for decay heat removal (in case of emergency) are directly connected to the primary circuit using cross duct piping from the pressure vessel and are equipped with heat exchangers and blowers.

Many of the structural materials and methods are being adopted from the VHTR, including the reactor pressure vessel, hot duct materials, and design approach. The pressure vessel is a thick metallic structure of martensitic chromium steel, ensuring negligible creep at operating temperature. The primary system is comprised of three main loops of 800 MWth, each fitted with compact intermediate heat exchangers and a gas blower enclosed in a single vessel.

3.4.4 Special Issues and Technology

As a high-temperature and high-power density system, the GFR gives special attention to safety and materials management for both economics and non-proliferation. During the viability phase that is underway now, there is special interest in examining (1) the use of pin-type fuel with a small diameter, (2) fuel and core performance optimized for a simplified GFR having no minor actinide recycle, but with limited Pu breeding and low fuel burnup, (3) core outlet temperature optimized to balance efficiency with materials limits, and (4) the potential of pre-stressed concrete vessel technology to replace the guard vessel.

3.5 LFR

The LFR has a long-term vision for highly sustainable reactors that requires significant development in a number of technical areas. The overall plan for the LFR is to be well underway with the development of its materials, design features, and operating parameters within the next five years.

3.5.1 LFR Mission and Overview

The LFR is dedicated to actinide management and also the production of electricity, and possibly heat if sufficiently high-temperature operation can be achieved. The LFR is an attractive energy source for nations that desire to make the best use of limited nuclear fuel resources and manage nuclear waste by closing the fuel cycle. If deployed widely, the SFR can reduce the intensity of CO_2 emissions.

There are two major options within the LFR, both cooled with liquid lead: one is a reference design of 600 MWe based on the European lead-cooled system (ELSY); the other is a small modular design of 20 MWe based on the small secure transportable autonomous reactor (SSTAR). Both are shown in Figure 5. The 600-MWe option has a compact and simple primary circuit with the objective that all internal components be removable to assure competitive electric energy generation and long-term investment protection. The reactor has a secondary water loop with steam generators and a steam Rankine cycle. Simplicity is expected to reduce both the capital cost and the construction time. These are enhanced by a compact reactor building of reduced footprint and height. The reduced footprint is possible due to the elimination of an intermediate cooling system, as well as the design of reduced-height components. The core consists of an array of open fuel assemblies of square pitch surrounded by reflector assemblies to reduce the risk of coolant flow blockage. Closed hexagonal assemblies are a second alternative.

The transportable 20-MWe option employs natural circulation in the primary lead loop, with a secondary supercritical CO_2 loop for power conversion in a direct Brayton cycle.

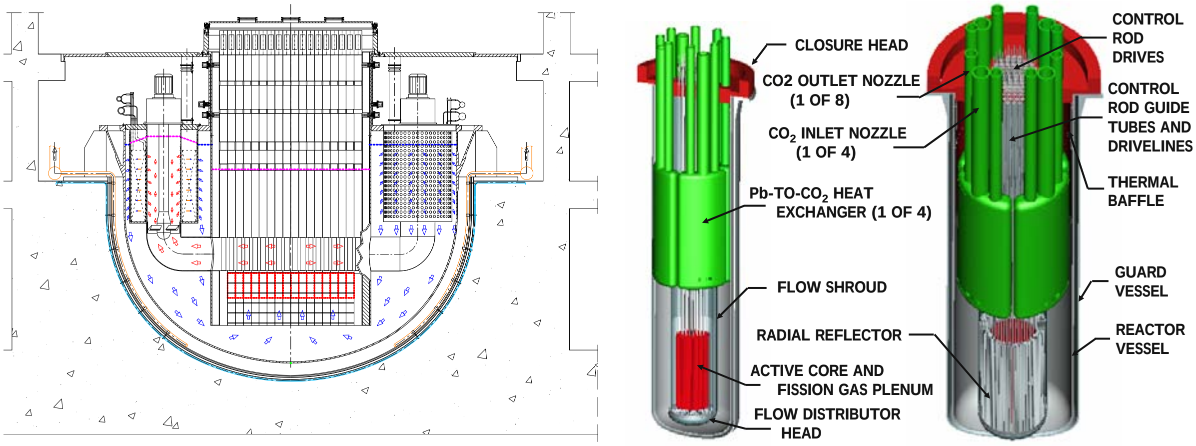

Figure 5. LFR options: ELSY (600 MWe) left, and SSTAR (20 MWe) right.

3.5.2 Fuel Cycle and Fuel

The 600-MWe option employs mixed oxide fuel with T91 cladding and has a core outlet temperature of 550°C. The 20-MWe option employs nitride fuel with Si-enhanced ferritic/martensitic SS cladding and has a core outlet temperature of 650°C. This will require considerable development of materials for service at this higher temperature.

3.5.3 Advanced Components and Materials

For the 600-MWe option, a newly designed steam generator, whose volume is about half that of a comparable helical-tube steam generator, features a spiral-wound tube bundle. The inlet and outlet ends of each tube are connected to the feed water header and steam header, respectively, both arranged above the reactor roof. An axial-flow primary pump, located inside the inner shell of the steam generator, provides the head required to force the coolant to enter from the bottom of the steam generator and to flow in a radial direction. This scheme is nearly equivalent to a counter-current scheme, because the water circulates in the tube from the outer spirals towards the inner spiral, while the primary coolant flows in the radial direction from the inside to the outside of the steam generator. This ensures that the coolant will flow over the steam generator bundles even in the event of reduction in the primary coolant level in case of leakage from the reactor vessel. As a by-product, the steam generator unit can be positioned at a higher level in the downcomer and the reactor vessel shortened, accordingly.

The installation of steam generators inside the reactor vessel is another major challenge of a LFR design. Particular challenges related to their operation include (1) a sensitive and reliable leak detection system, and (2) a highly reliable depressurization and isolation system. Careful attention has been also given to the issue of mitigating the consequences of a tube rupture accident to reduce the risk of pressurization of the primary boundary. All reactor internal structures are removable and in particular the steam generator can be withdrawn by radial and vertical displacements to disengage the unit from the reactor cover plate.

Corrosion of structural materials in lead is one of the main issues for the LFR. Recent experiments confirm that corrosion of steels strongly depends on the operating temperature and dissolved oxygen. Indeed, at relatively low oxygen concentration, the corrosion mechanism changes from surface oxidation to dissolution of the structural steel. Moreover, relationships between oxidation rate, flow velocity, temperature, and stress conditions of the structural material have been observed as well.

The compatibility of ferritic/martensitic and austenitic steels with lead has been extensively studied and it has been demonstrated that generally below 450°C, and with an adequate oxygen activity in the liquid metal, both types of steels build up an oxide layer which behaves as a corrosion barrier. However, above about 500°C, corrosion protection through the oxide barrier appears to fail and is being addressed with candidate materials like T91 and AISI 316. The prospects for extending much above this temperature are not proven at this time.

3.5.4 Special Issues and Technology

A number of unique approaches are being investigated in the 600-MWe option. The upper part of the core is novel because it extends well above the fixed reactor cover. The fuel elements are buoyant in lead, and are fixed at their upper end in the cold gas space, well above the molten lead surface. This avoids the classical problem of a core support grid immersed in the coolant which would greatly complicate in-service inspection in molten lead.

Fuel assemblies are directly accessible for handling using a simple handling machine that operates in the cover gas at ambient temperature, under full visibility. Considering the high temperature and other characteristics of the molten lead environment, any approach that foresees the use of in-vessel refueling equipment requires a large R&D effort and substantial technical risk, especially because of the need to develop reliable bearings operating in lead, which is an unknown technology at present.

3.6 MSR

The MSR has a long-term vision for highly sustainable reactors that requires significant development in a number of technical areas. The overall plan for the MSR is to be underway with the development of its design features, processing systems, and operating parameters within the next five years.

3.6.1 MSR Mission and Overview

Historically, MSR concepts used steam cycles, the only commercial power cycles available at that time. Today, Brayton power cycle technology is advanced, and supercritical CO_2 cycles are being adapted for use in the MSR.

3.6.2 Fuel Cycle and Fuel

In the MSR, the fuel is dissolved in a fluoride salt coolant. This is very different compared to all the other Generation IV systems. Its potential derives from the combination of the advantages of a very effective coolant and the many benefits of a liquid fuel. In addition, the MSR offers breeding in thermal spectrum (using a Th/U cycle) and in fast spectrum (using Th/U and U/Pu cycles). The reactor technology was partly developed in the 1950s and 1960s, but much remains to be developed, especially in the online refueling and processing systems.

Systematic analysis of parameters such as reprocessing time, moderation ratio, core size, and content of heavy nuclei in the salt has resulted in several attractive reactor configurations, in thermal, epithermal or fast spectrum in a family of thorium molten salt reactor TMSRs (see Figure 6). Many other options are being investigated. In addition, the use of a molten salt coolant in a solid-fuel system is being investigated, known as the advanced high-temperature reactor (AHTR), which adapts and may complement VHTR fuel and heat exchanger technology.

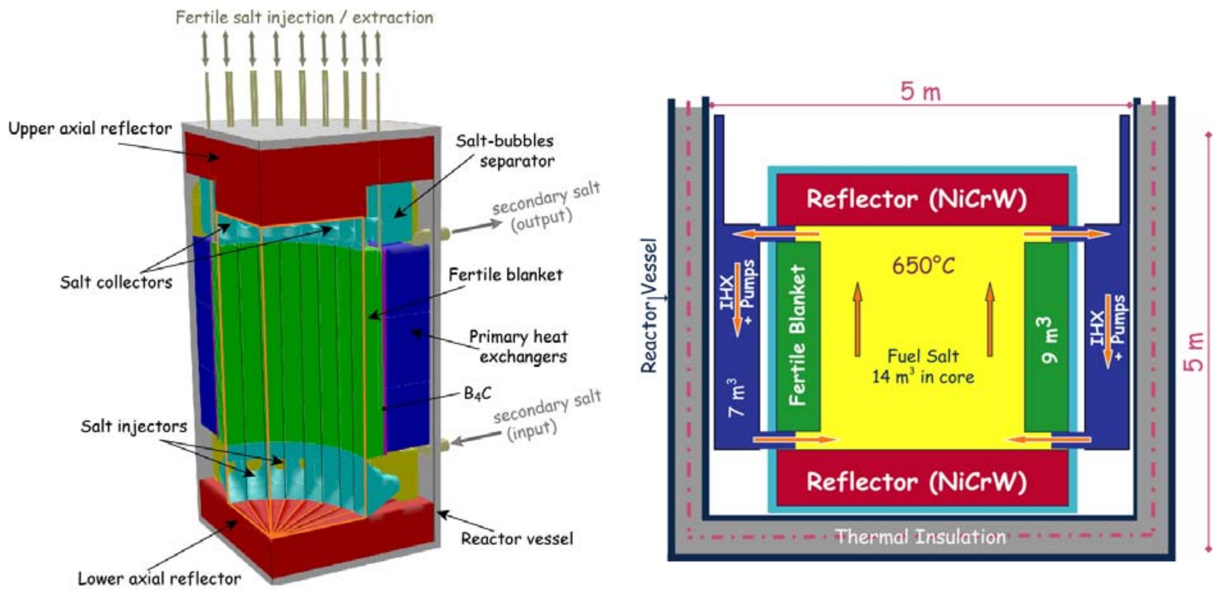

Figure 6. TMSR core volume (left) and reactor cross section (right).

The TMSR is based on a 2500-MWth (1000 MWe) graphite moderated reactor. Its operating temperature is 630°C and its thermodynamic efficiency is 40%. The salt used is a binary salt, LiF-(HN)F4, with the (HN)F4 content set to 22% (the eutectic point), corresponding to a melting temperature of 565°C. The 233U enrichment is about 3%. A graphite radial blanket surrounds the core to improve breeding performance. The reprocessing time of the total salt volume is specified to be 6 months, with external storage of the Pa and complete extraction of the fission products and TRU. It is assumed that the 233U produced in the blanket is also extracted every 6 months.

The R&D will focus on fuel salt cleanup, including pyrochemical separation technologies, extraction of gaseous fission products and noble metals by gas bubbling, tritium speciation and control, and conversion of various waste streams into final waste forms. The research will gradually advance from laboratory scale to larger and more integrated demonstrations. MSR burner and breeder fuel cycles will be evaluated and compared with other nuclear systems. This includes examination of the burning of actinides from other nuclear systems, startup of MSRs on various actinides, avoidance of the generation of most actinides by use of thorium fuel cycles, and alternative breeder reactor fuel cycles. The development of solid fuel (either prismatic, pebble bed, or pin-type) for the AHTR is also underway.

3.6.3 Advanced Materials and Salt Control

The MSR also addresses research related to the compatibility of fuel and coolant salts with core and structural materials and challenging MSR sub-system integrity: reactor components and reprocessing unit regarding mechanical and corrosion resistance. The high temperature, salt redox potential, radiation fluence, and energy spectrum pose a serious challenge for any structural alloy in an MSR. The design of a practical system demands the selection of salt constituents such as LiF, NaF, BeF2, UF4, ThF4, and PuF3 that are not appreciably reduced by available structural metals and alloys whose component Fe, Ni, and Cr can be in near equilibrium with the salt. Small levels of impurities in the salt may also aggressively corrode the metallics. Moderator or reflector materials need to be addressed.

The main steps are the experimental validation of specific properties (mechanical properties, corrosion) of structural materials (advanced Ni-based alloys) as applied to well-established and rather new liquid salt environments, including increased operational temperatures, and the investigation of fission product deposition on structures and Te-induced embrittlement of Ni-based alloys.

3.6.4 Special Issues and Technology

Circulating fuel raises unique challenges within the core (such as the loss of delayed neutrons, temperature differences between the salt, reflectors, and moderator). First core calculations have shown the sensitivity of the reactivity feedback coefficients to the core arrangement. This study has to be refined with integrated codes taking into account all effects (neutronics, thermal-hydraulics, and chemical properties). Due to the small values of the reactivity coefficients to the reprocessing conditions, which change the salt composition and affect breeding, the cross sections values have to be well known. In the thorium cycle, there have been only a few experiments to check the validity of the evaluated nuclear data. Some measurements have been undertaken to obtain more precise values, which will be evaluated and checked in sensitivity studies.

As mentioned above, the coupling between neutronics, thermal-hydraulics, salt composition, and properties will be needed to model the MSR. Sensitivity and uncertainty analysis will define best-estimate margins. Reactor physics codes will be developed to provide an accurate description of the core behaviour in steady-state and off-normal operation, as well as accidents.

The development of heat exchanges must also be addressed and is expected to have a large impact on the performance and economics of the system. Many additional components such as pumps, valves and piping need to be specialized or developed. Control systems also need development and qualification.

4. METHODOLOGY WORKGROUP ASSESSMENTS

4.1 Economic Assessment

Early in the Generation IV process it was realized that new tools may be needed to assess the progress toward the economic goals for GEN IV systems established by the GIF Policy Group. Foremost was the need for a consistent yet simplified methodology for cost estimation. Given that the missions for the GEN IV systems go beyond electricity production, it is also necessary to facilitate cost estimates of systems designed for nonelectric product application. The Economics Methodology Working Group (EMWG) was established to develop this methodology. To date, the basic assessment methodology has been developed, tested on both GEN III and GEN IV systems, and made available to all GIF participants as well as the general nuclear community.

The economic assessment methodology consists of a comprehensive guideline for cost estimation, “Generation IV Cost Estimating Guidelines,” Rev. 4; an EXCEL-based software package for reactor applications, G4ECONS; an EXCEL-based software package for fuel cycle facility applications, G4ECONS-FCF; and the software users’ manual covering both software packages. Both the Guidelines and the software facilitate application to electric and non-electric system cost estimating applications. This methodology is available through OECD NEA in its role as GIF Secretariat.

The EMWG continues to monitor the application of the cost estimating methodology and the progress of the GEN IV systems research. Improvements in G4ECONS are underway to facilitate assessment of heterogeneous reactor cores likely for actinide management missions and very long-lived cores for LFR application. Over the next 5 years, further improvements will be undertaken as experience with the methodology indicates or as the GEN IV systems details take shape, especially fuel assembly and fuel cycle designs.

4.2 Risk and Safety Assessment

The Risk and Safety Working Group was established to “promote a consistent approach to safety, risk, and regulatory issues” for Generation IV systems. In particular, the RSWG’s Charter calls for the RSWG to advise and assist the Experts Group and the Policy Group on matters related to Generation IV safety goals and evaluation methodologies, and interactions with the nuclear safety regulatory community and other relevant stakeholders.

The early work of the RSWG focused on definition of a coherent safety philosophy for Generation IV systems and identification of design attributes that may help achieve Generation IV safety goals. The principal recommendations that are embodied in the early work of the RSWG include the notion that Generation IV system designs should be driven by a “risk-informed” approach, a recognition that the principle of “defense in depth” should be preserved and formalized for Generation IV systems, and definition of an approach that examines safety in the context of a broad spectrum of possible accident conditions rather than a “design basis accident” that is presumed to be bounding. Throughout its work, the RSWG has had extensive interaction with the International Atomic Energy Agency (IAEA), and has developed useful interactions with selected national nuclear regulatory agencies.

More recent work of the RSWG has turned to focus primarily on development of an integrated framework for assessing risk and safety issues in Generation IV systems. Overall, the methodology is intended to provide useful guidance throughout the design process based on an understanding of risk and safety issues that is commensurate with each stage of design maturity. The methodology is practical and flexible, and allows for a graded approach to the analysis of safety issues based on their complexity and importance. Principally based on probabilistic safety analysis (PSA), the methodology consists primarily of analysis tools that are widely used, accepted, and validated, thus minimizing the need for development of new techniques. Significantly, recognizing the role of “safety margin” as an appropriate response to uncertainty, the integrated methodology provides for explicit consideration and characterization of uncertainties associated with Generation IV safety issues.

Looking forward, future work of the RSWG will result in further definition of the Generation IV safety assessment methodology, demonstration of the methodology, and developing guidance for its application.

4.3 Proliferation Resistance Physical Protection Assessment

The Generation IV Roadmap recommended the development of a methodology to define measures for proliferation resistance and physical protection (PR&PP) and to evaluate them for the six nuclear energy systems. Accordingly, the Forum formed a PR&PP Working Group (PRPPWG) to develop a methodology. The current version of this methodology, Revision 5 is available at the GIF website.[4]

The methodology was developed with the aid of a series of limited and focused studies. The studies were performed using an example sodium fast reactor consisting of four sodium-cooled fast reactors of medium size co-located with an on-site dry fuel storage facility and a pyrochemical spent fuel reprocessing facility. A report is being issued in 2009 on the results of the most recent study as they relate to the lessons learned with regard to the implementation of the methodology.

As part of the effort to familiarize GIF system researchers and program policy makers with the PR&PP methodology, a series of workshops were held in the United States in 2005, Italy in 2006, Japan in 2006, and Republic of Korea in 2008. Useful mutual information exchanges occurred during these workshops which helped to further define the methodological approach.

The PRPPWG and the Risk and Safety Working Group (RSWG) have initiated an effort to assure that PR&PP and safety are integrated in a compatible way in future nuclear energy systems. A first white paper has been jointly developed which outlines this process and there have been several beneficial interactions between the two groups. The efforts of these two groups will continue to be carefully coordinated as it has been so far through close working relations.

Over the next several years, the PRPPWG will refine and improve the methodology in response to feedback from users and other stakeholders. As a results of the studies carried out so far, the PR&PPWG plans to develop an update of the PR&PP methodology report in 2010 (Revision 6) . The PRPPWG will also continue to strengthen the link with GIF System Steering Committees and other designers of Generation IV systems. Four broad goals of these interactions are to: 1) capture the salient features of the design concepts that impact their PR&PP performance, 2) facilitate crosscutting studies of relevance for several of the Generation IV systems, 3) identify insights for enhancing PR&PP characteristics of future nuclear energy systems, and 4) foster the implementation of a PR&PP culture into the earliest phases of design.

The PRPPWG intends to continue to promote PR&PP goals and broad acceptance of the PR&PP methodology by conducting workshops for users, making presentations at professional society conferences and related meetings, and producing archival journal articles.

5. FACILITATING THE PROGRESS

A number of important issues have arisen during the startup of R&D within the Forum. This section presents four of them and examines how they are being addressed in a way that facilitates the systems' progress.

The signing of the Framework Agreement in February 2005 ushered in the formal legal documents that govern R&D collaborations in the Forum. In effect, it creates three levels of cooperation: (1) the government-to-government understandings in the Framework Agreement itself, (2) ministry-to-ministry understandings that govern each system in a System Arrangement, and (3) research organization-to-organization understandings that govern each project within a system in a Project Arrangement.

At the respective levels, these agreements broadly cover the research objectives, planning, and organization; the creation, ownership and protection of intellectual property; and the resource commitments brought to the collaboration. Each system is quite autonomous in the Forum, although the arrangements have tended to share and adopt many of the same provisions. Notwithstanding the comprehensive nature of the arrangements, areas of agreement on the research management approach are being developed to facilitate the systems' progress. An excellent example is that of Quality Management, which is reported next. A common approach to quality management avoids each system having to create it independently, and also sets the expectation for attention to quality at the highest levels. Additional examples of System Integration, System Assessment, and Outreach to the university research community follow.

5.1 Quality Management

In 2005 the Forum assembled an industrial advisory group (known as the Senior Industry Advisory Panel) for the purpose of bringing the perspective of industries that may eventually commercialize Generation IV systems in the market. In their first meeting, the Panel stressed the need for adopting quality management in R&D activities. The Experts Group of the Forum was tasked with creating an appropriate system, and they convened quality experts and specialists from the Members to assist with its development.

From the outset, the purpose of a quality management system (QMS) was to assist the research participants in doing the following:

- Conduct R&D that is both useful (meets established requirements) and usable (is well documented and validated)
- Minimize rework and duplication of efforts, thereby achieving cost efficiencies
- Create systems that will meet nuclear safety standards
- Transfer information and technology (eventually to industry) in an efficient and controlled manner
- Ultimately achieve a straight-forward nuclear licensing process by assuring the quality of the research results and data from their beginning.

Over the next two years, the quality experts developed a set of QMS Guidelines. This is a comprehensive guide to quality planning and execution that sets an example for the six systems to adopt and/or modify for their own use. The Guidelines outline the organizational entities and their responsibilities, quality planning activities for R&D, the many elements to be considered in the quality program, and suggestions for a graded approach to quality management in R&D. While not publicly available on the Generation IV website, the Guidelines (or a specialized version within each system) are shared with all new or potential project participants by the Steering Committees. The legally binding arrangements for systems and projects contain the specific roles and responsibilities for implementation of quality management.

Recognizing that quality must be driven from the highest levels, the Policy Group established a Policy Statement in 2006 that stated their commitment to the application of quality management principles and practices to all GIF-fostered R&D, and set the expectations for System and Project Arrangements to address the implementation of quality management.

In all of this, the Forum has addressed the need for adopting quality management in every aspect of its R&D, which should pay many returns in the future.

5.2 System Integration

The signatories to a system arrangement are generally comprised of the ministries or departments that address nuclear energy development within their respective governments. Independently, each maintains their respective national programs and manages a spectrum of research and technology development that supports their national objectives. In contrast, the most efficient progress on a Generation IV system would be facilitated by narrowing its mission, objectives, and technologies to reduce the amount of overall effort and focus the limited resources.

In practice, all of the Generation IV systems consider options that are sometimes referred to as *tracks*—for example, metal or oxide fuel, loop- or pool-type layout, prismatic or pebble fuel elements, size of power output, choice of coolant, and so on. In some cases, the tracks correspond to various national programs, although multiple tracks may also be found within a single national program. Some R&D may be common to all tracks within a system, such as some components or materials, energy conversion, computational methods, or safety analyses.

Recognizing that the collaborative R&D must support the vision of the system, all systems are integrating the activities into an efficient whole while still retaining the diversity of approaches found in the tracks. Of course, the approach within each system to integrating its R&D can be tailored to its situation and needs.

The Experts Group and the System Steering Committees have considered the process of system integration. It generally includes the following:

- Maintaining the preconceptual design requirements and information for each track; e.g., its rated output, coolant, fuel composition, core and system configuration, components and structures, as well as materials, neutronic, thermal-hydraulic and safety information and studies that yield performance measures or behavior
- Defining the technology gaps in performance that must be addressed by R&D, and understanding the tradeoffs that unresolved gaps may pose to the design requirements and system performance
- Reviewing the results of the R&D being performed and providing guidance to the R&D program to optimize the progress
- Providing feedback to the system designers from the R&D results, and suggesting revised R&D activities or objectives in response to emerging design issues
- Assessing the system performance against the Generation IV goals (assessment is discussed in the next section).

Some of the System Steering Committees have elevated this process to a separate System Integration and Assessment project with dedicated, specialized staff and management. While there are issues to resolve with the approach before the first such integration project can be established, the signatories realize the value of a well-integrated and optimized R&D program.

5.3 System Assessment

The foundations of Generation IV are built on the eight goals for the systems. The central question for each candidate concept in the *Roadmap* was “How well *can* this concept perform relative to the goals, given sufficient time and resources to mature?” The development of evaluation methodologies and the first assessment of the concepts was a central and sustained effort in the *Roadmap*. It became the basis for the eventual selection of six systems.

As the systems are being developed, it is natural to ask how the systems are actually progressing toward the goals. This is the purpose of *system assessment*, and its periodic update brings important news of both the research progress as well as the achievable benefits and value of the systems. These results are not used to prematurely downselect among systems. Rather, they are signals to the prospective users and vendors of the advancing readiness of Generation IV systems—signals that can stimulate useful feedback on the pacing and direction of the R&D.

Of course, the tools for assessment—evaluation methodologies—are themselves being improved. The previous section describes the outlook for the major crosscutting methodologies. Two methodologies (proliferation resistance and economics) have made significant advances since the Roadmap, and the third (safety) has a major work underway.

At the same time, the systems have varying degrees of activity. For example, the first formal arrangements of systems were established by the SFR in February 2006, and the VHTR, SCWR, and GFR in November 2006.

The Policy Group orchestrates these preparations and plans and frequently revisits the question of progress. There are no plans for a coordinated assessment with all systems cross-compared. On the other hand, the two most active systems, the SFR and VHTR, are encouraged to make formal system assessments in the next five years. Others are encouraged to make preparations for assessments in concert with their R&D programs.

5.4 Outreach to the University Research Community

The international collaborative activities on Generation IV systems have been an engine for renewed interest in nuclear energy at academic institutions around the world, particularly in those countries where the building of new nuclear plants has stagnated. In several of the GIF countries, requests for proposal aimed at the universities are now issued annually. These are often preceded by workshops explaining the Gen IV mission and the funding levels of the principal Gen IV program elements. This results in proposals that are focused on the Gen IV system R&D gaps that have been identified and that offer the best opportunities for student and junior academic staff engagement. For example, in the United States, 20 percent of the DOE Gen IV budget is currently dedicated exclusively to university participation in the program and many universities who compete for these funds have developed close collaborations with the U.S. national laboratories and private entities who lead the development efforts. Some of the funds are set aside for investigator-initiated projects that are less closely related to Gen IV programs but show innovation in the energy field. While each GIF partner uses its own approach in developing university nuclear programs, student enrollment at both undergraduate and graduate levels has steadily increased in the GIF countries and academic infrastructure in the nuclear energy area has improved greatly.

6. FIVE YEARS INTO THE PATH FORWARD

It has been a little more than seven years since the *Generation IV Roadmap* was published, and four years since the first signing of the Framework Agreement. The former heralded *what* to work on, the latter provided for *how*, and we now address the question of *when* by describing the next five years into the path forward. While much is being undertaken and advanced every year within our committees and working groups, it is important to revisit our expectation of what will be accomplished by the Generation IV International Forum in the next five years, through 2013.

6.1 System Technologies

As always, each Forum member is free to choose the systems that it will advance, as well as to pursue any options or alternatives to the systems outside the System Research Plan. With respect to the six Generation IV systems, presented in order of their level of cooperative activity today, the Forum expects the following progress in five years:

- For the VHTR, the full complement of technology projects will have been created. Feasibility issues regarding hydrogen production, fuel performance, and high-temperature design including both the core and intermediate heat exchanger will be resolved, or nearly so. An assessment of progress toward the goals will have been completed for the major options. Key performance issue tests will be in planning, with some in operation, and decisions will have been made about advancing one or more prototypes.
- For the SFR, the full complement of technology projects will also have been created. Feasibility issues regarding actinide recycling, competitive capital cost, in-service inspection and repair, and alternate energy conversion with gas or supercritical CO_2 cycle will be resolved, or nearly so. An assessment of progress toward the goals will have been completed for the major options. Key performance issue tests will be in planning, with some in operation, and decisions will have been made about advancing one or more prototypes. Fresh operating experience will be gathered from new SFRs in various countries or from the restart of Monju.
- For the SCWR, a set of essential technology projects will have been created. Feasibility issues regarding core layout and spectrum, fuel forms and possible recycling, and system thermal hydraulics and safety will be much better understood and on their way to resolution. The SCWR will be nearing a point at which it may assess its progress toward the goals. Key viability tests will be in operation.
- For the GFR, a set of essential technology projects will also have been created. Feasibility issues regarding fuel forms and actinide recycling, system safety and analysis, and cost will be much better understood and on their way to resolution. The GFR will be nearing a point at which it may assess its progress toward the goals. Key viability tests will be in operation.
- For the LFR, formal collaborations will have begun, and a set of exploratory projects will have been created. Feasibility issues regarding coolant and materials, energy conversion and components, actinide recycling, and system safety will be much better understood and preparations for viability testing will be underway.
- In Europe it is expected that a choice between gas and a heavy liquid metal coolant for fast reactors, to be pursued in parallel with sodium as a possible alternative technology, will be made with the potential launch of a project to construct an experimental reactor using the selected coolant.
- For the MSR, formal collaborations will also have begun, and a set of exploratory projects will have been created. Feasibility issues regarding its fuel cycle, salt chemistry with dissolved fuel isotopes (including transuranics), and materials compatibility will be much better understood and preparations

for viability testing will be underway. Issues on the operation and safety of the coupled MSR reactor and fuel processing unit will be clarified.

- R&D synergies will be developed between system steering committees, in domains such as requirements, design rules and codes, equipment, instrumentation, components and subsystems.

Generation IV is focused on four performance goals related to safety and reliability, proliferation resistance and physical protection, economics, and sustainability. Three crosscutting working groups have been created to develop evaluation methods that can assess the performance of new designs toward the Generation IV goals. During the coming five years these crosscutting working groups will continue to support the six-system steering committees in evaluating and guiding the optimization of their system designs. In addition, support for revitalizing and developing nuclear R&D infrastructure in terms of facilities, people, and new advanced simulation and validation tools will be emphasized.

6.2 Missions and Resources

The world is changing, and the Forum is monitoring the needs and pacing of our research and development. We anticipate some changes in emphasis or scope in the systems during the next five years, which are presented next.

While there is much debate about when or even if a large-scale deployment of a hydrogen economy may happen, it is now well understood how vital a role hydrogen currently plays in the production of premium transportation fossil fuels and chemical feedstocks. At the same time, there is a growing interest in the utilization of nuclear systems to produce high-grade process heat for a range of industrial applications. The Forum has encouraged its high-temperature systems to broaden their mission to include process heat applications more generally. This is an important way to make nuclear energy more relevant as a nongreenhouse-gas-emitting source of primary energy beyond electricity.

Second, a growing awareness of water shortages exists in many regions of the world. While the missions of Generation IV have included electricity, hydrogen production, and actinide management in the original *Roadmap*, we may be nearing a time when desalination should be highlighted in the missions if current generation reactors cannot successfully address it. We will continue to monitor this, as the development of such new energy products that can expand nuclear energy’s benefits beyond electrical generation contribute to the sustainability goals of the Forum.

Third, there is a growing interest in addressing the needs of countries and regions that are better served by smaller systems. While a few options with small module size are being pursued within the six Generation IV systems, these are intended to complement the evolutionary designs of industry for near-term deployment, and thereby provide for the long term future need. Of course, the specific technologies developed in Generation IV (such as new materials, fuels, or energy conversion technologies) may be adopted in these evolutionary designs in advance of their application in Generation IV systems.

Fourth, from the perspective of uranium resource conservation, many of the Generation IV systems investigated are fast neutron reactors that use plutonium and uranium recovered from spent fuel by reprocessing, and depleted uranium. Thorium was examined carefully by the Fuels Crosscutting Group during the original *Roadmap* and was not considered a first priority for Generation IV. However, we note an interest in the use of thorium resources and are already seeing exploration of thorium-based fuels in some Generation IV systems to understand their potential benefits. We encourage the systems to examine this alternative and take advantage of related insights gained in other collaborative activities.

6.3 Technical Cooperation and Membership

Technical cooperation and engagement of the research community worldwide plays a key role in the successful development of Generation IV systems. In the next five years, the Forum will expand the number of topical sessions that we sponsor in international conferences and events. These will inform the global research community of our technical interests, research problems, and breakthroughs with the hope of stimulating more participation by academia, industry, and laboratories. Second, the Forum will monitor the level of funded collaborations by industry, with the aim of significantly increasing this in the future. Third, the Forum will continue to facilitate cooperation amongst its members in the next stage of development of Generation IV systems, that of major technology demonstrations.

Finally, we note that our membership has changed over the years. While among the original signatories to the Generation IV Charter, Argentina and Brazil have made the decision to become inactive in the Forum largely as a result of changes in national research priorities. The United Kingdom decided to allow its technical community to continue to participate in Generation IV, though uniquely through the membership of Euratom. More recently, in 2006, China and Russia are the newest signatories to the Charter. In regards to the Framework Agreement, China acceded in 2007, the Republic of South Africa acceded in 2008, and Russia plans to accede in 2009. The original intent of the Forum remains the same—to bring the collaborative efforts of the major developers of next-generation nuclear energy systems to bear in a concerted effort. It is therefore important to be able to revisit the Forum's present membership and organizational structure from the viewpoint of each member's true input to its R&D activities. Likewise, we welcome the prospect of additional members that can bring significant resources and capabilities, and hope to report the successful entry of new members to the Forum over the next five years.

7. REFERENCES

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