The U.S. Generation IV Fast Reactor Strategy

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1 INTRODUCTION

In 2003, the Department of Energy (DOE) provided a report to Congress describing DOE's Generation IV nuclear energy systems implementation strategy[1]. That report indicated two priorities for Generation IV development. The first priority was to develop a more economically competitive system to meet growing energy demand and maintain the share of nuclear energy in the United States. To achieve this objective, the program has focused on developing a Very High Temperature Reactor (VHTR)-based system that is designed to produce cost-effective electricity, and which offers the potential to produce hydrogen. The second priority was to develop a fast spectrum reactor to further close the nuclear fuel cycle. Three fast reactor concepts have been under development as part of the Generation IV Program.

This year, the Senate Appropriations Committee encouraged DOE to give priority consideration to fast spectrum reactor technologies and requested a report on progress to focus fast spectrum reactor technology development. Specifically, Senate Report 109-84 stated:

> *The Committee encourages the Department to give priority consideration to fast spectrum technologies. Coupled with efforts of the Advanced Fuel Cycle initiative, research in this program must keep nonproliferation as a primary objective to reduce the amount of plutonium and other high level wastes that are a by-product of current technology. The Committee also recognizes that new advances in materials and fuels must be developed before these technologies can be deployed. In addition, the Department shall develop a R&D [research and development] road map by which the Department identifies the current technical challenges, proposes a research and development plan to resolve existing fast spectrum challenges within the Generation IV program, and downselects to no more than two technologies by the end of fiscal year 2007. The Department shall provide a copy of the Generation IV R&D roadmap to the Committee by the end of fiscal year 2006.*

This report provides an update to DOE's Generation IV implementation strategy with respect to fast spectrum reactors. It provides information on important developments with respect to nuclear energy that have resulted in DOE accelerating the fast reactor development program. As part of this acceleration, DOE has focused the fast reactor program on a single concept, the sodium-cooled fast reactor (SFR). The basis of this selection is provided, and the path forward for development and demonstration of the SFR is summarized below.

1.1 The Generation IV Nuclear Energy Systems Initiative

The Generation IV Nuclear Energy Systems Initiative (Generation IV) within DOE's Office of Nuclear Energy is the U.S. contribution to an international effort to develop next-generation nuclear energy technologies. Under DOE's leadership, the Generation IV International Forum (GIF), in conjunction with DOE's Nuclear Energy Research Advisory Committee, issued *A Technology Roadmap for Generation IV Nuclear Energy Systems*[2].

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[1] "The U.S. Generation IV Implementation Strategy," U.S. Department of Energy, September 2003, available at the Web site: http://www.ne.doe.gov/reports/reports.html

[2] "A Technology Roadmap for Generation IV Nuclear Energy Systems," Generation IV International Forum, GIF-002-00, December 2002, available at the Web site: http://www.ne.doe.gov/reports/reports.html

Figure 1. The members of the Generation IV International Forum (GIF) are Argentina, Brazil, Canada, Euratom, France, Japan, the Republic of Korea, the Republic of South Africa, Switzerland, the United Kingdom, and the United States

Based on the Roadmap, GIF countries (Figure 1) have jointly prepared collaborative research and development (R&D) programs to develop and demonstrate candidate concepts.

Within DOE, advanced reactors and associated advanced fuel cycles were conducted within the Office of Advanced Nuclear Research as two coordinated programs organized by technology area: the Generation IV Nuclear Energy Systems Initiative with its focus on next-generation reactor technology and the Advanced Fuel Cycle Initiative (AFCI) with the mission to develop the corresponding advanced fuel and fuel cycle technologies. Coordination activities have been expanded to include the Global Nuclear Energy Partnership (GNEP) with its emphasis on fast reactors and fuel recycling to ensure the effective utilization of resources. Accordingly, this report will discuss the role of fast reactors relative to GNEP as well as the Generation IV Program.

DOE's Technology Roadmap identified three major missions for Generation IV systems:

1. Electricity generation
2. Hydrogen (or other nonelectricity products)
3. Actinide management[3]

The U.S. Generation IV implementation strategy described in the 2003 Report to Congress addresses these missions through two priorities for R&D:

- Develop a Next Generation Nuclear Plant to achieve economically competitive energy products, including electricity and hydrogen, addressing the first two missions. The VHTR was selected for this priority.
- Develop a fast reactor to achieve significant advances in proliferation resistance and sustainability, addressing the third mission. Three reactor concepts were under development for this priority. The goal was to bring these systems to a state where the best system could be chosen based on economics, safety, reliability, sustainability, proliferation resistance, and physical protection.

1.1.1 The Actinide Management Mission

Actinide management is a mission with significant societal benefits, initiating the consumption of nuclear waste in the mid-term and providing assurance of nuclear fuel availability in the long term. This mission overlaps an area that is a national responsibility addressed in the Nuclear Waste Policy Act[4], namely, the disposition of used nuclear fuel and high-level waste.

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[3] Actinide elements are those starting with actinium and beyond in the periodic table. They include both uranium and transuranic elements. Transuranic elements are those above uranium, especially neptunium, plutonium, americium, and curium. Uranium and the transuranic elements have significant energy content because they can be fissioned, but they are also radioactive.

[4] Nuclear Waste Policy Act of 1982, as amended, available at the Web site: http://www.ocrwm.doe.gov/documents/nwpa/css/nwpa.htm

The mid-term component of the actinide management mission enables limiting or reversing the buildup of transuranic actinides (neptunium, plutonium, americium, and curium) through complete recycle of used nuclear fuel. The current fleet of light water reactors (LWR) that produces 20 percent of U.S. electricity generates these transuranics. Large inventories of transuranics have been accumulating since the 1960s with more than 20 metric tons of transuranic elements currently produced annually. Complete recycle results in the destruction of the transuranics by separating them and converting them through fissioning into much shorter-lived or stable isotopes while producing energy for electricity generation or other purposes. In the process, a great proportion of the long-lived radiotoxic constituents that would otherwise require isolation in a geologic repository are destroyed.

LWRs require an external supply of fissile material, currently supplied through mining and enrichment[5] of natural uranium. The longer term component of the actinide management mission involves the beneficial production of additional fissionable material from both recycled uranium and the large existing stocks of depleted uranium for use in either standard LWRs or fast reactors.

1.1.2 The Role of Fast Reactors

Fast reactors hold a unique role in the actinide management mission because they operate with higher energy neutrons than LWRs and are more effective in fissioning transuranic actinides recovered from LWR spent fuel. This allows fast reactors to operate with complete recycle of all of the uranium and transuranic isotopes. In contrast, thermal reactors, such as LWRs, use lower energy neutrons and extract energy primarily from fissile isotopes. The only fissile isotope in nature is uranium-235, which is only 0.7 percent of natural uranium; this natural concentration of uranium-235 is increased through enrichment to approximately 3-5 percent to enable a LWR to operate. Because LWRs cannot be employed for complete recycle, over 99 percent of uranium initially mined remains in used LWR fuel and in the residue from the enrichment process. Fast reactors are therefore the key to using uranium efficiently because they support multiple recycle that enables complete consumption of uranium and transuranic elements.

Fast reactors can operate in three different fuel cycle roles depending on their conversion ratios. The conversion ratio is defined as the amount of new transuranics created divided by the amount of transuranics consumed each pass through a reactor[6]. A conversion ratio less than one ("burner" mode) means that there is a net consumption of transuranics. Here "burn" does not mean incinerate or combust; it means to transmute or convert transuranics into shorter-lived isotopes to reduce long-term waste management burdens. A conversion ratio near one ("converter" mode) provides a balance in transuranic production and consumption. A conversion ratio greater than one ("breeder" mode) means there is a net creation of transuranics. An appropriately designed fast reactor has some flexibility to shift between these operating modes. Burner mode is appropriate to reduce existing amounts of transuranic elements, supporting the mid-term component of the actinide mission. Converter mode supports longer-lived cores of individual reactors but does not produce extra fissile material for other reactors or nuclear energy growth. Breeder mode is appropriate for the creation of new fissile isotopes from fertile uranium to offset the need for mining and enrichment of additional natural uranium.

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[5] Enrichment uses an isotopic separation process to increase the portion of the fissile isotope uranium-235 in a small portion of the uranium to usable levels (from 0.7 percent up to 5 percent) while producing a much larger portion of uranium depleted in uranium-235 (~0.2 percent to 0.3 percent). The remainder in both portions is fertile uranium-238.

[6] The conversion ratio is similar to the breeding ratio, which is the amount of fissile isotopes created (from fertile isotopes) divided by the amount consumed. The conversion ratio is a better measure for addressing waste management benefits.

1.2 Developments in the Generation IV Implementation Strategy

The 2003 Report to Congress indicated the primary driver for development of Generation IV nuclear energy systems was to enable increasing the share of domestic energy production provided by nuclear power. With recent fluctuations in natural gas prices and increasing concerns over potential global warming, there is an increased need to diversify domestic energy production.

The potential for nuclear energy to play an increasing role in energy production has also increased significantly. Since 2003, the number of U.S. nuclear plants filing for extensions of their operating licenses from 40 to 60 years has increased to the point that DOE now assumes that the licenses of over 75 percent of all reactors may eventually be extended[7]. The industry is also investing heavily in existing plants with completed cumulative capacity uprates more than doubling since 2000, providing the equivalent of several new plants, and the restart of a plant shut down since 1985 is scheduled for 2007 after a major refurbishment.

Interest in construction of new reactors is also growing quickly with several applications for early site permits filed with the Nuclear Regulatory Commission and declarations of intent to file for combined construction and operating licenses approaching 30 new plants[8]. The Energy Policy Act of 2005 included incentives for new nuclear plants in order to reduce the financial risks, thereby increasing industry interest.

The above events and statistics all point to the likelihood of large growth in domestic nuclear energy. Having anticipated this growth, DOE has continued to invest in the development of recycling technologies, as an alternative to the once-through fuel cycle that directly disposes of used nuclear fuel. Without recycling, under these nuclear energy growth scenarios, disposal capacity several times the current legal capacity of the first geologic repository will be needed to dispose of used fuel before the end of the century.

The continued and accelerating growth of nuclear energy internationally has also highlighted the need to reduce proliferation risks while maintaining the nuclear energy option. Whether the United States builds new plants or not, other nations are and will. At the same time, recent international events and proliferation concerns have underscored the need to reexamine U.S. policy and practices.

Another trend of note is the recent substantial increase in uranium prices. The ongoing U.S.-Russia program of downblending weapons-grade uranium has provided fuel for domestic commercial reactors for several years, partially helping to meet uranium needs. However, domestic license extensions, new international plants, and the potential of new domestic plants are all contributing to increased uranium demand projections. In response, spot prices have increased and the number of applications for new uranium mining is now rising.

As a result of these developments, the U.S. Government has recognized the need to influence the deployment of nuclear power around the world in a way that provides the benefits of nuclear power to the world without increasing the risk of nuclear proliferation. GNEP, summarized in the next section, responds to this evolving global energy situation and would promote earlier deployment of fast reactors than anticipated in the December 2002 Generation IV Technology Roadmap.

1.3 The Global Nuclear Energy Partnership

The development of a Generation IV reactor for actinide management is logically coupled with efforts to develop an advanced integrated fuel cycle for nuclear energy. As part of the

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[7] "Annual Energy Outlook 2006 with Projections to 2030," Energy Information Agency, February 2006, available at the Web site http://www.eia.doe.gov/oiaf/aeo/index.html

[8] Current status of new nuclear plants is available at the Web site http://www.nei.org/documents/New_Nuclear_Plant_Status.pdf

President's Advanced Energy Initiative addressing the growing need for U.S. and global energy security, the Department of Energy has proposed GNEP and identified advanced fuel cycle development as the key enabling technology.

GNEP seeks to develop worldwide consensus on enabling expanded use of economical, carbon-free nuclear energy to meet growing electricity demand. GNEP would use a more fully closed nuclear fuel cycle that enhances energy security while improving proliferation risk management. It would achieve its goal by having nations with secure, advanced nuclear capabilities provide fuel services - fresh fuel and recovery of used fuel - to other nations who agree to employ nuclear reactors for power generation purposes only.

The more fully closed fuel cycle model envisioned by this partnership requires development and deployment of technologies that enable recycling and consumption of long-lived radioactive waste. The Partnership would demonstrate the critical technologies needed to change the way used nuclear fuel is managed - recycle used fuel instead of direct disposal to significantly reduce the volume, thermal output, and radiotoxicity of the waste produced by energy generation requiring disposal in a geologic repository. GNEP aims to construct demonstration systems within the next 10-15 years.

GNEP will lead to recycling used nuclear fuel to minimize waste, recover energy from still-valuable used nuclear fuel, and reduce proliferation risk.

- GNEP aims to substantially improve the utilization of geologic waste repositories by recycling transuranic elements, e.g., the implementation of GNEP would help to ensure that one geologic waste repository would meet the U.S. need for the remainder of this century.
- The current once-through fuel cycle used in the United States and several other countries only extracts about 1 percent of the energy content in the original uranium ore. The remaining energy value resides in used nuclear fuel (transuranic elements and uranium) and uranium that is depleted during the uranium enrichment process. GNEP would enable the recovery of the energy content in the transuranic elements and separates excess uranium for possible future use.
- The current separation process in use outside of the United States, PUREX, creates a separated plutonium product. U.S. policy discourages the accumulation of separated plutonium in advanced nuclear fuel cycles. GNEP would instead encourage the use of an advanced separation process (e.g., UREX+) that does not separate plutonium. This process enables the reuse of the transuranics, minimizes waste, and reduces proliferation risk associated with the separation process relative to PUREX because it does not separate plutonium and incorporates highly radioactive actinides.
- GNEP 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 allow the International Atomic Energy Agency (IAEA) to more effectively and efficiently monitor and verify nuclear material.

1.3.1 The role of fast reactors in GNEP

Under GNEP, DOE would design and demonstrate an Advanced Burner Reactor (ABR) (Figure 2) that consumes transuranic elements (plutonium and other long-lived radioactive material) while extracting their energy. ABRs will be fast spectrum reactors. The demonstration of ABRs could enable an improved nuclear fuel cycle that recycles used fuel. ABRs would destroy almost all[9] the transuranics in used fuel from nuclear power plants, significantly reducing the limitations on accommodations of this radioactive, radiotoxic, and heat-producing material in a geologic repository.

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[9] Less than 1 percent of the transuranics would end up in high-level waste due to processing losses.

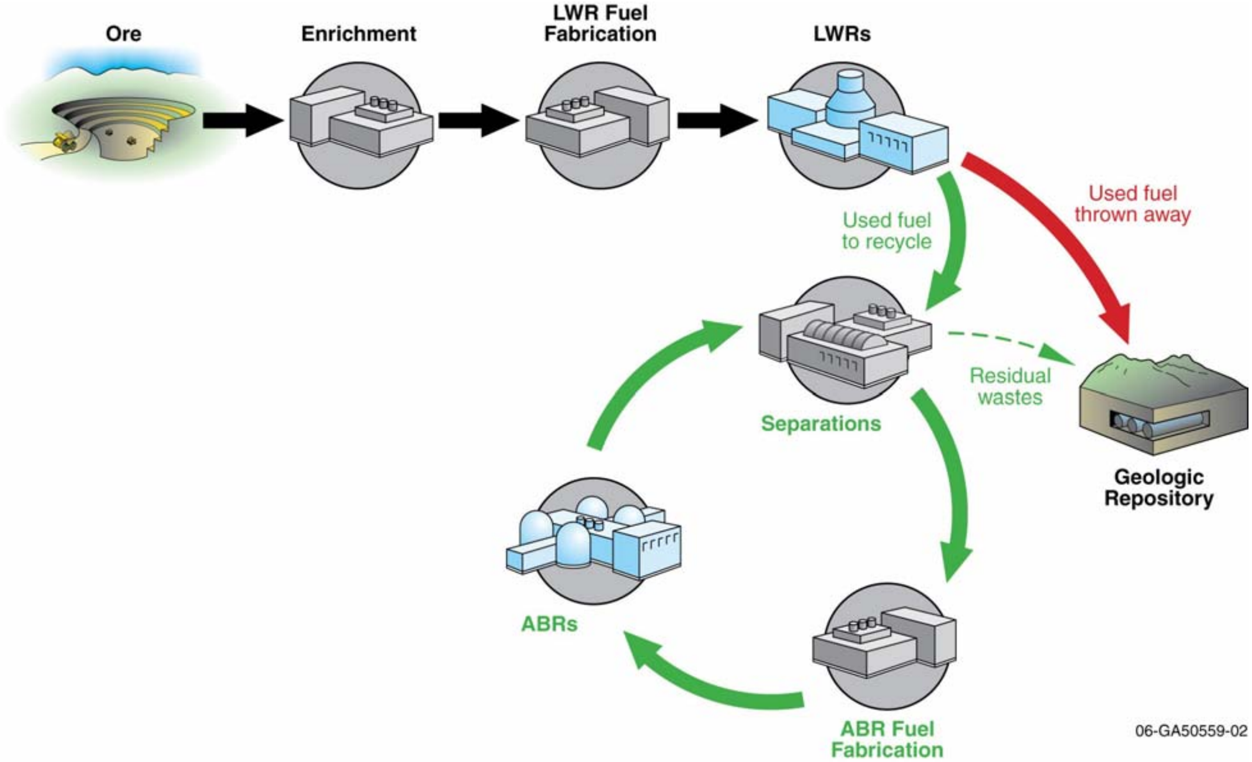

Figure 2. GNEP would shift from an open throw-away fuel cycle (red) to a recycle or closed fuel cycle approach (green)

To “burn” transuranics, an ABR takes advantage of high energy or fast neutrons to fission, or split apart, long-lived transuranics. As transuranics are consumed, significant energy is released and can be converted into electricity, thereby producing useful energy from material that would otherwise be disposed of as waste.

Given that typical U.S. LWRs are net producers of transuranics, using ABRs which are net consumers of transuranics is a logical approach. Significant prior U.S. investment in fast reactors provides a valuable technology base for DOE to support future development of an ABR.

2 FAST REACTOR TECHNOLOGY OPTIONS AND SELECTION

This section presents the reactor options for actinide management, comparing their relative strengths and weaknesses, and explains DOE's preference for SFR. Three of the six Generation IV reactor concepts are fast reactors (sodium, lead, and gas coolants). Two other Generation IV reactor concepts hold promise for supporting the actinide management mission. These are a fast-spectrum variant of the Supercritical-Water-Cooled Reactor and an epithermal-spectrum variant of the Molten Salt Reactor. Both require a significant amount of additional development prior to demonstration. Given the need to move forward with a reactor to support the actinide burning mission in the nearer term, they are not addressed further in this report.

DOE's Generation IV Program has conducted, jointly with its GIF partners, viability R&D on the gas-cooled and lead-alloy-cooled reactor concepts in anticipation of collecting enough information to provide a solid technical basis for recommending a fast reactor concept for commercial demonstration. Less effort was expended on the sodium-cooled reactor since it has amply demonstrated its technical viability. SFR development efforts underway in various countries are focused on design changes and advanced fuels and materials to improve operational and commercial performance.

The design concepts for the three fast reactors summarized in the next section are based on conceptual designs of varying maturity developed under national programs in a number of countries and in the past few years in bilateral collaborations with Euratom, France, Japan, and Republic of Korea (Korea). These collaborations extended also into the development of innovative fuels, irradiation testing of advanced structural materials, and the development and validation of advanced design and safety analysis methods. These collaborations also include the study and initial design effort of an advanced energy conversion system that is particularly well adapted to the typical fluid outlet temperatures of fast reactors. The energy conversion system incorporates a Brayton cycle with supercritical carbon dioxide as the working fluid and promises higher thermal efficiency, smaller footprint, and lower capital cost.

2.1 Description of Fast Reactor Options

The following subsections briefly describe the three fast reactor options identified in the December 2002 Generation IV Technology Roadmap under consideration by GIF.

The three fast reactor systems can operate on a range of fuel types including oxide, nitride and dispersion fuels (all), metal fuel (liquid metal coolant), and oxycarbide fuel (gas cooled). There is considerable operating experience for oxide and metal fuels but limited experience with the other types. All three systems can use fuels that are compatible with aqueous processing and pyroprocessing for recycling.

Sodium-Cooled Fast Reactor System

The SFR system features a fast-spectrum, sodium-cooled reactor (Figure 3) and a more fully closed fuel cycle for efficient management of actinides and conversion of fertile uranium. The fuel cycle employs full actinide recycle. Plant size options under consideration range from smaller sized (150 to 500 MWe) modular reactors to larger plants (up to 1,500 MWe). Fuel cycle options are either a metal alloy fuel that contains uranium and transuranic elements, supported by pyrometallurgical processing of spent fuel in facilities integrated with several collocated reactors, or a mixed uranium-transuranic oxide fuel supported by advanced aqueous processing of spent fuel (e.g., UREX+) at a central location serving a number of reactors. The outlet temperature is approximately 550°C for all options.

SFR is designed for management of high-level wastes and, in particular, management of plutonium and other actinides. Important safety features of the system include a long thermal response time (the reactor heats up slowly), a large margin between operating temperatures and the boiling temperatures of coolants (less chance for accidental boiling), a noncorrosive coolant

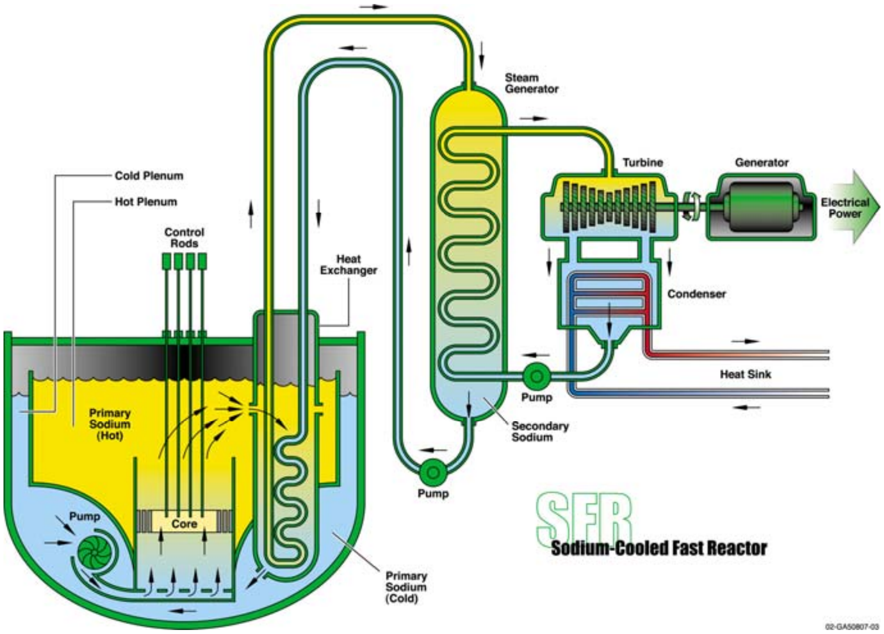

Figure 3. SFR Concept

(protects pipes and vessels), a primary system that operates near atmospheric pressure (piping is not pressurized), and an intermediate sodium system between the radioactive sodium in the primary system and the water and steam in the power plant. SFR's fast spectrum makes it possible to utilize available fissile and fertile materials (including depleted uranium) considerably more efficiently than thermal reactors such as LWRs.

2.1.1 Lead-Cooled Fast Reactor System (LFR)

The LFR system features a fast-spectrum reactor using pure lead or lead/bismuth eutectic liquid as coolant and a more fully closed fuel cycle for efficient conversion of fertile uranium and management of actinides. The system supports the actinide management mission with central or regional fuel cycle facilities. Options include a range of plant ratings including a battery[10] of 50-150 MWe (Figure 4) that features a very long interval between refueling to reduce the number of shipments of nuclear fuel, a modular system rated at 300-400 MWe, and a large plant option at 1200 MWe. The fuel is metal or nitride, containing fertile uranium and transuranics. The LFR battery concept is cooled by natural circulation with current development on a reactor outlet coolant temperature of 550°C, possibly ranging up to 800°C with advanced structural materials. The higher temperature enables process heat applications including the production of hydrogen by high-temperature electrolysis processes. A lower temperature variant (~480°C) could be demonstrated with less technical risk but with a somewhat lower thermal efficiency.

The LFR battery is a small factory-built turnkey plant operating on a closed fuel cycle with a very long refueling interval (15 to 20 years) cassette core or replaceable reactor module. Its features are designed to meet market opportunities for electricity production in isolated locations or on small grids and for countries that may not wish to deploy an indigenous fuel cycle infrastructure to support their nuclear energy systems. The battery system is designed for distributed generation of electricity and other energy products including hydrogen and potable water.

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[10] The term "battery" refers to the long-life, factory-fabricated core not to any provision for electrochemical energy conversion.

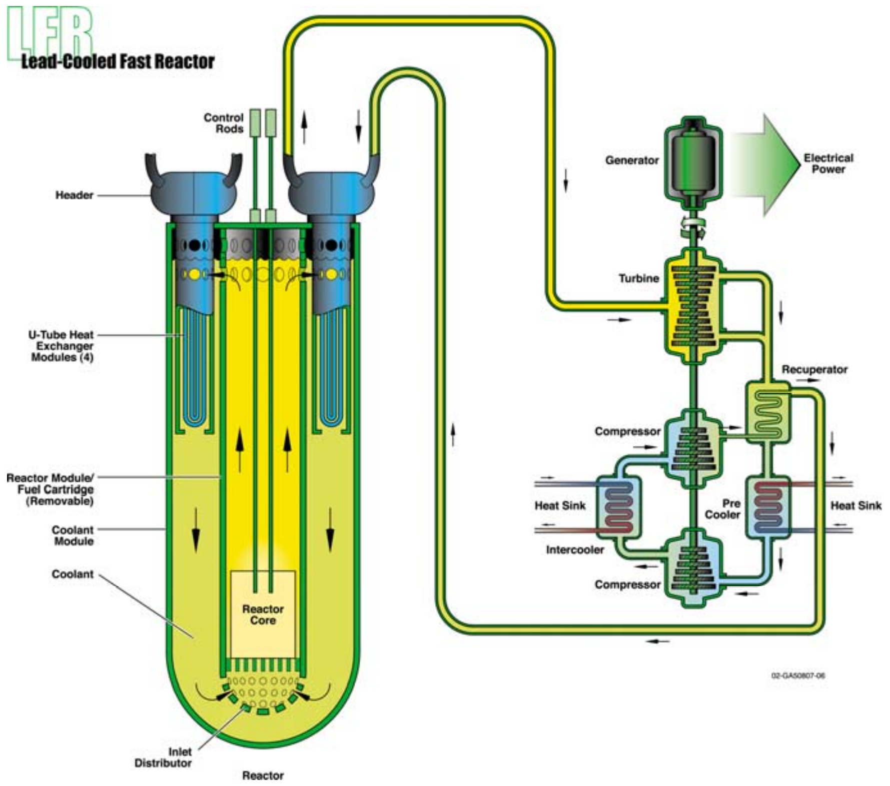

Figure 4. LFR Concept

2.1.2 Gas-Cooled Fast Reactor System (GFR)

The GFR system features a fast-spectrum, helium-cooled reactor (Figure 5) and a more fully closed fuel cycle. Like thermal-spectrum, helium-cooled reactors, the high-outlet temperature of the helium coolant makes it possible to deliver electricity, hydrogen, or process heat with high efficiency. The reference reactor is a helium-cooled system, ranging from 288 MWe to 1,200 MWe, operating with an outlet temperature of 850°C. Several innovative fuel forms are candidates that hold the potential to operate at very high temperatures and to ensure an excellent retention of fission products: composite ceramic fuel, advanced fuel particles, or ceramic clad elements of actinide compounds. Core configurations may be based on prismatic blocks, pin- or plate-based fuel assemblies. The GFR reference has an integrated, on-site used fuel treatment and refabrication plant.

The reference GFR uses a direct Brayton cycle helium turbine for high-thermal efficiency in electricity generation or can optionally use its process heat for production of hydrogen. Steam cycle GFRs have been designed in the past, operating at lower temperatures.

2.2 Comparison of Fast Reactor Performance Potential

This section compares the Generation IV fast reactor options from the perspective of potential performance for deployed systems. This comparison is based on a recent report provided to Congress[11] with adjustments to reflect the reactor systems performance at the time of the earliest possible deployment (i.e., without the benefit of long-term R&D).

The Generation IV Program is based on achieving improved performance for reactors and associated fuel cycles against a range of objectives. All fast reactors perform very well on objectives related to waste management benefits due to their ability to burn transuranics.

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[11] "U.S. Department of Energy Office of Nuclear Energy Advanced Fuel Cycle Initiative (AFCI) Comparison Report, FY 2006 Update," July 2006.

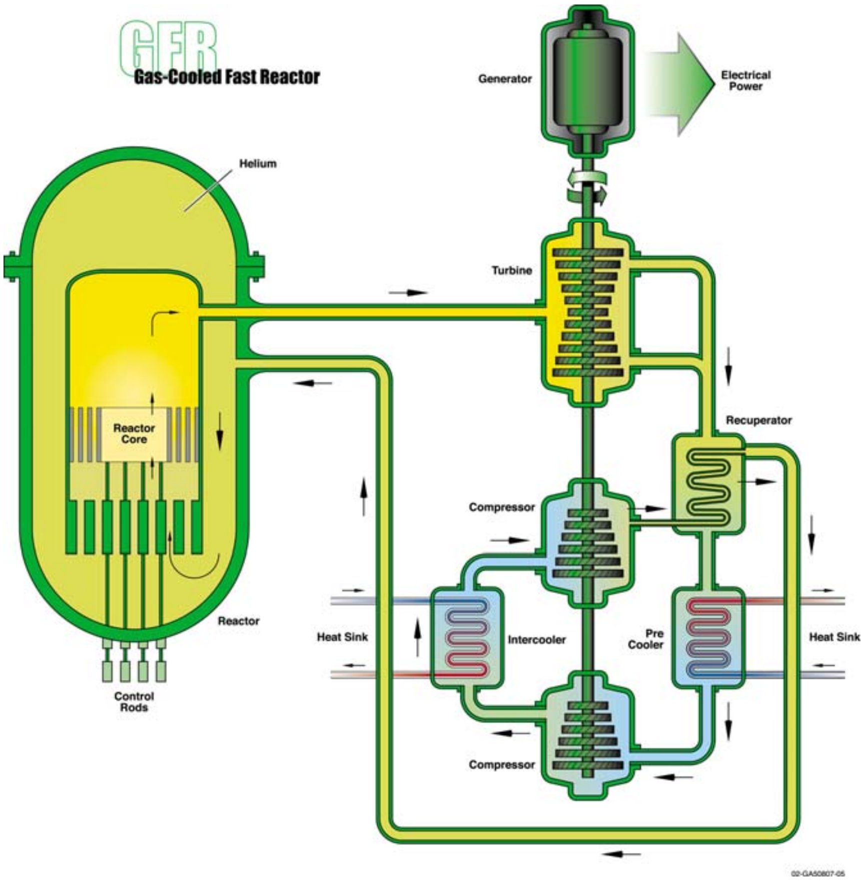

Figure 5. GFR Concept

Fast reactors can also destroy transuranic materials that otherwise may present proliferation concerns. Likewise, fast reactors perform very well on their ability to extract the maximum energy from uranium resources, supporting the sustainability of nuclear energy for the very long term.

Where the fast reactor systems differ somewhat is on objectives related to economics and safety.

Economics – There are several issues associated with the economic performance of reactor systems.

Higher thermal efficiency may provide improved economics but only if it does not require additional expense in construction. SFR and lower temperature LFR systems both exhibit moderately higher temperatures and thermal efficiencies versus current generation LWRs, while the less mature high-temperature LFR and GFR systems have much higher thermal efficiency potential. The efficiency range of SFR and lower temperature LFR can be enhanced somewhat by moving from a standard steam cycle to supercritical steam or a supercritical CO_2 Brayton cycle (under development).

The power density of the reactor core drives the size of many components and structures. The higher SFR power density allows for a more compact system.

All Generation IV fast reactor efforts are actively pursuing design simplifications for cost reduction. All are also assessing both economies of scale and factory fabrication options to decrease capital costs.

Safety - All Generation IV reactors are designed for improved safety with an emphasis on passive safety. There are relative differences between the fast reactor systems, but all achieve this general improvement in safety. Sodium interacts energetically with water; however, a number of sodium fast-test reactors have been operated both domestically and internationally for long periods without any coolant interaction problems. Lead interacts corrosively with steel alloys; however, the Russians have overcome most of the corrosion issues, successfully operating lead-cooled reactors for long periods at lower operating temperatures. The gas fast reactor operates at high pressure and requires active heat removal after shutdown, but its fuel form is very robust and can withstand very high temperatures without damage.

2.3 Comparison of Fast Reactor Maturity

The previous section provides a generalized discussion on comparative fast reactor features. Little doubt exists that all three fast reactor concepts would, if fully developed and so designed, be capable of functioning in a burner, converter, or breeder mode. The Generation IV Roadmap stipulated that viability R&D on the fast reactor concepts could be completed jointly by the GIF partners by 2014.

DOE's strategy for selecting a fast reactor technology has been revised to place more weight on the probability of success of a near-term fast reactor demonstration project. Given the prominence of GNEP and DOE's desire to optimize the use of appropriated funds, the Generation IV fast reactor program is focusing its efforts to support GNEP. Experience relevant to probability of project success is summarized below for different fast reactor technologies.

2.3.1 Technical Readiness

Technical readiness reflects how soon a system could be deployed. In order to achieve the significant performance improvements envisioned under the Generation IV Program, considerable research and development is necessary in order to achieve the Technical Readiness level of "proof of performance." At the present time, these Generation IV reactors would be considered at the Technical Readiness level of "concept development." In spite of the long-term R&D needs, current versions of most fast reactor systems exist that would require minimal development prior to deployment but would overall provide lower performance than mature Generation IV reactors.

Technical Readiness Levels

- Concept Development – The concept is still at a basic level. Suitable options for various applications are defined based on first principles and fundamental knowledge with the critical technical issues or "showstoppers" identified, a work around for showstoppers defined, and a verification plan developed.
- Proof of Principle – The concept has been shown to be technically feasible, but performance characteristics for operational plant performance are uncertain. Development is performed using laboratory-scale experiments and analytic extrapolations to full-scale behavior.
- Proof of Performance – The concept is known to be technically feasible, and there is considerable performance data, but the economics of scale up to commercial scale is uncertain. Large-scale demonstrations on portions of the processes are performed, yielding final performance specifications including statistical assessments and initial indications of economic performance.

The two most relatively mature concepts, at the "proof-of-performance" stage, are SFR and the low-temperature, lead/bismuth variant of LFR. The higher temperature LFR that has been the focus of Generation IV research is less mature at the "proof-of-principle" stage. GFR is still in "concept development". However, GFR designs were developed in the 1970s to operate at lower temperatures with steam cycle plants utilizing SFR technology. These designs would be closer to "proof-of-principle" maturity but still not ready for scale-up demonstration.

2.3.2 Operating Experience

Operating experience provides important input into the design process and has the potential to influence the maturity of the various fast reactor concepts. The greater the number of operating experience years, the greater the opportunity to modify the design based on operating lessons learned.

The SFR relies on technologies already developed and demonstrated for sodium-cooled reactors and associated fuel cycles that have successfully been built and operated in worldwide fast reactor programs. Overall, approximately 300 reactor years of operating experience have been logged on SFRs including 200 years on smaller test reactors and 100 years on larger demonstration or prototype reactors.

In the United States, SFR technology was employed in the 20 megawatt electric (MWe) Experimental Breeder Reactor (EBR) II that operated from 1963 to 1994 (Figure 6). EBR-II R&D included development and testing of metal fuel and passive safety tests. The 400 megawatt thermal (MWt) Fast Flux Test Facility (FFTF) was completed in 1980. FFTF operated successfully for ten years with a full core of mixed oxide (MOX) fuel and performed SFR materials, fuels, and component testing. The U.S. SFR development program stalled with cancellation of the Clinch River demonstration reactor in 1983, although DOE research for advanced SFR technology continued until 1994, and monitoring of international research is ongoing through the Generation IV Program. SFR experience also extends to the commercial sector with the operation of Detroit Edison’s FERMI 1 plant from 1963 to 1972.

Significant SFR research and development programs have also been conducted in Russia, Japan, France, India, and the United Kingdom (U.K.). The only current fast reactor for electrical generation is the BN-600 (Russia) that has reliably operated since 1980 with a 75 percent capacity factor. Currently operating test reactors include PHENIX (France), JOYO (Japan), and BOR-60 (Russia). The most modern fast reactor construction project was the 280 MWe MONJU (Japan) that was completed in 1990. In addition, SFR technology programs have recently been started in both Korea and China with the Chinese Experimental Fast Reactor scheduled for startup in 2008.

Figure 6. The EBR-II sodium fast reactor operated in Idaho from 1963 to 1994

LFR experience is primarily in Russia and exclusively on smaller reactor designs. The Russians have operated 12 lead/bismuth eutectic-cooled reactors including 10 submarine reactors and 2 land prototypes and have accumulated approximately 80 reactor years of operating experience. Rosatom has recently decided to accelerate development of the SVBR-75/100 LFR based on submarine reactor technology that could lead to construction and operation as early as 2013.

There has been nearly a decade of research on lead/bismuth eutectic and lead coolant technologies with over a dozen test loops in Europe, Japan, Korea, and the United States. The MEGAPIE lead/bismuth eutectic target system was recently placed in full operation at the Paul Scherer Institute in Switzerland. In this accelerator-based system, a proton beam with 1 megawatt of energy impinges on the MEGAPIE lead/bismuth target creating spallation neutrons. There are no LFR test reactors outside of Russia, but the European Union and Italy are funding development of the European Lead System reactor. There is no existing experience with commercial scale LFRs equivalent to the BN-600 SFR.

Experience with gas-cooled fast reactors goes back to the 1960s and pertains to designs only--no GFRs have been built. The features of the previous designs are dated in comparison to the innovative GFR designs that are being pursued under the GIF umbrella primarily by Euratom, France, and the United States. Under the auspices of the Generation IV Program, France is currently leading a collaborative GIF effort to design, develop, and ultimately build a 50 MWt GFR that will start at lower temperatures with near-term core fuel technology, then transition to the higher Generation IV goal core temperatures as the required advanced fuel technology is developed and tested in the reactor. The GFR is the only Generation IV fast reactor system with a thermal-spectrum reactor equivalent. The VHTR and GFR share many common technology features since both use helium as the coolant. Even the modern thermal-spectrum helium-cooled reactor has no full-size prototype reactor operating today.

2.4 Selection of the Sodium Fast Reactor

For near term deployment of fast reactor technology, the option with the most viable technical maturity is the SFR. A demonstration reactor could be pursued today with SFR technology, in roughly 5 to 10 years with LFR, and roughly 20 years with GFR. The challenges for SFR technology are well understood, and ongoing international R&D activities may help improve performance for both energy and fuel cycle applications.

The alternate LFR and GFR technologies offer some advantages, particularly for high-temperature applications; and it is prudent to retain a backup fast reactor technology option. DOE plans to monitor international developments for the LFR and GFR and participate in international collaboration under GIF at a level sufficient to “retain a seat at the table,” while proceeding with the focused development and demonstration of the SFR.

3 SODIUM FAST REACTOR DEMONSTRATION PROGRAM

Section 1 of this report presented the drivers for accelerating the fast reactor development effort in the United States including the need to support the deployment of fast reactor technologies much sooner than was originally projected in the Generation IV roadmap. Section 2 presented the fast reactor options and the basis for selecting the SFR as the system to support the Generation IV actinide management mission. This section presents the path forward for enabling the deployment of commercial SFRs including making final technology decisions, updating existing SFR support infrastructure, and proceeding with the demonstration of a full-actinide burning SFR.

3.1 Technology Decisions

While the decision to focus on the SFR technology has been made, several additional technology selection decisions are required to move forward with a demonstration system design.

Fuel Type - SFR could operate with a number of different fuel types; only two are being considered by DOE for the accelerated program - metal and oxide. The United States has extensive experience with both; EBR-II employed metal fuel, and FFTF employed oxide fuel. In both cases, there were no minor actinides in the fresh fuel. Full-actinide transmutation fuel is required to support the actinide management mission, and a fast spectrum reactor is needed to develop this fuel. Demonstrating the SFR will support the development of full-actinide transmutation fuels, providing key data to support selection of the final transmutation fuel type.

To reduce technical risk and shorten the schedule for design and construction of the demonstration SFR, it has been decided that the start-up “driver” fuel for the reactor will not be transmutation fuel. Instead, traditional uranium-plutonium fuel will be used. Experience from the two U.S. SFR test reactors has provided most of the needed data to qualify this fuel for safe operation. The decision on whether to employ metal or oxide driver fuel will be based on a combination of factors including fabrication schedule and objectives, fuel performance and reliability, reactor safety, and the impact that safety-related design accommodations have on construction and operating cost and mission schedules.

Cost Reduction Design Features – Although the sodium-cooled fast reactor technology is mature, the capital cost of previous experimental reactors has been high. Recent cost studies[12] estimate that the capital cost of current designs may be approximately 26 percent greater than conventional LWRs. Much of this difference is due to LWR cost reductions achieved from the experience of 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 deployment in accordance with market principles, a number of innovative SFR design features will be assessed for possible inclusion in the demonstration system design. Potential improvements include:

- **Long-lived Materials** - Standard reactor-grade stainless steels will be used for the reactor vessel and support structures. However, to compete better with LWRs, these structures and their associated materials need to be qualified for 60-year lifetimes.
- **Seismic Isolation** – A seismic isolation system is being considered for the demonstration SFR to demonstrate the feasibility and benefit of seismic isolation systems to nuclear applications. This is a reasonably mature technology, but it has not been demonstrated in the higher temperatures and radiation fields of a reactor.
- **Digital Instrumentation and Control** – Advanced digital control systems have been proposed for advanced LWRs, but their applicability to the harsher operating environment of the SFR needs to be validated.

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[12] Accelerator-Driven Systems (ADS) and Fast Reactors (FR) in Advanced Nuclear Fuel Cycles – A Comparative Study, Nuclear Energy Agency – Organization for Economic Cooperation and Development (OECD), 2002.

- **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 a specialized in-vessel handling machine.
- **Improved Operations and Maintenance Technology** – Innovative ideas are being considered for in-service inspection and repair to support operations and maintenance. Remote handling and sensor technology for use under sodium are being developed including ultrasonic techniques. In addition, increased reliability for sodium-water steam generators is being pursued by advanced detection and diagnostic techniques.
- **Balance of Plant** – There are two options for conversion of the reactor's thermal energy into electricity: a standard steam cycle using proven sodium to water heat exchanger technologies or a less mature supercritical carbon dioxide (CO_2) Brayton cycle for higher efficiency.

3.2 Fast Reactor Infrastructure

Considerable effort will be required to update the U.S. infrastructure for sodium fast reactors. Much of the required infrastructure has atrophied since the last domestic SFRs were shut down in the early 1990s. Key infrastructure needs include:

- **Coolant Control Technology** – This includes the necessary engineering and knowledge base to fill, drain, and operate flowing sodium systems and for clean up and purification of the sodium coolant; chemistry control; heating and cooling systems; and instrumentation and control. This technology was well established in the United States with the liquid metal reactor programs in the 1990s and needs to be reestablished to effectively build domestic sodium systems.
- **Component Fabrication and Testing -** There are no current domestic industrial fabrication and testing capabilities for metal-cooled fast reactor components. The DOE facility previously used to conduct research and development in liquid metal applications and for testing large sodium components in a prototypic environment has been decommissioned (along with most U.S. fast reactor development facilities) and is no longer available for use.
- **Reactor Start-up Fuel Fabrication** – As mentioned previously, a decision on the type of start-up fuel needs to be made. Facilities previously used for making both metal and oxide (ceramic) fast reactor fuels are currently operational but will require installation of new equipment and other updating.
- **Reactor Design -** Design resources and tools are available from the previous U.S. fast reactor program and in most cases reflect international standards. However, the current design process includes conservative margins, and significant cost savings may be possible with higher fidelity simulation and optimization methods. Many of the existing codes are based on the computer architecture of twenty years ago – to overcome computing limitations modeling assumptions were used to approximate physics phenomena, many of which can now be directly modeled.
- **Safety Analysis -** The available fast reactor safety analysis tools developed in the United States also reflect the current standard and are utilized in all the major international fast reactor programs. As with reactor design codes, improvements are envisioned to provide more accurate analyses with modern simulation techniques.
- **Licensing and Regulation -** The international standard for fast reactors is severely outdated since the last fast reactor was built in 1990. The last fast reactors receiving U.S. regulatory approval were FFTF (test reactor, 1980) and FERMI-1 (commercial plant, 1966). Thus, the regulatory resources and competency to review fast reactor safety needs to be reestablished.

3.3 Fast Reactor Demonstration

A fast reactor is needed to complete transmutation fuels development and proof-test actinide management. The ABR would also help to reestablish the infrastructure needed to deploy commercial-scale fast reactors and begin building the experience base of reactor operations and the pool of trained personnel.

Design and construction of an ABR would take some time with initial operation projected by 2020. This is a full decade earlier than previous Generation IV timelines. The program will address a number of significant issues associated with deployment of a fast reactor system, and the time required for potential licensing and construction of future plants is anticipated to be competitive with advanced LWRs.

A detailed schedule will be developed after the scope of needed development is better defined and an acquisition strategy for any GNEP technology program has been determined.

4 COLLABORATIONS

4.1 Industry Partnerships

The direct customers of new nuclear technology are the energy companies who own and operate the reactors and fuel cycle facilities and the vendors and architect-engineers who must build them with the ultimate beneficiaries being the American public. Generation IV efforts for fast reactors and fuel cycles up to this point have consisted primarily of viability research and early component performance development. Industry involvement has been limited to monitoring and to a small extent participating in the development efforts.

U.S. industry was an active participant in the domestic research and development of SFR technology in previous DOE programs (e.g., as recently as 1994 in the Advanced Liquid Metal Reactor project). The success of GNEP and SFR development relies on the early and extensive involvement of industrial partners. As with other partners, it is expected that industrial partners will provide a significant amount of cost sharing for all DOE activities.

4.2 Academic and University Partnerships

The U.S. Generation IV Program has been focused on aggressive technology advances, which require many innovations and explorations of alternatives for its success. The role of U.S. universities and national laboratories has been central to these advances. Throughout the current R&D phases of the U.S. Generation IV Program and AFCI, the nature of these partnerships has focused on peer-reviewed, investigator-led projects in academia that are of high relevance to the program outcomes as well as program R&D tasks jointly undertaken by the national laboratories and universities. In moving forward with development and demonstration, the focus of research will become more applied.

4.3 International Partnerships

DOE has achieved significant progress in formulating and initiating international collaborations. Largely through the strong leadership of DOE, GIF has now advanced from formulating intentions (2001) to developing R&D plans for most-promising concepts (2003) to establishing the Generation IV Framework Agreement (2005) and negotiation of implementing arrangements (2006).

The Generation IV Framework Agreement is a government-to-government agreement specifying the nature and content of two levels of implementing arrangements[13], see Figure 7. At the second level, the SFR System Arrangement defines the nature and extent of collaboration on specifically the SFR system[14]. At the third level, the Project Arrangement is the contractual document that specifies the collaboration terms and conditions between the parties on development in accordance with the Project Plan. Plans for additional collaborative R&D projects are underway.

To prepare the way for the multilateral GIF collaboration framework, DOE initiated bilateral collaborations with interested GIF countries. Starting in 2001, DOE now has several International Nuclear Energy Research Initiative (I-NERI) projects underway. These joint projects have been increasingly focused on elements of the joint GIF System Research Plans.

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[13] As of September 2006, Framework Agreement signatories are Canada, Euratom, France, Japan, Korea, Switzerland, U.K., and U.S.

[14] Generation IV International Forum (GIF), System Arrangement on Advanced Fuel for the International Research and Development of the Sodium-Cooled Fast Reactor Nuclear Energy System, 2006. Current signatories are France, Japan, Korea, and U.S.

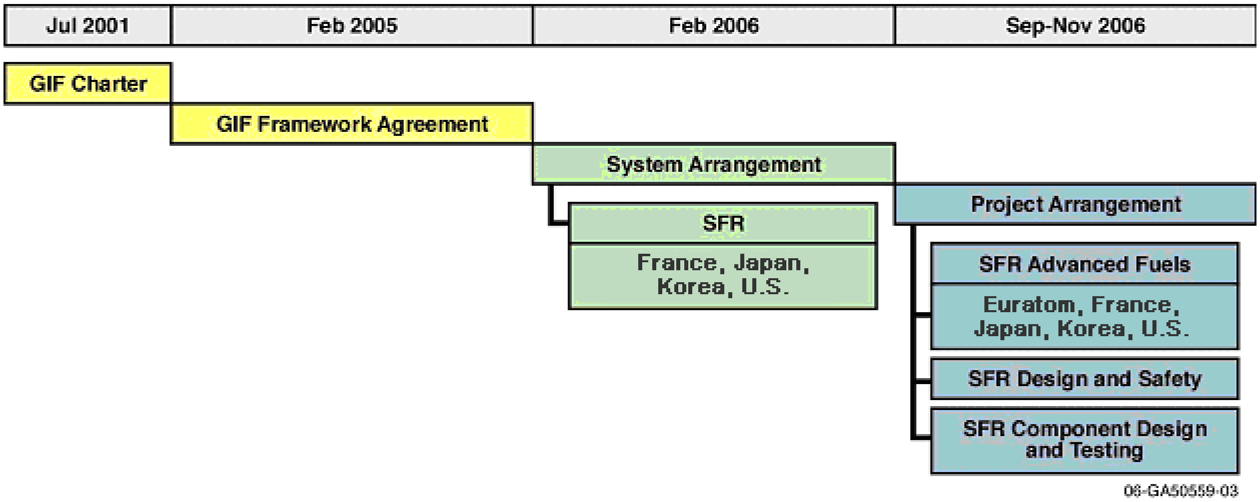

Figure 7. Relationship of Agreements and Arrangements within the GIF Charter

Table 1 shows the number of three-year I-NERI joint research projects by country as of September 2006.

DOE is currently evaluating how to best structure international collaboration to support the goals of GNEP. The GIF collaboration projects are held in high regard by our key partners, and DOE will endeavor to define the SFR Project Arrangements to optimize their usefulness to the ABR development and demonstration. International collaboration on sensitive technologies, such as advanced aqueous separation of spent nuclear fuel, will be limited to a subset of GIF countries and may best be conducted under I-NERI arrangements or even under tailored multilateral agreements.

4.4 Important Linkages and Interfaces to Other DOE Programs

As described in Section 1.3, the fast-reactor component of the Generation IV program and GNEP are intimately connected. Both programs share a strong common interest in the development of advanced fast reactor and fuel cycle technology that will minimize the risk of nuclear proliferation worldwide and assist in the management of U.S. high-level nuclear waste. Therefore, the Generation IV Program is also linked, through the GNEP Program, to DOE’s National Nuclear Security Administration (NNSA) and the Office of Civilian Radioactive Waste Management.

Collaborator	FY 2001	FY 2002	FY 2003	FY 2004	FY 2005	FY 2006	Total
France	4	1		11			16
Korea		6	5	6	4		21
Euratom				8	2		10
Canada				7			7
Brazil					1	1	2
Japan					1	1	2
Total	4	7	5	32	8	2	58

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Table 1. Distribution of I-NERI joint research projects

The U.S. Generation IV Fast Reactor Strategy