GENERATION IV NUCLEAR ENERGY SYSTEMS TEN-YEAR PROGRAM PLAN

Fiscal Year 2006

Volume I

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DISCLAIMER

The *Generation IV Nuclear Energy Systems Ten-Year Program Plan* describes the updated system and crosscutting program plans that were in force at the start of calendar year 2006. However, the Generation IV research and development plans continue to evolve, and this document will be updated annually or as needed. Even as this Program Plan is being released, several system research and development plans are still under development, most in collaboration with international, university, and industry partners. Consequently, the Program Plan should be viewed as a work in progress. For current information regarding this document or the plans described herein, please contact:

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EXECUTIVE SUMMARY

According to the International Atomic Energy Agency, 443 nuclear power plants were operating worldwide in 2004, generating electricity for nearly one billion people. These plants account for approximately 17 percent of the worldwide installed base capacity for electricity generation and provide half or more of the electricity in a number of countries. Concerns over continued energy resource availability, climate change, air quality, and energy security suggest an important role for nuclear power in fulfilling future energy needs. In 2004, the nuclear power plants operating worldwide displaced two billion tons of carbon dioxide emissions that would have been released into the atmosphere, if the electricity had been generated by fossil fuels.

While the current nuclear power plant designs provide an economically, technically, and publicly acceptable electricity supply in many markets, further advances in nuclear energy system design can broaden the opportunities for the use of nuclear energy. To explore these opportunities, the United States (U.S.) Department of Energy's (DOE's) Office of Nuclear Energy (NE) has engaged governments, industry, and the research community worldwide in a wide-ranging discussion on the development of several next-generation nuclear energy systems commonly known as "Generation IV." This effort commenced in January 2000, when 10 countries and the European Atomic Energy Community (Euratom) joined together to form the Generation IV International Forum (GIF), with a mission of developing future-generation nuclear energy systems that can be licensed, constructed, and operated to provide competitively-priced and reliable energy products while satisfactorily addressing nuclear safety, waste and non-proliferation. Two additional related programs also support the advanced nuclear energy goals: the Nuclear Hydrogen Initiative (NHI) and the Advanced Fuel Cycle Initiative (AFCI). The NHI focuses on the demonstration of economic commercial-scale production of hydrogen using nuclear energy and the AFCI focuses on developing a life-cycle fuel process to minimize nuclear waste and reduce proliferation risks.

Recent actions initiated by President George W. Bush and Congress reflect the need for the expansion of nuclear energy as a key energy source for long-term energy security.

- In 2005, the President signed the first comprehensive energy legislation in over a decade. The 42 USC 14801, Energy Policy Act of 2005 (EPACT2005) was passed by the U.S. Congress on July 29, 2005 and signed into law on August 8, 2005. EPACT2005 includes specific references to the Generation IV Nuclear Energy Systems Initiative and the Next Generation Nuclear Plant (NGNP) Project.
- The Advanced Energy Initiative was announced by President Bush during his State of the Union Address on January 31, 2006. This initiative focuses on reducing America's dependence on imported energy sources. In line with this initiative, the Global Nuclear Energy Partnership (GNEP) was announced by Secretary of Energy Samuel Bodman on February 6, 2006. GNEP is a comprehensive strategy to increase U.S. and global energy security, encourage development of clean nuclear power around the world, reduce the risk of nuclear proliferation, and improve the environment.

Earlier work put a framework in place to help accomplish these goals. Issued in 2002, *A Technology Roadmap for Generation IV Nuclear Energy Systems* (herein called the Generation IV Roadmap [DOE 2002]), documented a comprehensive evaluation of nuclear energy concepts and selected the most promising ones as candidates for next-generation nuclear energy systems. For these systems, detailed research and development (R&D) plans were developed for establishing technical and commercial viability, demonstration, and potential commercialization. More than 100 experts from 10 countries and international organizations collaborated on this document. It was issued jointly by DOE's Nuclear Energy Research Advisory Committee (NERAC) and the GIF.

International collaboration is expected to continue for the life of the program and is coordinated through the GIF. The GIF shares the goals for future nuclear energy systems as expressed in the Generation IV Roadmap (DOE 2002). The GIF allows for the coordination of member nation R&D programs to leverage the resources available for technology development.

The Generation IV Roadmap (DOE 2002) identified the six most promising nuclear energy systems as well as several crosscutting technology R&D areas. These Generation IV reactor systems were selected based on their ability to meet the roadmap goal areas of sustainability, economics, safety and reliability, and proliferation resistance and physical protection. The six nuclear energy systems are being pursued in the U.S. at varying levels based on their technical maturity and potential to meet national energy needs. The emphasis of the Generation IV Program is to develop a more economically competitive nuclear energy system to meet growing energy demand and maintain the share of nuclear energy in the U.S.

While the evaluations of nuclear energy systems for their potential to meet all goals were a central focus of the Generation IV Roadmap (DOE 2002), it was recognized that countries would have various perspectives on their priority uses, or missions, for Generation IV systems. The major Generation IV mission interests include: (1) electricity production, (2) hydrogen production, (3) actinide management, and (4) small grid electricity production with limited nuclear infrastructure.

Two of the six Generation IV nuclear energy systems employ a thermal neutron spectrum: the NGNP and the Supercritical-Water-Cooled Reactor (SCWR).

- ***NGNP:*** The primary mission of the NGNP is to produce both electricity and commercial quantities of hydrogen through the employment of a Very-High-Temperature Reactor system. The reference system includes a helium-cooled, graphite-moderated, thermal neutron reactor. The reference NGNP prototype system was selected based on the technology with the lowest development risk that will achieve the needed requirement to provide economically competitive nuclear energy and hydrogen production capability. The NGNP will produce both electricity and hydrogen using an indirect cycle with an intermediate heat exchanger to transfer the heat to either a hydrogen-production demonstration facility or a gas turbine.
- ***SCWR:*** The SCWR system offers potentially significant advances in economics through plant simplification and increased thermal efficiency. The main mission of the SCWR is to generate low-cost electricity (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). It is built upon two proven technologies: Light Water Reactors (LWRs), which are the most commonly deployed power-generating reactors in the world, and supercritical fossil-fired boilers. DOE anticipates an international effort to resolve the most pressing materials and system design uncertainties needed to demonstrate technical viability of the SCWR.

Three of the six Generation IV nuclear energy systems employ a fast-spectrum to enable more effective management of actinides through recycling of most components in the discharged fuel: the Gas-Cooled Fast Reactor (GFR), the Lead-Cooled Fast Reactor (LFR), and the Sodium-Cooled Fast Reactor (SFR). These technologies are better suited for transmuting waste and supporting the efficient recycling of spent fuel than thermal-spectrum reactors. Widespread deployment of fast-spectrum reactors could contribute substantially to making nuclear power sustainable for thousands of years by recycling fuel and reducing waste volume and toxicity.

- ***GFR:*** The GFR is primarily envisioned for missions in electricity production and actinide management, although it may be able to support hydrogen production as well. It was chosen as one of the Generation IV nuclear energy systems based on its excellent potential for sustainability through reduction of the volume and radiotoxicity of both its own fuel and other spent nuclear fuel, and for extending/utilizing uranium resources orders of magnitude beyond what the current open fuel cycle can realize. The reference GFR system features a fast-spectrum, helium-cooled reactor and closed fuel cycle. The reference GFR design will utilize a direct-cycle, helium turbine for electricity and process heat for production of hydrogen. The main characteristics of the GFR are: a self-generating core with a fast neutron spectrum, robust refractory fuel, high operating temperature, direct energy conversion with a gas turbine, and full actinide recycling.
- ***LFR:*** The LFR has the potential to meet many of the Generation IV mission interests. The LFR is mainly envisioned for electricity and hydrogen production and actinide management. Options for the LFR also include a range of plant ratings and sizes from small modular systems to monolithic plants. Two key technical aspects of the LFR are the use of lead (Pb) coolant and a long-life, cartridge-core architecture in a small, modular system intended for deployment with small grids or remote locations. The LFR envisioned in the Generation IV Program is the Small Secure Transportable Autonomous Reactor (SSTAR) concept, which is a small modular fast-spectrum reactor. The main mission of the SSTAR is to provide incremental energy generation to match the needs of developing nations and remote communities without electrical grid connections. Some technologies for the LFR have already been successfully demonstrated internationally.
- ***SFR:*** The SFR nuclear energy system features a fast-spectrum reactor and closed fuel-recycle system. The primary mission for the SFR is to produce electricity, burn transuranics, and produce fissile material. With innovations to reduce capital cost, the mission can extend to electricity production, given the proven capability of sodium-cooled reactors to utilize almost all of the energy in natural uranium. Sodium-cooled nuclear energy systems have been significantly developed and may not require as much system design R&D as other Generation IV nuclear energy systems.

  The Molten Salt Reactor (MSR) is a liquid-fuel system with an epi-thermal neutron spectrum.

- ***MSR:*** The MSR employs a circulating liquid fuel mixture that offers considerable flexibility for recycling actinides. Electricity production and waste burndown are envisioned as the primary missions for the MSR. MSRs are liquid-fueled reactors that can be used for production of electricity, actinide burning, production of hydrogen, and production of fissile fuels. The MSR can leverage technology from the MSR programs of the 1950s and 1960s that provided the technological foundation. Because of ongoing synergistic programs, advances in development and understanding of MSRs are expected to occur within the next decade with a modest investment of resources.

The additional Generation IV Program elements include three of the crosscutting R&D areas for the six selected reactor systems.

- ***Design and Evaluation Methods (D&EM) Crosscut:*** The D&EM Crosscut is responsible for developing and validating design and evaluation methods, both crosscutting and system-specific, for all Generation IV nuclear energy systems.
- ***Energy Conversion Crosscut:*** The Energy Conversion Crosscut is responsible for the R&D on innovative energy conversion systems.
- ***Materials Crosscut:*** The Materials Crosscut is responsible for the materials R&D, both crosscutting and system-specific, for all Generation IV nuclear energy systems.

The AFCI and Generation IV Programs have an integrated management structure that shares a common systems analysis function. While the Generation IV has primary responsibility for the three crosscut areas listed above, the areas of Systems Analysis and Fuel Cycle Crosscut are managed primarily by AFCI. The systems analysis function develops and applies tools to formulate, assess, and steer program activities to meet programmatic goals and objectives. Examples of this function include integrating R&D by formulating recommendations to focus program development direction, and evaluating nuclear systems and fuel cycles based on economics, environmental and societal aspects. Also interfacing with the Generation IV Program is the Fuel Cycle Crosscut. The Fuel Cycle Crosscut is responsible for exploring the impact of fuel cycles, especially in the areas of waste management and fuel utilization.

This document consists of two separate volumes. Volume I of the *Generation IV Nuclear Energy Systems Ten-Year Program Plan Fiscal Year 2006* includes a description of the Generation IV Program, program organization and responsibilities, program interfaces and an R&D summary for each of the Generation IV systems and crosscutting areas. Volume II describes in detail each of the six candidate Generation IV systems and the three Generation IV crosscut areas, the R&D plans for each of the areas, and the corresponding ten-year projected budgets, schedules, and milestones.

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ACRONYMS

AFCI	Advanced Fuel Cycle Initiative
AGR	Advanced Gas Reactor
AMSR	Advanced Molten Salt Reactor
ANL	Argonne National Laboratory
ASME	American Society of Mechanical Engineers
B&PV	Boiler and Pressure Vessel
BNL	Brookhaven National Laboratory
BOP	balance-of-plant
CFD	Computational Fluid Dynamics
CO_2	carbon dioxide
C_f/C	carbon-carbon
CV	cross vessel
D&EM	Design and Evaluation Methods
DOE	U.S. Department of Energy
-ID	Idaho Office
-NE	Office of Nuclear Energy
-HQ	Headquarters
-RW	Office of Civilian Radioactive Waste Management
EG	Experts Group
EMWG	Economics Modeling Working Group
EPACT	Energy Policy Act
F/M	ferritic-martensitic steels
FY	fiscal year
GFR	Gas-Cooled Fast Reactor
GIF	Generation IV International Forum
GNEP	Global Nuclear Energy Partnership
GPRA	Government Performance Results Act
HTDM	High-Temperature Design Methodology
IAEA	International Atomic Energy Agency
IHX	intermediate heat exchanger
I-NERI	International-NERI
INL	Idaho National Laboratory
ISI	in-service inspection
LFR	Lead-Cooled Fast Reactor
LLNL	Lawrence Livermore National Laboratory
LWR	Light Water Reactor
MA	minor actinides
MI	materials irradiation
MIT	Massachusetts Institute of Technology
MSR	Molten Salt Reactor
MW_e	megawatt electric
MWG	Methodology Working Groups
MW_t	megawatt thermal
NE	DOE Office of Nuclear Energy
NERAC	Nuclear Energy Research Advisory Council
NERI	Nuclear Energy Research Initiative
NGNP	Next Generation Nuclear Plant
NHI	Nuclear Hydrogen Initiative
NMCP	National Materials Crosscut Program

NNSA	National Nuclear Security Administration
NRC	U.S. Nuclear Regulatory Commission
NTD	National Technical Director
OECD	Organization for Economic Cooperation and Development
ORNL	Oak Ridge National Laboratory
PCHE	printed circuit heat exchangers
PCS	power conversion system
PICS	Program Information Collection System
PIE	postirradiation examination
PIRT	phenomena identification and ranking table
PMB	Project Management Board
PNNL	Pacific Northwest National Laboratory
PR&PP	proliferation resistance and physical protection
R&D	research and development
RSWG	Risk and Safety Working Group
S-CO_2	supercritical carbon dioxide
SCWR	Supercritical-Water-Cooled Reactor
Si_fC/SiC	silicon carbide/silicon carbide
SFR	Sodium-Cooled Fast Reactor
SIM	System Integration Manager
SNL	Sandia National Laboratories
SSC	System Steering Committee
SSTAR	Small Secure Transportable Autonomous Reactor
TRISO	tri-isotopic
VHTR	Very-High-Temperature Reactor
WBS	Work Breakdown Structure

1. PURPOSE OF THE GENERATION IV TEN-YEAR PROGRAM PLAN

This *Generation IV Nuclear Energy Systems Ten-Year Program Plan* identifies the objectives and priorities of the United States (U.S.) Generation IV Program to provide programmatic direction within the U.S. Department of Energy (DOE) complex and among the program participants, including national laboratories, industry, universities, and international participants. Furthermore, for the upcoming ten years, the plan gives an overview of the integrated program and how the goals identified in *A Technology Roadmap for Generation IV Nuclear Energy Systems* (hereafter referred to as the Generation IV Roadmap [DOE 2002]) will guide the research and development (R&D). This plan reflects the priorities of *The U.S. Generation IV Implementation Strategy* reported to Congress in September 2003 (DOE-NE 2003), which itself is compatible with the R&D plan formulated in the Generation IV Roadmap (DOE 2002). The Program Plan formulates the R&D that must be accomplished to determine the technical and economic viability of the system concepts of choice. The Program Plan uses a nominal milestone schedule and associated out-year budgets over a sliding ten-year period. This is adjusted annually based on appropriated funds for the Generation IV Program and provides a basis for future DOE budget requests. The Program Plan reflects to some extent the R&D contributions expected from other Generation IV International Forum countries, but this is recognized to be an area of considerable uncertainty.

This plan also addresses recent legislation and initiatives that impact the future direction of nuclear energy R&D and describes the relationship and interactions between the Generation IV Program and two related programs: the Advanced Fuel Cycle Initiative (AFCI) and the Nuclear Hydrogen Initiative (NHI).

In 2005, the President signed the first comprehensive energy legislation in over a decade. The 42 USC 14801 Energy Policy Act of 2005 (EPACT2005), was passed by the U.S. Congress on July 29, 2005 and signed into law on August 8, 2005. To help meet the nation's energy needs, EPACT2005 encourages more nuclear energy production by authorizing DOE to develop accelerated programs for the production and supply of electricity and setting the stage for building new nuclear reactors by reauthorizing Price-Anderson nuclear liability protection for 20 years and providing significant incentives for new plant construction. The Generation IV Nuclear Energy Systems Initiative and the Next Generation Nuclear Plant (NGNP) Project are specifically addressed in EPACT2005.

The Advanced Energy Initiative, announced on January 31, 2006 during President Bush's State of the Union Address, focuses on reducing America's dependence on imported energy sources. In line with this initiative, the Global Nuclear Energy Partnership (GNEP) was announced by Secretary of Energy Samuel Bodman in February 2006. GNEP is a comprehensive strategy to increase U.S. and global energy security, encourage development of clean nuclear power around the world, reduce the risk of nuclear proliferation, and improve the environment. GNEP is based on the principle that energy and security go hand in hand. The focus of GNEP is to develop and demonstrate new proliferation-resistant technologies to recycle nuclear fuel and reduce waste. The U.S. will also work with other fuel cycle nations to develop a fuel services program that will provide nuclear fuel and recycling services to nations in return for their commitment to refrain from developing enrichment and recycling technologies. GNEP is designed to provide developing nations access to reliable, clean nuclear energy for electricity and potable water production in a safe and cost-effective manner. While a mutual accommodation of the technology demonstration programs of GIF and GNEP is in process, no results are available as of this writing.

2. GENERATION IV PROGRAM DESCRIPTION

The Generation IV Program is managed by the DOE Office of Nuclear Energy (NE) with the objective of advancing nuclear energy to meet future energy needs jointly with international partners. To this purpose, the DOE and organizations in ten other countries have formed a framework for international cooperation known as the Generation IV International Forum (GIF).

2.1 Introduction

Generation IV connotes the next generation of nuclear energy systems. Three previous generations of reactors existed from the 1940s to the present. Generation I consisted of the early prototype reactors of the 1950s and 1960s, such as Shippingport, Dresden, and Magnox. The Generation II systems, patterned after Generation I, began operation in the 1970s and comprise most of the large commercial power plants, such as the Pressurized Water Reactors and Boiling Water Reactors currently in operation in the U.S. The Generation III nuclear systems were developed in the 1990s and include a number of standardized, evolutionary designs that offer significant advances in safety and economics. A number of Generation III systems have been built, primarily in East Asia. Within DOE, the technology focus of the Nuclear Power 2010 program is Generation III+ advanced reactors.

The first three generations of nuclear energy have been successful in the following ways:

1. Nuclear energy supplies a significant share of electricity for today's needs—over 20% of U.S. and 17% of world demand.
2. The U.S. nuclear industry dramatically improved its safety and operational performance since the 1970s and by 2002 was among world leaders, with average net capacity factor over 90%, much higher than any other major electricity source. In addition, all safety indicators exceeded targets.
3. In 2004, the nuclear power plants operating worldwide displaced two billion tons of carbon dioxide (CO_2) emissions that would have been released into the atmosphere if the electricity had been generated by fossil fuels.
4. U.S. nuclear plants are highly reliable and currently produce electricity for 1.8 cents per kilowatt-hour. This is slightly below the operating cost of a coal-fired power plant and well below natural-gas-fired generation at current prices.
5. In return for access to peaceful nuclear technology, over 180 countries have signed the Nuclear Non-Proliferation Treaty to help ensure that peaceful nuclear activities will not be diverted to making nuclear weapons.

Although nearly all current U.S. Light Water Reactor (LWR) owners are expected to file for 20-year license extensions, it is clear that new nuclear energy systems are needed. Initially, the mature Generation III+ designs are attractive options for additional nuclear generation. In the mid and long term, next-generation systems will offer hydrogen production capability and greater deployment flexibility. These new systems should continue the improvements made over prior generations in issues of safety, economics, nuclear waste, and proliferation resistance through a robust R&D program. Advances in all of these areas can contribute to increasing the sustainability of nuclear energy.

2.1.1 U.S. Energy Demand Outlook

The *Annual Energy Outlook 2006* (AEO2006) (DOE 2006) produced by the DOE Energy Information Administration, forecasts growth in electricity demand of 1.8% annually through 2025. To satisfy that demand, DOE predicts the U.S. must increase electricity production by nearly 50%. Today, nuclear power plants – the second largest source of electricity in the U.S. – supply about 20% of the nation's electricity each year. In the next 15 years, AEO2006 (DOE 2006) projects a 10% increase in electricity generating capacity for nuclear power. Further increases in nuclear energy production will be required to meet growing U.S. demands.

It is vital that the increase in U.S. electricity production be made through sources that decrease carbon dioxide emissions and protect the environment. Of all energy sources, nuclear energy has perhaps the lowest impact on the environment, including water, land, habitat, species, and air resources. Nuclear power plants produce no controlled air pollutants, such as sulfur and particulates, or greenhouse gases. Per the Nuclear Energy Institute, in 2005, U.S. nuclear power plants prevented 3.32 million tons of sulfur dioxide, 1.05 million tons of nitrogen oxide, and 681.9 million metric tons of carbon dioxide from entering the earth's atmosphere. Currently, nuclear energy represents 73% of the nation's emission-free electricity generation (Figure 2.1).

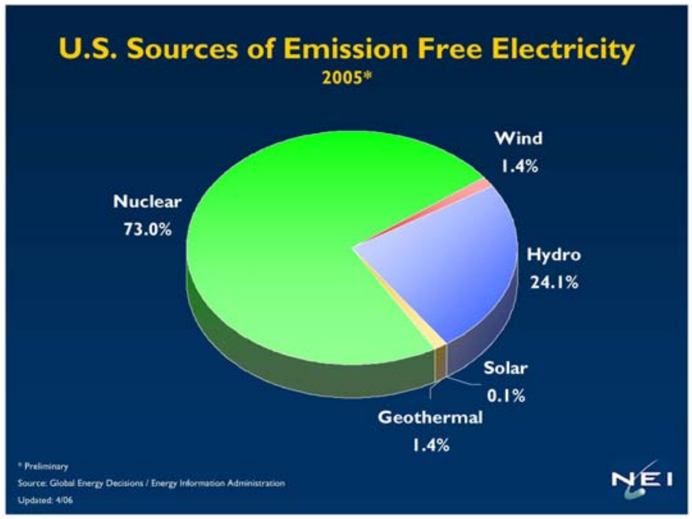

Figure 2.1. U.S. sources of emission free electricity.

The outlook for energy demand within the major sectors of energy use other than electricity also points out an emerging role for nuclear energy in hydrogen production. AEO2006 projects an annual growth of 1.4% per year for the transportation sector (Figure 2.2). Transportation is almost exclusively dependent on petroleum. This dependence has caused major fluctuations in fuel prices and several "energy shocks" since the 1970s. This volatility creates a significant need to diversify with new fuels, such as hydrogen for use in emissions-free fuel cells that power electric vehicles. Large-scale production of hydrogen by nuclear energy would be free of greenhouse gas emissions. To achieve these benefits, new nuclear energy systems that specialize in hydrogen production at competitive prices need to be developed.

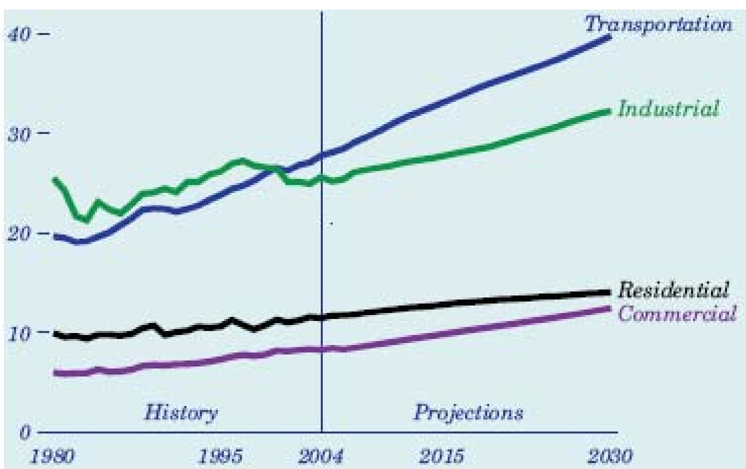

Figure 2.2. Energy consumption by sector.

Two long-term technology development objectives for nuclear energy in the U.S. are derived from the needs identified above:

1. Develop advanced nuclear energy systems that can significantly increase the share of nuclear electric generation while increasing their sustainability in the long-term.
2. Develop systems for nuclear-generated hydrogen that can diversify the energy supply for the transportation sector and reduce the dependence on petroleum.

2.1.2 The Generation IV Roadmap

Beginning in January 2000, 10 countries and Euratom joined together to form the GIF with the mission of developing future-generation nuclear energy systems that can be licensed, constructed, and operated to provide competitively priced and reliable energy products while satisfactorily addressing nuclear safety, waste, proliferation, and public perception concerns. The overarching objective for Generation IV systems is to have them available for international deployment before the year 2030.

From its inception, the GIF discussed the necessary R&D to support next-generation nuclear energy systems. From those discussions, efforts to develop a technology roadmap were begun to guide the Generation IV systems. With the participation of over 100 experts from the GIF countries, the effort ended in December 2002 with the issuance of the Generation IV Roadmap (DOE 2002). Especially noteworthy was the recognition gained by the U.S. for leading the formation of the GIF and the development of the Generation IV Roadmap (DOE 2002). These efforts helped strengthen U.S. leadership in the peaceful uses of nuclear energy and underscored the importance of collaborative R&D on future nuclear energy systems.

The Generation IV roadmap process evaluated over 100 future nuclear energy systems proposed by researchers around the world. The R&D scope described in the Generation IV Roadmap (DOE 2002) covers the six most promising Generation IV systems. It is important to note that each GIF country will focus on those systems and the subset of R&D activities that are of greatest interest to them. Thus, the Generation IV Roadmap (DOE 2002) provides a foundation for formulating national and international program plans on which the GIF countries will collaborate to advance Generation IV systems.

Of the six most promising nuclear energy systems identified, two employ a thermal neutron spectrum with coolants and temperatures that enable electricity production with high efficiency (the NGNP and the Supercritical-Water-Cooled Reactor [SCWR]). Three employ a fast neutron spectrum to enable more effective management of actinides through recycling of most components in the discharged fuel (the Gas-Cooled Fast Reactor [GFR], the Lead-Cooled Fast Reactor [LFR], and the Sodium-Cooled Fast Reactor [SFR]). The Molten Salt Reactor (MSR) employs a circulating liquid fuel mixture that offers considerable flexibility for recycling actinides. Each of these systems is described in Section 5.

The Generation IV Roadmap (DOE 2002) defines a number of common or crosscutting R&D areas for the six selected reactor systems. These areas include fuel cycle, fuels and materials, energy conversion, risk and safety, economics, and proliferation resistance and physical protection (PR&PP). Many of the Generation IV reactor systems share similar development needs.

2.2 Generation IV Goals

The high-level objective of the Generation IV Program is to advance the systems in accordance with DOE priorities for their deployment in the U.S. The advancement of each system is measured in terms of its ability to meet the Generation IV goals as defined in the Generation IV Roadmap (DOE 2002), which have three purposes. First, they serve as the basis for developing criteria to assess and compare the systems in the Generation IV Roadmap (DOE 2002). Second, they are challenging and stimulate the search for innovative nuclear energy systems—both fuel cycles and reactor technologies.

Third, they will serve to motivate and guide the R&D on Generation IV systems as collaborative efforts get underway. Eight goals for Generation IV are defined in four broad areas: sustainability, economics, safety and reliability, and PR&PP. These four broad areas are described below.

- ***Sustainability*** is the ability to meet the needs of present generations while enhancing and not jeopardizing the ability of future generations to meet society's needs indefinitely. There is a growing desire in society for the production of energy in accordance with sustainability principles. Sustainability requires conserving resources, protecting the environment, and preserving the ability of future generations to meet their own needs, as well as avoiding placing unjustified burdens upon them.
- ***Economic competitiveness*** is a requirement of the marketplace and is essential for Generation IV nuclear energy systems. Future nuclear energy systems should accommodate a range of plant ownership options and anticipate a wider array of potential roles and options for deploying nuclear power plants, including load following and smaller units. While it is anticipated that Generation IV nuclear energy systems will primarily produce electricity, they will also help meet anticipated future needs for a broader range of energy products beyond electricity. For example, hydrogen, process heat, district heating, and potable water will likely be needed to keep up with increasing worldwide demand and long-term changes in energy use. Generation IV systems have goals to ensure that they are economically attractive while meeting changing energy needs.
- ***Safety and reliability*** are essential priorities in the development and operation of nuclear energy systems. Nuclear energy systems must be designed so that during normal operation or anticipated transients safety margins are substantial, accidents are prevented, and off-normal situations do not deteriorate into severe accidents. At the same time, competitiveness requires a very high level of reliability and performance for Generation IV systems. As a result, the goals have been set to achieve high levels of safety and reliability through further improvements relative to current reactors. The three safety and reliability goals seek simplified designs that are safe and further reduce the potential for severe accidents and minimize their consequences. Achieving these designs relies not only on technical improvements but also on systematic consideration of human performance as a major contributor to plant availability, reliability, inspectability, and maintainability.
- ***Proliferation resistance and physical protection*** are also essential priorities in the expanding role of nuclear energy systems. The safeguards provided by the Nuclear Nonproliferation Treaty have been highly successful in preventing the use of civilian nuclear energy systems for nuclear weapons proliferation. This applies to all inventories of fissile materials involved in the entire fuel cycle, which includes mining, enrichment, conversion, fabrication, power production, recycling, and waste disposal. In addition, existing nuclear plants are highly secure and designed to withstand external events such as earthquakes, floods, tornadoes, plane crashes, and fires. This points out the need to increase public confidence in the security of nuclear energy facilities against terrorist attacks. Advanced nuclear energy systems need to be designed from the start with improved physical protection against acts of terrorism.

    The eight specific goals for Generation IV nuclear energy systems are shown in Figure 2.3.

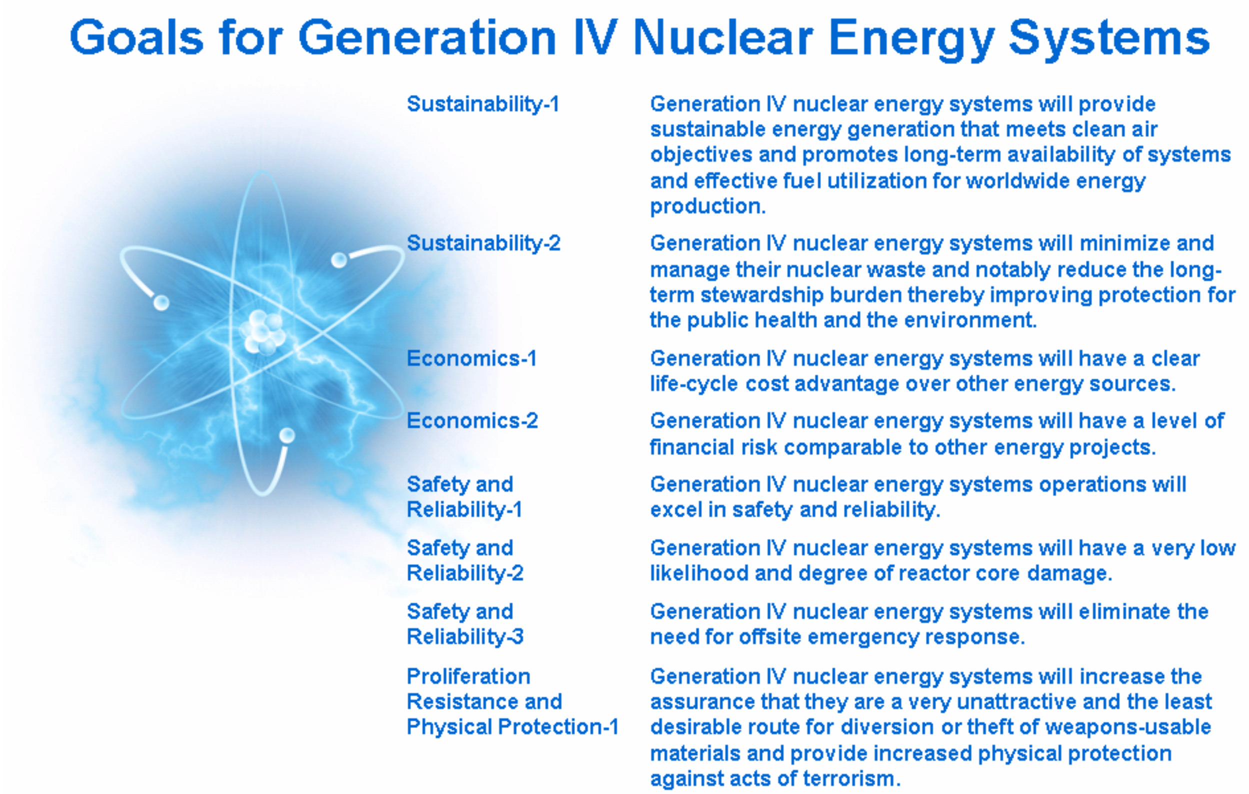

Figure 2.3. Eight goals defined for Generation IV nuclear energy systems.

While the evaluations of nuclear energy systems for their potential to meet all goals were a central focus of the Generation IV Roadmap (DOE 2002), it was recognized that countries would have various perspectives on their priority uses, or missions, for Generation IV systems. The major Generation IV mission interests include: (1) electricity production, (2) hydrogen production, (3) actinide management, and (4) small grid electricity production with limited nuclear infrastructure.

The approach for achieving Generation IV goals is to complete the R&D tasks outlined in the Generation IV Roadmap (DOE 2002) for the various systems and crosscutting technologies jointly with our international partners. The R&D tasks will be updated based on the key research findings that arise during the Generation IV effort over the subsequent years. As collaborative efforts by the GIF countries are formed and multilateral agreements are finalized, the tasks in the Generation IV Roadmap (DOE 2002) will be updated.

2.3 Priorities for the Generation IV Program

For each of the six systems, the Generation IV Roadmap (DOE 2002) develops the R&D goals in considerable detail and highlights the major R&D issues, benefits, and risks. The specific issues and risks identified in the Generation IV Roadmap (DOE 2002) and reviewed by the Nuclear Energy Research Advisory Committee (NERAC) Subcommittee on Generation IV Technology R&D Planning had a strong bearing on the prioritization of the systems versus the U.S. goals and technology objectives discussed above. From these studies and interactions, *The U.S. Generation IV Implementation Strategy* (DOE-NE 2003) was developed and the following two principal priorities emerged:

Priority 1: ***Develop a Next Generation Nuclear Plant to achieve economically competitive energy products, including electricity and hydrogen in the mid term.***

The NGNP system is considered the nearest-term reactor design that has the capability to efficiently produce both electricity and hydrogen through the development of a Very-High-Temperature Reactor (VHTR)-based system. The plant size, reactor thermal power, and core configuration will ensure passive decay heat removal without fuel damage or radioactive material releases during accidents.

The objectives of the NGNP project are to:

- Demonstrate safe and economical nuclear-assisted production of hydrogen and electricity
- Demonstrate the basis for commercialization of the nuclear system, the hydrogen production facility, and the power conversion concept
- Establish the basis to license the commercial version of NGNP by the U.S. Nuclear Regulatory Commission (NRC).

Priority 2: ***Develop a fast reactor to achieve significant advances in proliferation resistance and sustainability for the long term.***

The high priority on fast-spectrum reactors reflects their potential to make significant gains in reducing the quantity and radiotoxicity of spent nuclear fuel wastes and thereby increasing their manageability. These advances may enable the U.S. to avoid a second geological repository. Fast-spectrum reactors also hold the potential for extending the useful energy yield of the world's finite uranium supply many-fold in the very long term. The principal issues in the development of a next-generation, fast-spectrum reactor for use in the U.S. are its economic competitiveness and the associated deployment of a closed fuel cycle.

Three of the most promising Generation IV systems for enhancing long-term sustainability employ closed fuel cycles and fast-spectrum reactors (i.e., GFR, LFR, and SFR) for enhanced sustainability. Among these, the LFR and GFR will be given the most emphasis in resolving technical issues and uncertainties since these reactors offer potential benefits that have not been fully demonstrated. The SFR technology has been demonstrated in multiple countries, except for partitioning and transmutation of transuranic-bearing fuel. The GIF objective is to bring all of these systems to a state where a down-selection based on economics, safety and reliability, sustainability, and PR&PP can be undertaken. Finally, the MSR will be studied with a lower priority given the system's uncertainties and development needs. The ultimate selection of the most promising system will likely be driven by fuel cycle decisions that will follow from the AFCI and the development of an effective fast transmutation system. In addition to the five systems described above, the Generation IV Program also includes the SCWR system, which features a once-through uranium fuel cycle with a thermal-spectrum reactor as the primary option. The SCWR system, which is primarily aimed at electricity production, is highly ranked in economics because of the high thermal efficiency and plant simplification.

In addition, since there is a common need for advances in design and evaluation methods, energy conversion and materials research, the Generation IV priorities support the activities performed by the crosscut areas.

2.3.1 Timelines

Proposed timelines for the two priorities are shown in Figure 2.4. The NGNP in Priority 1 shows a 17-year period. This balances the benefit of demonstrating a large-scale, economically competitive nuclear hydrogen system in the near term with the technical issues and risks that must be addressed for its development.

The fast-spectrum reactor in Priority 2 shows a 22-year timeline. This fits with the expected future need for radiotoxicity reduction and closure of the U.S. nuclear fuel cycle. It also allows the progression of several of the most promising candidate systems to a down-selection in about 2010 followed by a demonstration of all elements of a closed fuel cycle within a decade thereafter. The commercial-scale fast-spectrum reactor schedule shown in Figure 2.4 is from the *Generation IV Ten-Year Program Plan Fiscal Year 2005* (DOE-NE 2005). Development of a fast-spectrum test reactor for radiotoxicity reduction (the so-called Advanced Burner Reactor) is part of the proposed GNEP technology development and demonstration program. The schedule for a commercial scale fast-spectrum reactor will be updated as GNEP planning proceeds.

U.S. Generation IV Timelines

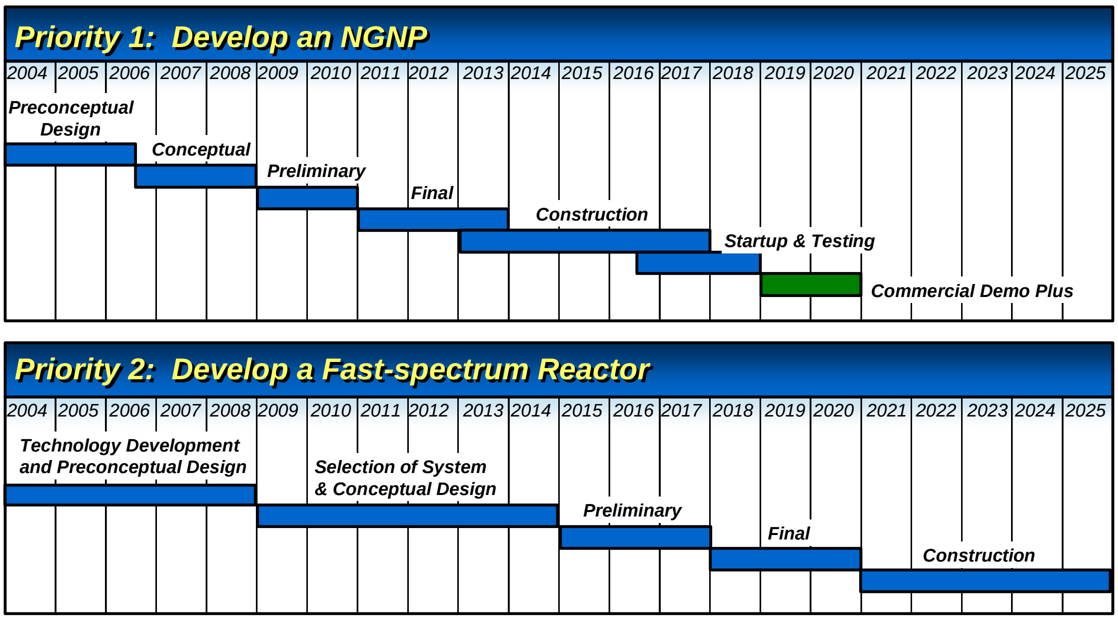

Figure 2.4. Timelines for U.S. Priorities 1 and 2.

Presently, plans have been formulated for implementation of R&D projects in the U.S. to support these systems and their associated crosscutting R&D needs. These plans are presented in Volume II of this Program Plan. Plans by other GIF members to advance these systems are reflected in this Program Plan from available information. Future updates to this Program Plan will be made as the plans of the other countries are completed and collaborations are formalized in implementing Project Arrangements.

2.4 Research and Development Programs for Individual Generation IV Systems

This section highlights the major milestones and development needs that have been identified for the joint R&D activities. System maturation is organized into three phases: viability, performance, and demonstration.

Table 2.1 gives the objectives and endpoint products of the R&D during the viability and performance phases. The R&D activities in the Generation IV Program Plan have been defined to support the achievement of these endpoints.

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

Table 2.1. Generation IV objectives and endpoints during the viability and performance phases.

Viability Phase	Performance Phase
Objective *Basic concepts, technologies, and processes are proven under relevant conditions, with all potential technical show-stoppers identified and resolved.*	**Objective** *Engineering-scale processes, phenomena, and material capabilities are verified and optimized under prototypical conditions.*
Endpoints	**Endpoints**
Preconceptual design of the entire system, with nominal interface requirements between subsystems and established pathways for disposal of all waste streams.	Conceptual design of the entire system, sufficient for procurement specifications for construction of a prototype or demonstration plant, and with validated acceptability of disposal of all waste streams.
Basic fuel cycle and, if applicable, energy conversion process flow sheets established through testing at appropriate scale.	Processes validated at scale sufficient for demonstration plant.
Cost analysis based on preconceptual design.	Detailed cost evaluation for the system.
Simplified probabilistic risk assessment for the system.	Probabilistic risk assessment for the system.
Definition of analytical tools.	Validation of analytical tools.
Preconceptual design and analysis of safety features.	Demonstration of safety features through testing, analysis or relevant experience.
Simplified preliminary environmental impact statement for the system.	Environmental impact statement for the system.
Preliminary safeguards and physical protection strategy.	Safeguards and physical protection strategy for system, including cost estimate for extrinsic features.
Consultation(s) with regulatory agency on safety approach and framework issues.	Pre-application meeting(s) with regulatory agency.

The *performance* phase R&D activities undertake the development of performance data and optimization of the system. Although general milestones were shown in the Generation IV Roadmap (DOE 2002), specific milestones and dates will be defined based on the viability phase experience. As in the viability phase, periodic evaluations of the system progress relative to its goals will determine if the system development is to continue. The viability and performance phases will likely overlap because some of the performance R&D activities may have long lead times that require their initiation as early as possible.

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

2.5 Performance Indicators and Exit Criteria

Performance indicators are used to assess the progress of individual reactor development programs toward answering key technical issues and generally improving knowledge and reducing uncertainty about system capabilities. These indicators are separated into two categories—outputs and outcomes—as described below.

2.5.1 Performance Indicator Outputs

R&D outputs are typically specified on an annual basis and are focused on individual technical issues or system-specific milestones. Examples of outputs supporting the successful completion of the viability phase (the first outcome given, in Section 2.5.2) include the following system or crosscut items:

- Development of a qualified particle fuel
- Development of structural materials that can withstand sustained operational temperatures
- Specification of a reactor safety approach
- Selection of fuel and core structural materials
- Determination of a fuel fabrication method (if new fuel type)
- Successful demonstration cycle for electricity production (if a new process).

Examples of outputs supporting the successful completion of the performance phase (the second outcome given in Section 2.5.2) include the following items:

- Completion of a reactor system design that is sufficient to support commercialization and regulatory approval
- Resolution of fabrication and manufacturing issues for major system components and fuel
- Demonstration by analysis that the major economic, safety, sustainability, and security goals are met.

The goals and priorities established by DOE and the budget available to the Generation IV Program will drive which outputs are actively scheduled for R&D and completion.

2.5.2 Performance Indicator Outcomes

The term "outcome" is defined as an ultimate, significant result of the R&D work that is being performed under the Generation IV Program. Outcomes are aligned with the end of the R&D phases. The first outcome is the resolution of all viability issues. Second is the development of one or more Generation IV reactor systems to the point that allows construction of a prototype or demonstration plant.

In the long term, the final outcome is the commercialization of one or more Generation IV reactor systems for each mission area.

2.5.3 Exit Criteria

If any particular system proves not to be technically viable during the viability phase, it will be removed from further consideration. If certain aspects of a reactor system prove not to be viable without eliminating the system altogether, alternatives will be examined and researched, within the limits of schedule and budget, to make the overall system viable.

The process used for systems evaluation and comparison will be similar to that used during the Generation IV Roadmap (DOE 2002) development and will use the same goals and criteria. However, the level of documentation and independent review is expected to be much greater, commensurate with the increase in technical knowledge and decrease in system uncertainty. Intermediate evaluations will occur every two to three years during the viability phase to support (and drive) the development of this documentation, as well as to identify any refinement of evaluation criteria needed to better document and differentiate systems.

2.6 International Program Implementation

The GIF was established in January 2000 to investigate innovative nuclear energy system concepts for meeting future energy challenges. GIF members include Argentina, Brazil, Canada, Euratom, France, Japan, Republic of South Africa, Republic of Korea, Switzerland, United Kingdom, and U.S. (Figure 2.5), with the Organization for Economic Cooperation and Development (OECD) Nuclear Energy Agency and the International Atomic Energy Agency (IAEA) as permanent observers. The forum serves to coordinate international R&D on promising new nuclear energy systems for meeting future energy challenges. With international collaboration, approximately 100 systems were analyzed and evaluated for their potential to meet the goals of the Generation IV Program.

The GIF provides an international framework for implementing R&D on the Generation IV systems by:

- Enabling participation and collaboration among GIF members
- Allowing for the coordination of member nation R&D programs to leverage the resources available for technology development
- Coordinating the timing of R&D to best leverage each country’s contribution.

System Steering Committees (SSCs) were established by GIF for the six reactor systems. The SSCs will coordinate R&D among the member countries. The GIF member countries are expected to sign the Framework Agreement (government to government) which will provide the legal arrangements enabling the productive, yet protected, sharing of R&D. Seven member countries (Canada, France, Japan, Republic of Korea, Switzerland, the United Kingdom, and the U.S.) acceded to this agreement in 2005. Participation by specialists or facilities in other countries is desired and will be funded by individual member countries.

The GIF expects to define cooperative System Arrangements under which multiple countries participate in system-specific research projects. For any Generation IV system, multiple projects will be defined that are governed by Project Arrangements. The arrangements will establish the R&D objectives, obligations, intellectual property rights, dispute resolution, and other necessary items. For example, development of fuel for a given system may constitute a project. The R&D described in this Program Plan will be considered for inclusion in such arrangements and has been specified to avoid overlaps with known or projected activities in the other countries.

Table 2.2. GIF participating nations.

	Argentina	Brazil	Canada	Euratom	France	Japan	Republic of Korea	Republic of South Africa	Switzerland	UK	USA
NGNP			●	●	●	●	●	●	●	●	★
SCWR			★	●	●	●	●				●
GFR				●	★	●	●	●	●	●	●
LFR				●		●	●				★
SFR				●	●	★	●			●	●
MSR				●	★						●

NGNP - Next Generation Nuclear Plant
SCWR - Supercritical-Water-Cooled Reactor
GFR - Gas-Cooled Fast Reactor
LFR - Lead-Cooled Fast Reactor
SFR - Sodium-Cooled Fast Reactor
MSR - Molten Salt Reactor
★ Lead ● Participant

Table 2.3 shows the GIF SSCs, GIF Project Management Boards (PMBs), and GIF Working Groups the U.S. participates in and the individuals that represent the U.S. All GIF SSCs and GIF PMBs are provisional at this time except for the SFR GIF SSCs.

Table 2.3. U.S. participants in GIF SSCs, PMBs and Working Groups.

U.S. Participation in GIF System Steering Committees (SSCs)				
VHTR		Trevor Cook/Kevan Weaver	Co-Chair	NE/INL
SCWR		Vacant	Co-Chair	
GFR		Tom Wei	Co-Chair	ANL
LFR		Craig Smith	Organizer	LLNL
SFR		Bob Hill/Rob Versluis	Co-Chair	ANL/NE
MSR		Charles Forsberg	Organizer	ORNL
U.S. Participation in GIF Project Management Boards (PMBs)				
VHTR:	Reactor Design and Safety	Kevan Weaver	Co-chair	INL
	Fuels and Fuel Cycle	Dave Petti	Member	INL
	Materials and Components	George Hayner/Bill Corwin	Co-Chair/Member	INL/ORNL
	Hydrogen Production	Carl Sink/ Paul Pickard	Co-Chair	SNL
	Computational Methods Validation and Benchmarks	Richard Schultz/Hussein Khalil	Co-Chair	INL/ANL
	Turbo-machinery and Balance of Plant	Vacant	Member	
SCWR:	Basic Thermal-Hydraulic Phenomena, Safety, Stability and Methods Development	Jim Wolf	Member	INL
	Chemistry and Materials	Gary Was	Chair	University of Michigan
	Design and Integration	Vacant		
GFR:	Fuels, Core Materials and Fuel Cycle	Mitch Meyer	Co-Chair	INL
	Design and Safety Management	Tom Wei	Member	ANL
SFR:	Design and Safety	Jim Cahalan	Member	ANL
	Advanced Fuels	Doug Crawford	Co-Chair	INL
	Component Design and Balance-of-Plant	Jim Sienicki	Member	ANL
	Monju R&D	Kemal Pasamehmetoglu	Member	INL
	Design and Safety Reactor Operation and Technology Testing Work Package Group	Doug Crawford	Member	INL
Crosscutting R&D Fuel Cycle		Jim Laidler	Member	ANL

Table 2.3. (continued).

U.S. Participation in GIF Working Groups			
Economics Modeling Working Group (EMWG)	Bill Rasin	Co-chair	Consultant
	Gene Onopko	Member	Consultant
	Geoffrey Rothwell	Member	Stanford University
	Kent Williams	Member	ORNL
	Dave Shropshire	Liaison AFCI	INL
	Hussein Khalil	Liaison GIF EG	ANL
	Rob Versluis	Liaison GIF EG	NE
Proliferation Resistance and Physical Protection (PR&PP) Methodology Working Group	Robert Bari	Co-chair	BNL (NNSA)
	Per Peterson	Co-chair	University of California, Berkeley (NE)
	Ike Therios	Member	ANL (NE)
	Dennis Bley	Member	Consultant (NE)
	Michael Golay	Member	MIT (NE)
	Gary Rochau	Member	SNL (NNSA)
	Joe Pilat	Member	LANL (NNSA)
	Jorshan Choi	Member	LLNL (NNSA)
	Mike Zentner	Member	PNNL (NNSA)
	Trond Bjornard	Liaison INL	INL
	Mike Ehinger	Liaison ORNL	ORNL
	Jim Laidler	Liaison AFCI	ANL
	Burrus Carnahan	Liaison State	U.S. State Department
	Heather Looney/Ed Wonder	Liaison NNSA	NNSA
	Hussein Khalil	Liaison GIF EG	ANL (NE)
	Rob Versluis	Liaison GIF EG	NE
Risk and Safety Working Group (RSWG)	Tim Leahy	Co-chair	INL
	Hussein Khalil	Liaison GIF EG	ANL
	Rob Versluis	Liaison GIF EG	NE
	Kevan Weaver	Liaison VHTR	INL
	Robert Bari	Liaison PR&PP	BNL
Quality Management Systems (temporary task force)	Gary Roberts	Member	INL

3. PROGRAM ORGANIZATION AND RESPONSIBILITIES

3.1 Organizational Structure

DOE-NE is responsible for the Federal government’s investment in nuclear science and technology with the goal of improving the nation's access to diverse and environmentally responsible sources of energy and helping to advance the country's economic and technological competitiveness. Figure 3.1 shows the DOE-NE organizational structure. The Generation IV Program is closely linked to two other DOE-NE Programs: AFCI and NHI. AFCI’s mission is to develop and demonstrate technologies that enable the transition to a stable, long-term advanced fuel cycle that is environmentally, economically, and politically acceptable. AFCI technology development focuses on reducing the environmental burden of nuclear waste, improving nuclear fuel-cycle proliferation resistance, and enhancing the use of nuclear fuel resources. The primary objective of NHI is to develop efficient, large-scale hydrogen production methods suitable for use with advanced nuclear reactors. By integrating AFCI and NHI with the Generation IV Program through a common systems analysis function, DOE-NE has established a structure that coordinates the three programs to support a unified R&D effort. Within this structure, the Generation IV Program has been organized to maximize and leverage technical expertise while enhancing communication between program participants through systems analysis and technical integration (Figure 3.2). Additionally, DOE-NE established the Nuclear Energy Research Initiative (NERI) program which enables university participation, and the International-NERI (I-NERI) program, which enables international collaboration. The NERI and I-NERI collaborations are described in Section 4.1.

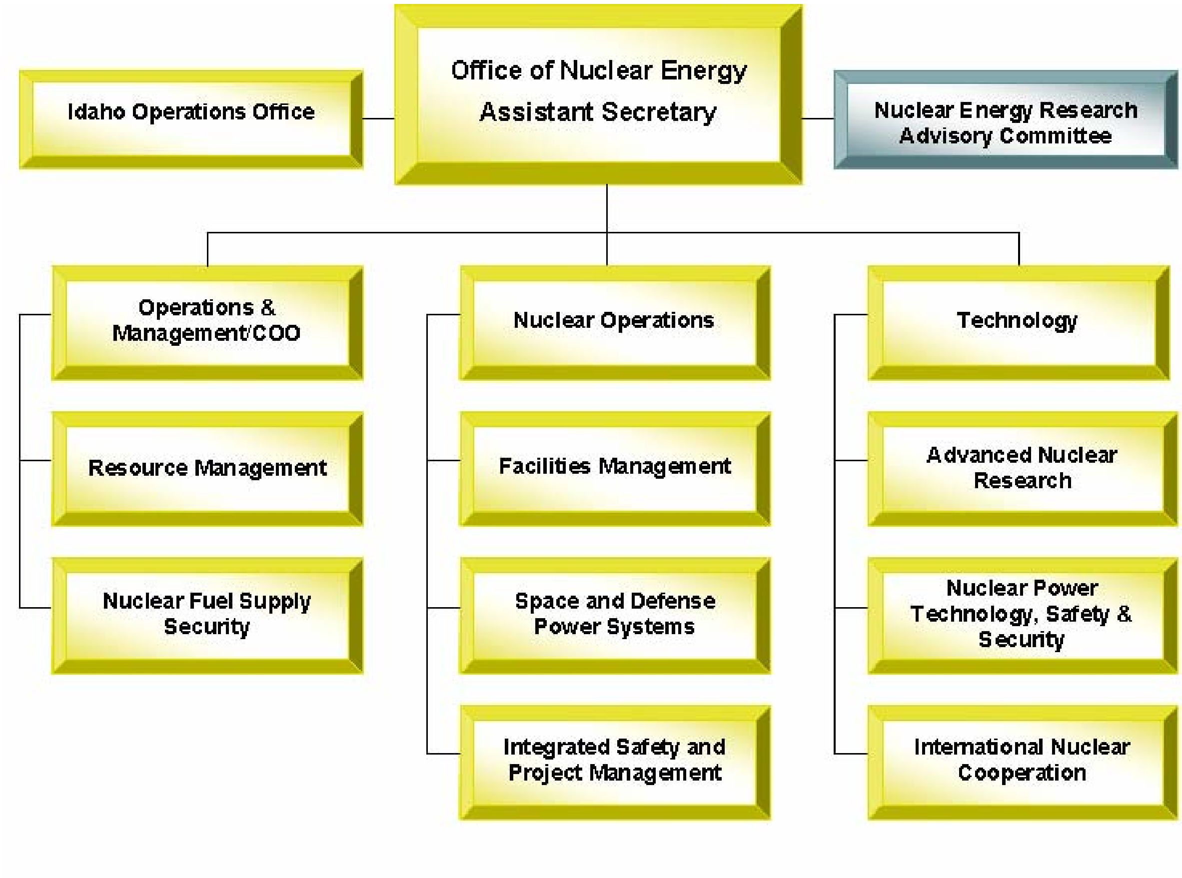

Figure 3.1. DOE-NE organizational structure.

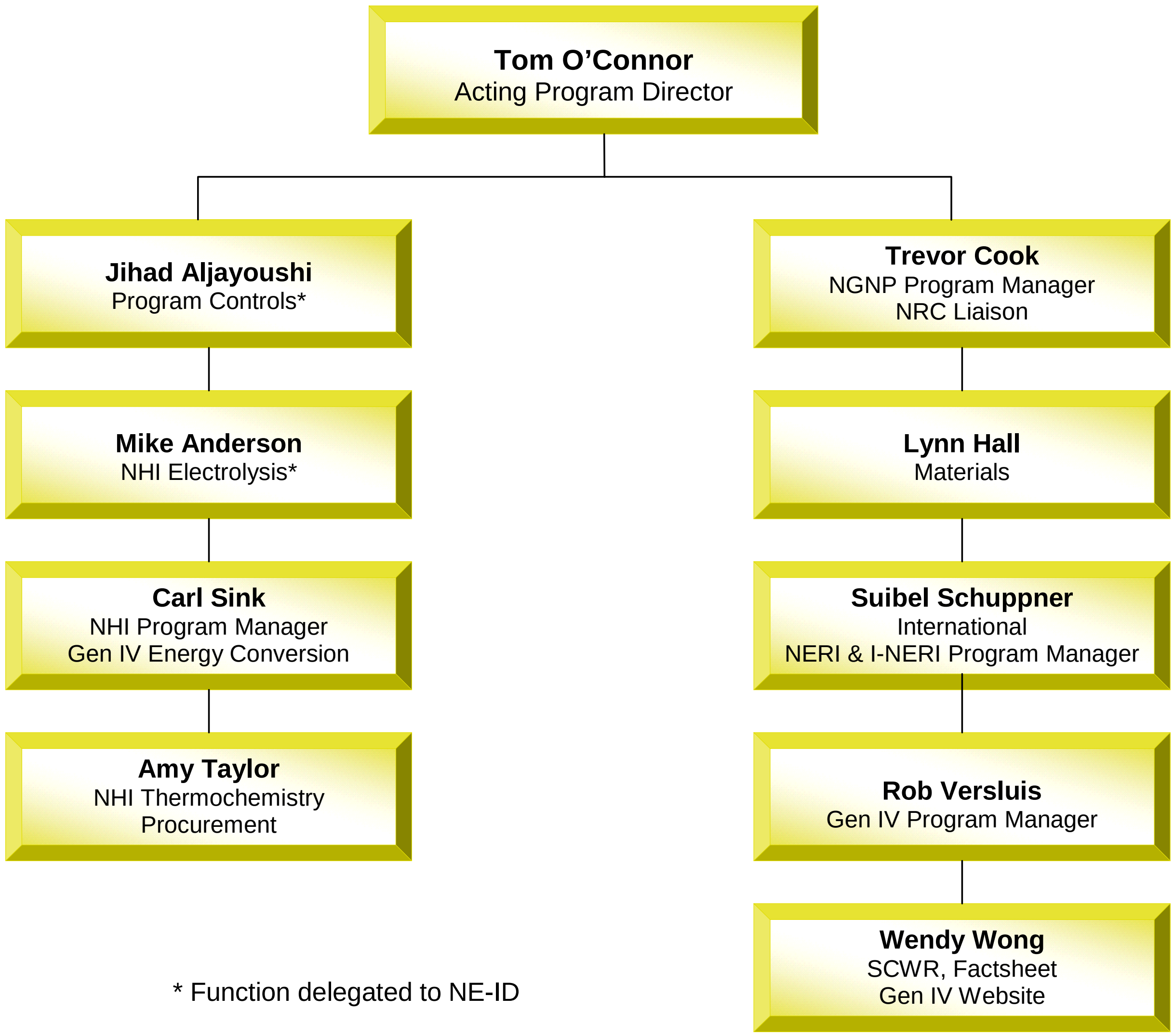

Figure 3.2. Generation IV Program organizational structure.

3.2 Roles and Responsibilities

The AFCI and Generation IV Programs have an integrated management structure that shares the National Technical Directors (NTDs), one for each major technology area, and a common systems analysis function. Roles and responsibilities for key Generation IV Program functions are shared between DOE-NE, DOE-Idaho (DOE-ID), Technical Integration, Program Controls, Systems Analysis, System Integration Managers (SIMs) for the specific systems, and NTDs for each of the primary Generation IV technology crosscut areas. Generation IV and AFCI each have primary management and funding responsibility for three NTDs. Figure 3.3 shows the AFCI, NHI, and Generation IV Program organizational structure. Specific roles and responsibilities for each of these functional groupings are described later in this document.

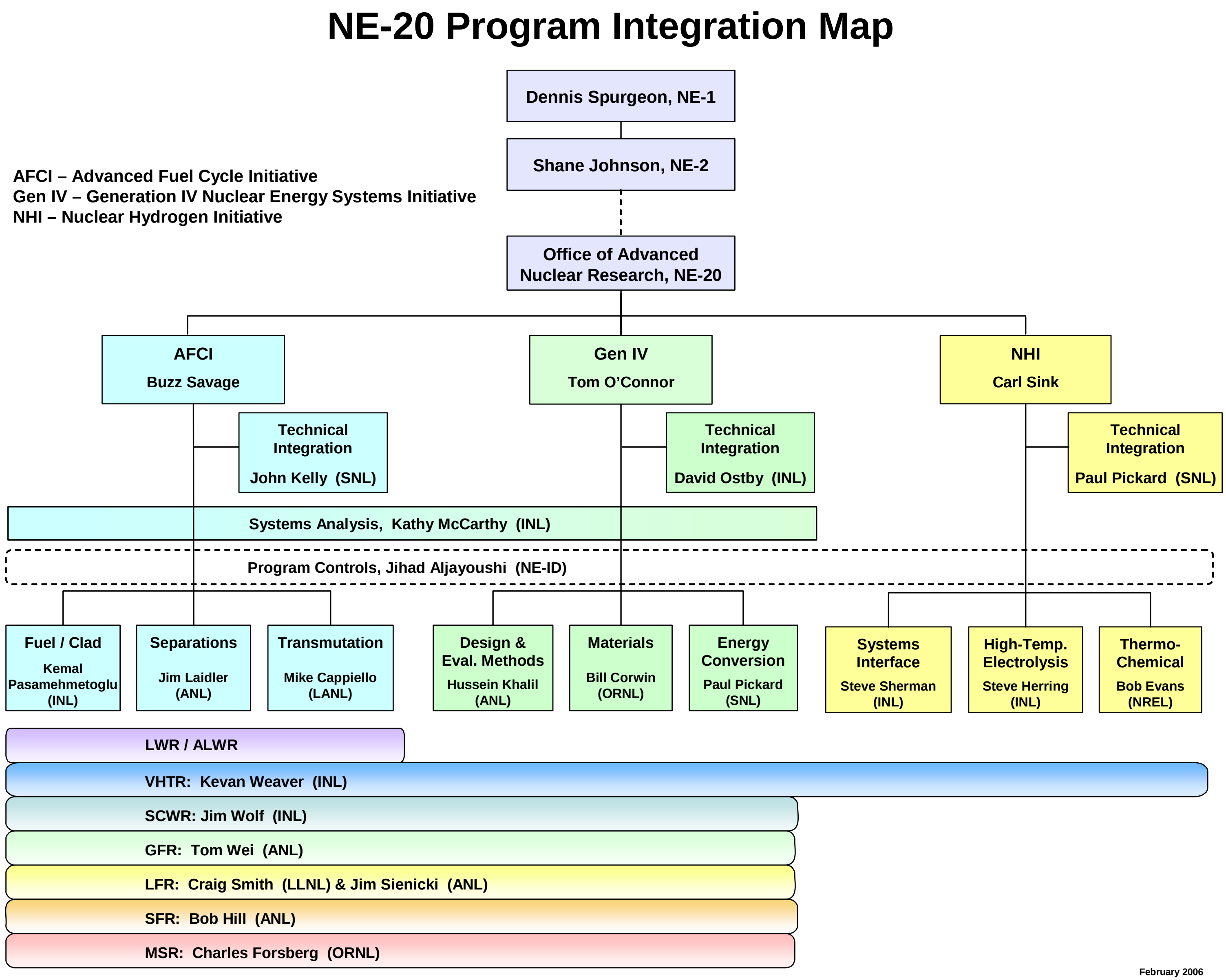

Figure 3.3. Generation IV, AFCI, and NHI organizational structure.

3.2.1 DOE Office of Nuclear Energy

Essential programmatic functions include, but are not limited to, the following:

- Manage the development of a program strategic plan
- Establish program policy and issue program guidance
- Develop program requirements, standards, and procedures
- Establish performance measures and perform annual performance reviews
- Manage program planning and processes
- Coordinate, review, comment on, and approve final Generation IV Program Plan
- Review, comment on, and give final approval to all tasks at the work package level
- Evaluate and assess program progress
- Provide program interface to external organizations, including the National Nuclear Security Administration, the DOE Office of Civilian Radioactive Waste Management, National Policy Agencies, NERAC, the NERAC Generation IV Subcommittee, and foreign government and non-governmental entities
- Manage and approve international agreements and foreign travel.

3.2.2 Integrated Generation IV, AFCI, and NHI Programs

The Generation IV R&D process begins with systems analyses based on energy demand scenarios, policy decisions and program objectives. From the systems analyses flow the technology requirements for fuel cycles and reactors needed to satisfy national objectives for future energy supply from nuclear generation. A SIM is named for each nuclear energy system of choice who is responsible for developing conceptual system designs of increasing specificity sufficient to establish, together with the NTDs, requirements for fuels, materials, components, safety analysis and design methods; and to make preliminary evaluations of system safety and economic performance. The task of demonstrating new technology developments to meet these requirements and to iterate with the SIMs on realistic technology expectations is the responsibility of the NTDs. For each of six technology development areas an NTD is named who is responsible for coordinating and integrating the R&D efforts in that technology area and who represents the expertise in that area on behalf of the programs. The six technology development areas are: design and evaluation methods, fuels and cladding, structural materials, chemical separations, energy conversion, and spent-fuel transmutation. This process and the roles of SIMs and NTDs are illustrated in Figure 3.4.

The NHI technology R&D areas consist of thermo-chemistry, high-temperature electrolysis, and systems interface and supporting systems. Much of the NHI R&D is relatively independent of Generation IV and AFCI. Interfaces with Generation IV exist in the areas of materials and systems interfaces.

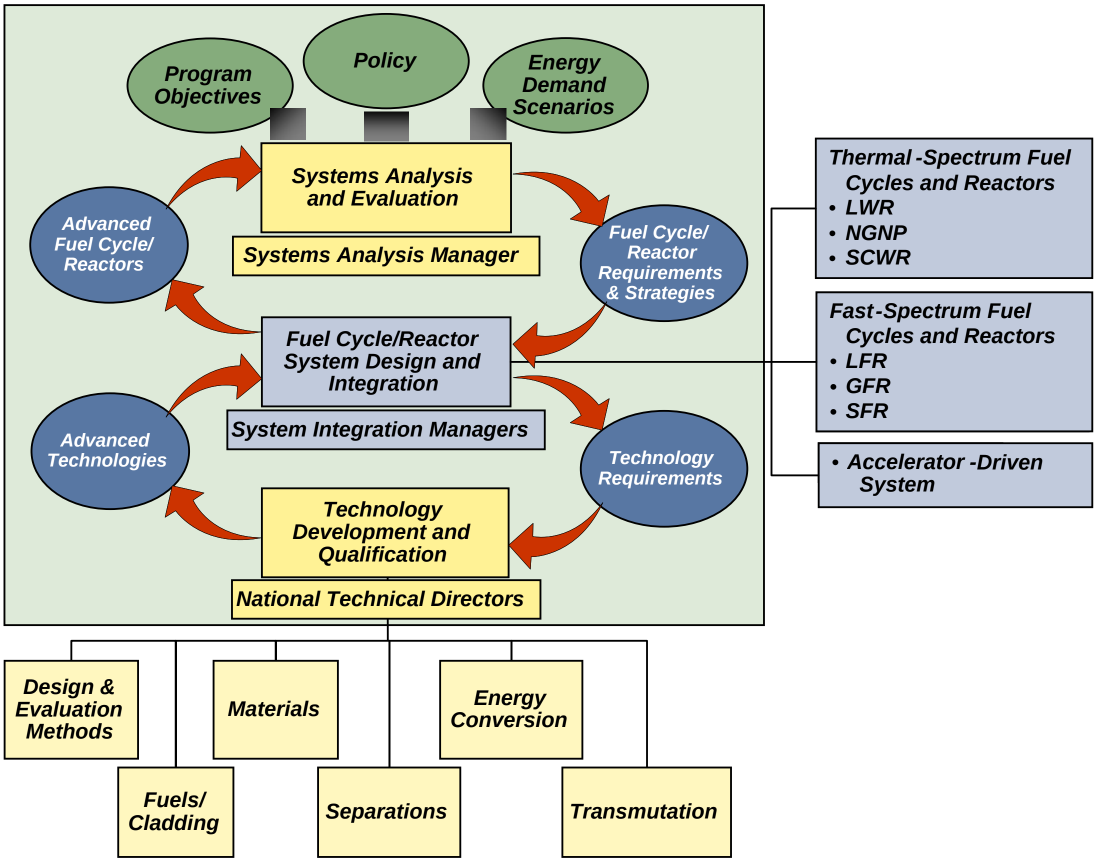

Figure 3.4. Integrated Generation IV and AFCI programs.

3.2.3 Systems Analysis Functions

The systems analysis function develops and applies tools to formulate, assess, and steer program activities to meet programmatic goals and objectives, including:

- Integrate R&D by formulating recommendations to focus program development direction
- Integrate program-level systems analysis for both Generation IV and AFCI
- Deploy system tools to develop recommended priorities for technology development
- Develop sustainability metrics encompassing economics, environmental, and societal aspects, capable of:
  - Evaluating nuclear energy systems and fuel cycles
  - Comparing nuclear energy with other means of producing primary energy.

The systems analysis function is led by the NTD for Systems Analysis with oversight of both the Generation IV and AFCI programs.

3.2.4 System Integration Manager Functions

System integration teams for each Generation IV system address the technical issues and develop R&D plans that identify the milestones and deliverables that support their innovative systems and new facilities with key R&D activities. System integration teams are identified for each Generation IV system, and each is directed by a SIM that brings substantial technical credentials and leadership. The system integration teams:

- Define major AFCI and NHI facility and Generation IV system requirements
- Develop conceptual system designs of increasing specificity
- Perform, together with the NTDs, product-specific R&D and demonstrate advancements in technology
- Perform regular evaluations of the safety and economic performance of the system.

3.2.5 National Technical Director Functions

The NTDs manage the technology R&D activities listed below:

- Coordinate and integrate technology developments in their area of expertise and advise the programs on their technology areas
- Perform, together with the SIMs, trade studies on system performance and required technology development to meet the system requirements
- Ensure that system requirements are integrated into the R&D activities
- Define and conduct the needed R&D in their technology area.

3.2.6 Technical Integration Functions

The technical integration function integrates the program technical activities listed below:

- Coordinate and implement technical program guidance with the NTDs and SIMs
- Develop and update, as necessary, the Generation IV Ten-Year Program Plan
- Coordinate, facilitate, and manage (semi)-annual Generation IV Program Review Meetings and all other major meetings
- Develop monthly reports
- Coordinate with project controls and track the activities to ensure that work package scope, cost, and schedule are met and to alert DOE-NE to any potential problems or issues.

3.2.7 Project Controls Function

The Generation IV R&D Program is managed in accordance with the principles of DOE Order 413.3, *Program and Project Management for the Acquisition of Capital Assets*. This order will be fully adhered to for all capital projects developed under the Generation IV Program. The work is organized in terms of work breakdown structure (WBS) elements and work packages. The Program Information and Collection System (PICS) has been established to define, approve, and track work packages. PICS is web-based, allowing work package managers, SIMs, NTDs, and Federal staff to enter data and approve or disapprove changes. The status of each work package is evaluated monthly by the relevant SIM and/or NTD, DOE-NE lead, Technical Integrator, and Program Controls group to assess program performance. Work packages that exceed a 10% cost and schedule threshold will be evaluated, and a corrective action plan developed as necessary.

3.3 Generation IV Program Management Processes

DOE-HQ has provided a high-level Program Plan, which supports the Government Performance Results Act (GPRA) and provides the overall view and direction of the Generation IV Program. This Program Plan is a vehicle for planning and executing the program at the laboratories. On an annual basis, DOE-NE provides draft budget guidance to the national laboratory participants based upon the DOE budget request and technical activities outlined in this Program Plan, which will be updated as necessary. Upon receiving the draft budget guidance from DOE-NE, each participant develops draft work packages that include cost, schedule, and scope by individual WBS elements consistent with this Program Plan. The SIMs, NTDs, and the Technical Integrator review the draft work packages for completeness and overall program integration. DOE-NE reviews and approves/disapproves the work packages. The approved work packages are used by DOE-NE to develop program guidance. DOE-NE then distributes final fiscal year (FY) budget program guidance for each participant. Program participants revise and finalize their work packages based upon the final program guidance. The SIMs, NTDs, and the Technical Integrator again review the final work packages for completeness and integration, and DOE-NE reviews them for final approval. Once DOE-NE approves the work packages, this establishes the cost, schedule, and technical baseline for each participant and the overall integrated program baseline.

The Technical Integrator and the NTDs/SIMs monitor program performance against the established baseline. Changes to the baseline must be approved through the Generation IV Baseline Control Process. These baselines also support the development of performance metrics that are used in the program reviews conducted by the Generation IV Program.

3.4 Key Program Assumptions, Uncertainties, and Risks

A number of critical assumptions and uncertainties form the planning basis for the Generation IV Program. Associated with each assumption is a degree of uncertainty, which represents some technical and programmatic risks to the program. Critical assumptions and uncertainties are listed below.

3.4.1 Assumptions and Uncertainties

- ***Planning Budget:*** This plan is based on the $68.5 million FY 2006 Congressional appropriation (including $13.5 million of FY 2005 carryover funding), and the FY 2007 budget request of $32 million. The budgets for FY 2006 through FY 2015 represent the required levels to achieve the work scopes formulated in Section 5 and defined further in the appendices.
- ***Major Facilities Design and Construction Schedule:*** DOE will lead the effort to perform the R&D and engineering-scale experiments and demonstrations to provide industry with a high level of confidence in production-scale facility construction costs and schedules. DOE will participate with industry in facility design activities through preliminary design to achieve the desired technical readiness level. DOE expects industry to take the lead in construction and operation of the production facilities needed to implement Generation IV technologies, including fuel cycle facilities. Actual deployment dates will depend on industry's needs and economic factors.
- ***Generation IV System Selection:*** It is assumed that at least one fast-spectrum Generation IV reactor system with closed fuel cycle will be developed to achieve the Generation IV and AFCI goals. Currently, an initial down-selection is scheduled for 2010.
- ***Legacy Cleanup Costs:*** The legacy cleanup costs associated with Generation IV testing activities have not been included in cost estimates provided in this Ten-Year Program Plan.

3.4.2 Technical Risks: Viability Phase to Performance Phase Transition

Although the processes proposed for incorporating the results from a viability phase into the performance phase are well understood, there is technical risk associated with moving from small-scale technology demonstrations to a production-scale plant. The role that intermediate, engineering-scale demonstrations can serve to mitigate this risk needs to be examined.

3.4.3 Programmatic Risks

The programmatic risks are listed below:

- ***Budget Allocation:*** The Generation IV Program has aggressive schedules so that it can provide time-critical, credible technical options. Substantial and stable long-term funding will be required to achieve this objective. It will be necessary for the program to continuously update its technical plan based on available funding levels.
- ***Evolving National Policy:*** A program aimed at proving advanced reactor technology for building advanced systems in the U.S. is subject to national policy priorities and regulatory requirements. The Generation IV Program management must monitor and/or recommend changes to these policies to ensure that proposed activities can be conducted within the imposed requirements.
- ***Public Support:*** The probability of success of the Generation IV Program can be greatly increased by obtaining public support. Public outreach efforts would enhance future funding and public acceptance of the technology and must be conducted during all phases of the program.

4. PROGRAM INTERFACES

4.1 External

External program interfaces exist with NERAC, NRC, industry, and international and university partners as described below.

4.1.1 Nuclear Energy Research Advisory Committee

The NERAC was established on October 1, 1998 to provide independent advice to DOE on complex science and technical issues arising from the planning, management, and implementation of DOE's nuclear energy program. This committee periodically reviews DOE-NE program elements and provides advice and recommendations on long-range plans, priorities, and strategies to effectively address the scientific and engineering aspects of the R&D efforts. In addition, NERAC provides advice on national policy and scientific aspects of nuclear energy research issues as requested by the Secretary of Energy or the DOE-NE Assistant Secretary. NERAC includes representatives from universities, industry, and national laboratories. The disciplines, interests, experience, points of view, and geographic locations of NERAC members are balanced and diverse.

The NERAC Subcommittee on Generation IV Nuclear Energy Systems Technology was established to provide advice on Generation IV Program activities. The NERAC Subcommittee on Evaluations conducts regular reviews of Program Plans.

4.1.2 Nuclear Regulatory Commission

The NRC is an independent agency established by the Energy Reorganization Act of 1974 to regulate civilian use of nuclear materials. The NRC's primary mission is to protect the public and the environment from the effects of radiation from nuclear reactors, materials, and waste facilities. The NRC carries out its mission by setting commission direction, policymaking, ensuring public and radiation worker protection, and implementing the NRC regulation process.

Generation IV systems selected for near-commercial demonstration will require licensing by the NRC in their demonstration phase. Frequent interactions between the Generation IV Program and the NRC will be required to achieve timely licensing as required to achieve program goals.

EPACT2005 Title VI, Subtitle C requires DOE and NRC to develop jointly and submit to Congress a Licensing Strategy for the prototype NGNP within three years after the date of enactment. The technology-neutral Licensing Strategy is to include a description of ways in which current licensing requirements need to be adapted for the prototype reactor. The Licensing Strategy is due to Congress in August 2008.

4.1.3 Industry Partners

The nuclear industry is interested in Generation IV systems for two reasons. One is the potential commercialization of new Generation IV systems in the long term. The other is the significant potential for spin-off technology that can be applied to improve systems deployed in the nearer term. Partnerships with industry are expected to be cost-shared projects that explore key viability issues with the selected Generation IV systems that contribute to the development of performance data. As more information is gained, the partnerships are expected to broaden into full-fledged demonstration projects that address detailed design, construction, licensing, and operational aspects of the systems.

4.1.4 International Partners

A major element of the Generation IV Program is a robust, cooperative program with international partners. DOE-NE will exchange information with its current international partners and will explore the potential for similar cooperation with other countries. This effort will greatly leverage the resources of the U.S. and other countries. The collaborations will ultimately be managed by multilateral cooperative agreements among GIF members. In the interim, collaboration is conducted under bilateral agreements between the U.S. and collaborating countries. Under I-NERI, DOE-NE has signed bilateral agreements with Brazil, Canada, Euratom, France, Japan, and the Republic of Korea.

4.1.5 University Partners

DOE-NE created NERI in 1999 to address the principal technical and scientific concerns affecting the future use of nuclear energy in the U.S. Many NERI projects have combined the talents of U.S. universities, industry, and national laboratories to bring innovative solutions to Generation IV systems. NERI also helps preserve the nuclear science and engineering infrastructure within our nation's universities and the nuclear industry, and it maintains a competitive position worldwide by advancing the state of nuclear energy technology. Starting in FY 2004, a portion of Generation IV, AFCI, and NHI program funding was reserved for NERI to fund university participation in these programs. The new formulation of the NERI program will be continued in subsequent years.

4.2 Internal

Internal interfaces exist with the Nuclear Power 2010 Program, NHI, GNEP, and AFCI. These important interfaces will share objectives and research results each year.

4.2.1 Nuclear Power 2010 Program

The DOE believes that it is critical to deploy new base load nuclear generating capacity within this decade to support the EPACT2005 objectives of energy security and supply diversity. The Nuclear Power 2010 Program is focused on reducing the technical, regulatory, and institutional barriers to deployment of new nuclear power plants. The technology focus of the Nuclear Power 2010 Program is on Generation III+ advanced LWR reactor designs that offer advancements in safety and economics over current nuclear plant designs certified by NRC in the 1990s. To meet this objective, it is essential to demonstrate the new, untested Federal regulatory and licensing processes for the siting, construction, and operation of new plant designs. In addition, an independent expert analysis commissioned by DOE and carried out by NERAC has shown that R&D is needed on near-term advanced reactor systems offering enhancements to safety and economics to enable these new technologies to come to market. The Generation IV Program must coordinate with the Nuclear Power 2010 Program to ensure that the results of its R&D efforts complement the industry R&D needs and the development and demonstration of the new regulatory processes. The Generation IV and Nuclear Power 2010 Programs have a common interest and both will benefit from using a risk-based licensing approach that is technology-neutral.

4.2.2 Nuclear Hydrogen Initiative

The NHI focuses on hydrogen production technologies best suited for use with advanced nuclear systems. Although significant quantities of hydrogen are already produced in the U.S., it is primarily produced by steam reforming of natural gas. Hydrogen is used primarily by the petrochemical industry for use in refining lower-grade crude oil to produce gasoline and by the agricultural industry for use in fertilizer production. The current production level in the U.S. would be equivalent to about 100 GW of nuclear or fossil power, assuming 50% efficiency for hydrogen production. The focus of NHI is on hydrogen production options for nuclear energy that utilize high temperatures or efficient electricity from nuclear reactors, such as the NGNP, to produce hydrogen from non-fossil resources (i.e., water). The NHI will augment, complement, and collaborate with ongoing DOE research efforts in the Generation IV Program where appropriate, and will initiate needed R&D in nuclear-specific areas to accomplish NHI program goals.

4.2.3 Global Nuclear Energy Partnership

The GNEP is a comprehensive strategy aimed at increasing U.S. and global energy security, encouraging development of clean nuclear energy around the world, reducing the risk of nuclear proliferation, and improving the environment. GNEP is based on the principle that energy and security go hand in hand. As part of President Bush's Advanced Energy Initiative, GNEP seeks to develop a worldwide consensus on enabling expanded use of economical, carbon-free nuclear energy to meet growing electricity demand. Employing a closed nuclear fuel cycle that enhances energy security while promoting non-proliferation is integral to this effort. The closed fuel cycle model envisioned by this partnership requires development and deployment of technologies that enable recycling and consumption of long-lived isotopes in radioactive waste.

4.2.3.1 Advanced Fuel Cycle Initiative. The AFCI Program is now being executed in an integrated manner under the GNEP Program. AFCI's responsibility to provide an effective transition strategy to address the legacy of the current open fuel cycle is separate from Generation IV. This program has the responsibility to develop reactor fuels and supporting fuel cycle technologies for the transitional strategy to address the legacy of the open fuel cycle and advanced fuel cycles for Generation IV reactors. Integration of these programs enhances cost effectiveness and maximizes the use of unique facilities.

The mission of AFCI is to develop fuel cycle technologies that will meet the need for economic and sustained nuclear energy production while satisfying requirements for a controlled, proliferation-resistant nuclear materials management system. AFCI is designed to develop these new technologies so that they may be deployed to support the operation of current nuclear power plants, Generation III+ advanced light water reactors (ALWRs), and Generation IV advanced reactors in order to achieve a significant reduction in the amount of high-level radioactive waste requiring geologic disposal, to reduce significantly accumulated plutonium in civilian spent fuel, and to extract more useful energy from nuclear fuel.

In the longer term, AFCI is to develop a system involving spent-fuel partitioning and recycling of actinides and other long-lived radioactive components in fast-spectrum reactors for destruction through transmutation. As part of GNEP, DOE will focus its AFCI R&D toward engineering-scale demonstration of the most promising processing technologies. In addition, DOE has announced it will focus transmutation development activities on a sodium-cooled fast transmutation (or "burner") reactor demonstration facility.

5. GENERATION IV RESEARCH AND DEVELOPMENT PLANS

5.1 Next Generation Nuclear Plant

5.1.1 System Description

The reference NGNP prototype system is based on what is judged to be the lowest risk technology development that will achieve the needed commercial functional requirements to provide an economically competitive nuclear heat source and hydrogen production capability. This is the primary mission of the NGNP. The reference system includes a helium-cooled, graphite moderated, thermal-spectrum reactor. The reactor outlet temperature will be in the range of 850 to 950ºC, with future capabilities that could reach above 1,000ºC. The reactor core technology will either be a prismatic block or pebble bed concept; the decision on the reference will be made during the definition phase. The NGNP will produce both electricity and hydrogen using an indirect cycle with an intermediate heat exchanger (IHX) to transfer the heat to either a hydrogen-production demonstration facility or a gas turbine. The IHX and primary gas circulator are located in an adjoining power conversion vessel. Figure 5.1 is a conceptual schematic of the NGNP.

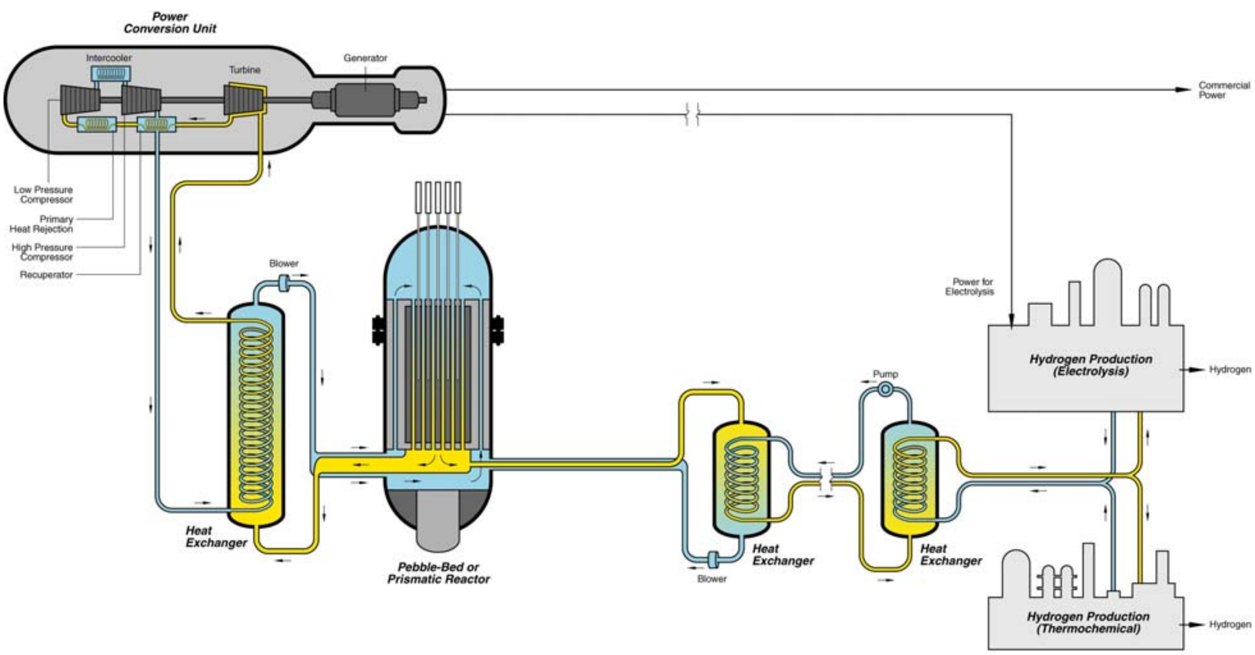

Figure 5.1. NGNP conceptual schematic showing power generation and hydrogen production.

The reactor thermal power (~600 MW_t) and reactor configuration will be designed to ensure passive decay heat removal without fuel damage during licensing basis accidents. The initial fuel cycle will be a once-through, high-burnup, low-enriched uranium fuel cycle. Other fuel cycle possibilities will be considered after the prototype has become operational.

The nuclear fuel is tri-isotopic (TRISO)-coated fuel particles embedded in graphite, either as compacts to be placed in prismatic blocks or as pebbles. The center of the core is a non-fueled graphite reflector. Normal operating maximum fuel temperatures do not exceed 1,250°C.

Passive safety is achieved by designing for a core cooldown during a postulated long-term depressurized loss-of-forced-convection accident that limits the peak fuel temperatures to 1,600°C. This is accomplished by conducting the decay heat radially through the core and pressure vessel, by radiation to the reactor building structure, and finally, by conduction to the ground. A cross vessel (CV) connects the reactor vessel to the IHX, or a power conversion vessel, that is deliberately made as short as possible to minimize thermal expansion differences between the two large vessels. Within the CV, the reactor inlet gas flows in an annular duct along the inside surface of the CV to the reactor inlet. The core exit hot gas flows in a central duct along the centerline of the CV to the IHX. Other design configurations will be considered during the conceptual design process.

One or more processes will use the heat from the high-temperature helium coolant to produce hydrogen. The first process of interest is the thermo-chemical splitting of water into hydrogen and oxygen. The second process of interest is thermally-assisted electrolysis of water.

The result of this project is the demonstration of a NRC-licensed, full-scale prototype (~600 MW_t), helium-cooled reactor for electricity production and/or hydrogen production.

Currently, to support the anticipated project schedule, Critical Decision 1 must occur in 2009 so the prototype can be operational no later than 2021. The NGNP Project prototype will require over 12 years from initiation of conceptual design through completion of acceptance testing.

The objectives of the NGNP Project are to:

- Demonstrate safe and economical nuclear-assisted production of hydrogen and electricity
- Demonstrate the basis for commercialization of the nuclear system, the hydrogen production facility, and the power conversion concept
- Establish the basis to license the commercial version of NGNP by the NRC.

The current R&D work is addressing fundamental issues that are relevant to a variety of possible NGNP designs.

5.1.2 Highlights of Research and Development

Idaho National Laboratory (INL), under the direction of the DOE, will lead the development of the NGNP by integrating, conducting, and coordinating all necessary R&D activities and by organizing project participants.

Section 643 (a)(1-5) of the EPACT2005 outlines five specific areas of research, called “Major Project Elements,” that would support the NGNP project. These major project elements are:

1. High-temperature hydrogen production technology development and validation
2. Power conversion technology development and validation
3. Nuclear fuel development, characterization, and qualification
4. Materials selection, development, testing, and qualification
5. Reactor and balance-of-plant (BOP) design, engineering, safety analysis, and qualification.

The five areas described above have current research programs and R&D plans associated with them. Also, note that Items 1 and 2 are covered under separate R&D plans, and will not be discussed in this section.

5.1.2.1 Fuel Development. The DOE Advanced Gas Reactor (AGR) Fuel Development and Qualification Program is designed to provide a fuel qualification baseline.

- ***Fuel Form:*** The fuel for the NGNP is based on the TRISO-coated particle fuel design (Figure 5.2) demonstrated in High-Temperature Gas-Cooled Reactors in Germany, the United Kingdom, the U.S., and elsewhere. Without a design for the NGNP, the AGR Fuel Development and Qualification Program is currently focusing on the more bounding fuel form for development and qualification (uranium oxycarbide [UCO] TRISO).

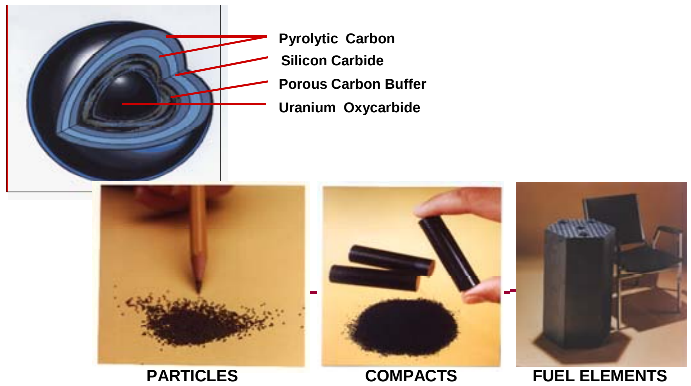

Figure 5.2. Cutaway of a TRISO-coated fuel particle and pictures of prismatic-fueled high-temperature gas reactor fuel particles, compacts, and fuel elements.

- ***Fuel Fabrication:*** The fuel-fabrication portion of the AGR program will produce coated-particle fuel that meets fuel performance specifications and includes process development for kernels, coatings, and compacting; quality control methods development; scale-up analyses; and process documentation needed for technology transfer. Fuel and material samples are produced for characterization, irradiation, and accident testing as necessary to meet the overall goals. Automated fuel fabrication technology suitable for mass production of coated-particle fuel at an acceptable cost will eventually be developed in later stages of the program and in conjunction with industrial partners.

- ***Fuel Irradiation:*** The fuel irradiation activities will produce fuel performance data to support fuel process development, to qualify fuel for normal operating conditions, and to support development and validation of fuel performance and fission product transport models and codes. The irradiations will also produce irradiated fuel for postirradiation examination (PIE) and ex-core high-temperature furnace safety testing. Eight irradiation capsules will be used to obtain the necessary data and sample materials.

  Data from the PIE will supplement the in-reactor measurements (primarily fission gas release-to-birth ratio [R/B] measurements) as necessary to demonstrate compliance with the fuel performance requirements and support development and validation of the computer codes. This work will also support the fuel manufacture with feedback on the performance of kernels, coatings, and compacts.

- ***Safety Testing:*** An important goal of this program is to evaluate the integrity and performance of the coated particle fuel under high-temperature accident conditions, which is essential to the safety case for the NGNP. In particular, three environments are of interest: helium, air, and steam. The data needed from safety testing are fission product release, TRISO coating layer integrity, and fission product distribution within fuel particles (likelihood of corrosion) and fuel elements.

- ***Fuel Performance Modeling:*** The fuel performance modeling will address the structural, thermal, and chemical processes that can lead to coated-particle failures. The models will also simulate the release of fission products from the fuel particle and the effects of fission product chemical interactions with the coatings, which can lead to degradation of the coated-particle properties.
- ***Fission Product Transport and Source Term:*** Transport of fission products produced within the coated particles will be modeled to obtain a technical basis for source terms for AGRs under normal and accident conditions. The design methods (computer models) will be validated by experimental data as necessary to support plant design and licensing.

5.1.2.2 Materials. The NGNP Materials R&D Program will focus on selection, development, testing, and qualification of key materials. The materials R&D program will address the materials needs for the NGNP reactor, power conversion unit, IHX, and associated BOP. Materials for hydrogen production will be addressed by the NHI Program.

- ***Component Candidate Materials:*** A variety of materials options have been identified for potential use in the NGNP reactor and BOP components. Graphite will be the major structural component and nuclear moderator in the NGNP reactor core.
  - The reactor internals may include a core barrel, inside shroud, core support floor, upper core restraint, and shutdown cooling system shell and tubes.
  - An IHX will be needed for hydrogen production and other process heat applications. It may also be desirable to use an indirect cycle for electricity production.
  - Several possible primary coolant pressure boundary systems are envisioned for the NGNP. These comprise (1) a large reactor pressure vessel (RPV) containing the core and internals, (2) a second vessel containing an IHX and circulator (or a power conversion unit), and (3) a pressure vessel containing a CV joining the two vessels. Because these three vessels will be exposed to air on the outside and helium on the inside, emissivity of the material is an important factor regarding radiation of heat to the surrounding air to ensure adequate cooling.
  - The key components of the NGNP power conversion unit will include turbines, generators, and various types of recuperators or heat exchangers. Considerable materials work may be involved in both the turbine and the generator components and existing component manufacturers are an excellent source for the needed materials information. The recuperator may be a modular counter-flow helium-to-helium heat exchanger, and current technology for the expected temperatures and pressures of operation is relatively mature.
- ***Graphite Testing and Qualification:*** Significant quantities of graphite have been used in nuclear reactors and the general effects of neutron irradiation on graphite are reasonably well understood. However, models relating structure at the micro and macro level to irradiation behavior are not well developed. Engineers at INL, in consultation with graphite experts at Oak Ridge National Laboratory (ORNL), have started an Advanced Test Reactor creep capsule design. Prior Oak Ridge Research Reactor and Idaho Engineering Test Reactor graphite creep test capsule designs are being used as the basis for the new design. The graphite samples will be loaded under compressive stress and irradiated at representative temperatures. In addition to creep rate data, PIE of the control samples will yield valuable irradiation-effects data. Mathematical models that describe and predict the behavior of nuclear graphite under neutron irradiation must be developed. In addition, there is little data for the irradiation behavior of graphite at temperatures greater than 1,000°C. Hence, a high-temperature graphite irradiation capsule for use in the High-Flux Isotope Reactor at ORNL will be designed that will be capable of irradiating graphite samples at temperatures up to 1,200°C.

- ***High-Temperature Design Methodology:*** The High-Temperature Design Methodology (HTDM) project will develop the data and simplified models required by the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (B&PV) Code subcommittees to formulate time-dependent failure criteria that will ensure adequate life. The HTDM project will produce test data, analyze results, and develop constitutive models for high-temperature alloys. Equations are needed to characterize the time-varying thermal and mechanical loadings of the design. Test data are needed to build the equations. The project will directly support the reactor designers on the implications of time-dependent failure modes and time- and rate-dependent deformation behaviors.
- ***Support for the ASTM and ASME Code:*** There are a number of areas relating to ASTM standard method development and ASME B&PV Code development that must be pursued to meet the NGNP goals. Much of this effort will provide required technological support and recommendations to the Subgroup on Elevated Temperature Design (NH) as they develop methods for use of Alloy 617 at very high temperatures. ASME design code development is also required for the graphite core support structures of the NGNP and later for the carbon-carbon (C_f/C) composites structures of the core. A project team under Section III of ASME is currently undertaking these activities. Standard test methods for graphites and composites are also required to generate data that may be used in the design code. INL and ORNL will also support the formation of an ASTM working group on silicon carbide/silicon carbide (Si_fC/SiC) composite testing development, and will ensure that setting guidelines for testing tubular Si_fC/SiC structures proceeds.
- ***Environmental Testing and Thermal Aging Project:*** The three primary factors that will most affect the properties of the metallic structural materials from which the NGNP components will be fabricated are (1) the effects of irradiation, (2) high-temperature exposure, and (3) interactions with the gaseous environment to which they are exposed. An extensive environmental testing and thermal aging evaluation program is needed to assess the effects of these factors on the properties of the potential materials to qualify them for the service conditions required.
- ***Test and Qualify Reactor Pressure Vessel and Core Materials:*** Some VHTR designs assume the use of higher alloy steel than currently used for LWR pressure vessels. The irradiation damage and property changes of these materials must be measured. Therefore, an irradiation facility that can accommodate a relatively large complement of mechanical test specimens will be designed and fabricated for placement in a material test reactor. This facility will replace the irradiation facility that was shut down last year at the Ford Test Reactor at the University of Michigan.
- ***Composites Research and Development:*** The composites R&D program is directed at the development of C_f/C and Si_fC/SiC composites for use in selected very-high-temperature/very-high-neutron fluence applications such as control rod cladding and guide tubes (30 displacements per atom [dpa] projected lifetime dose) where metallic alloys are not feasible. It is believed that Si_fC/SiC composites have the potential to achieve a 60-year lifetime under these conditions. The usable life of the C_f/C composites will be less, but their costs are also significantly less. This program will eventually include a cost comparison between periodic replacement of C_f/C materials and use of Si_fC/SiC composites.
- ***Data Management and Handbook:*** The NGNP data will be managed by incorporating final materials data into the Generation IV Materials Handbook. Existing Materials Handbooks will be examined to determine what information might be extracted and incorporated into the Generation IV Materials Handbook. Once fully implemented, the Generation IV Materials Handbook will become the repository for the NGNP materials data and serve as a single source for researchers, designers, vendors, codes and standards bodies, and regulatory agencies. Near-term activities in this area will include assembling and inputting existing data on materials of interest to NGNP.

- ***Additional Materials Research and Development:*** Additional materials R&D will also include the power conversion unit and generator; RPV emissivity; metallic reactor internals; IHX and piping fabrication; hot duct liner and insulation; and valves, bearings and seals.
- ***Energy Transfer:*** Molten salt is a leading candidate for efficient transfer of heat from the NGNP reactor to the hydrogen production plant. The heat transfer loop application does not impose radiation damage constraints, but the NGNP loop application does impose very high temperatures. For this reason, a new optimization of materials for the heat transfer loop is required. Recent studies highlight the advantages of a molten salt coolant (INL 2005) for the intermediate heat transport loop and indicate the primary importance of materials compatibility at the higher temperatures envisioned for the NGNP loop. An assessment of molten salts as a primary reactor coolant established the factors to be used in selection and ranking of molten salt coolants (ORNL 2006). A report that extends this analysis to the additional salt options possible for a secondary coolant application is being prepared.

5.1.2.3 Design and Evaluation Methods. The NGNP Design and Evaluation Methods (D&EM) Program will develop the state-of-the-art software analysis tools and supporting data required to calculate the behavior of the NGNP system during normal and off-normal scenarios. The software tools discussed here include those necessary to calculate the neutronic and thermal-fluid behavior, the interactions between neutronics and thermal-fluids, and the structural behavior where necessary. The D&EM R&D implementation methodology is shown in Figure 5.3.

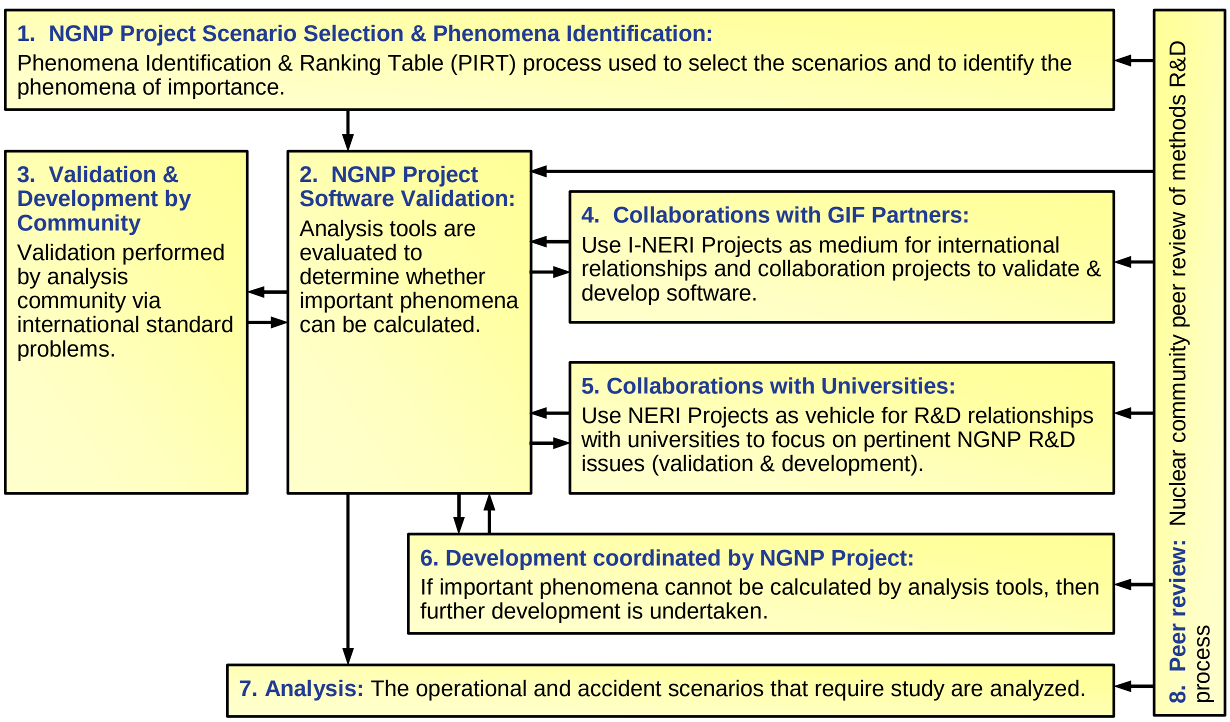

Figure 5.3. NGNP D&EM R&D process.

A rigorous phenomena identification and ranking table (PIRT) analysis of the NGNP has not been performed because the design has not yet been identified. However, a “first-cut” PIRT has been defined and used to specify the R&D for FY 2005 and subsequent years. The PIRT has identified a number of important phenomena (INEEL 2004). Based on these phenomena, R&D will be focused on five major tasks: (1) computational fluid dynamics (CFD) code validation experiments (lower plenum, hot channel, and reactor cavity cooling), (2) validation of thermal-hydraulic software, (3) core physics methods development, (4) nuclear data tasks, and (5) liquid salt-cooled methods development and design assessments.

The D&EM R&D areas supporting these major tasks are described below.

- ***Validation of Thermal-Hydraulics Software and Computational Fluid Dynamics Codes Including Computational Fluid Dynamics Validation Experiments:*** The thermal-hydraulics of the NGNP encompasses the heat generation by the fuel; its transport to the helium coolant; and the laminar, transition, or turbulent flow of the helium as it flows from the upper plenum through the core, into the lower plenum, then out the exit duct to the IHX or power generation vessel. Also included are the heat losses from the reactor vessel during normal operation as well as accident scenarios that may occur from failures in the system. The system designed to remove the heat in the event of an accident, the reactor cavity cooling system, is also included in the thermal-hydraulics of the NGNP.

  Advanced simulation tools are available to simulate turbulent flow and heat transfer in complex systems. These tools must be validated for application on the NGNP. CFD codes are needed to simulate regions of complex turbulent flow in the plant. Because of the size and complexity of the plant, thermal-hydraulics systems analysis codes will also be applied, in conjunction with CFD codes, to analyze the plant.

  The high-priority research areas identified in the “first-cut” PIRT include (1) the core heat transfer, (2) mixing in the upper plenum, the lower plenum, hot duct, and turbine inlet, (3) the heat transfer in the reactor cavity cooling system, (4) air ingress following a system depressurization, and (5) the behavior of the integral system during the key scenarios, including the contributions of the BOP.

- ***Reactor Kinetics and Neutronics Analysis Development:*** The design and operational analyses of the NGNP must have the ability to carry out the following reactor physics computations: (1) fuel cell and assembly spectrum cross section generation calculations to produce effective nuclear parameters for subsequent global reactor analysis, (2) static reactor analysis for core design and fuel management, (3) kinetics, thermal module coupling, and feedback, (4) material-neutronics interface, and (5) validation and verification and ongoing improvement of code suite. This R&D focuses on the development of a suite of deterministic code systems, including spectrum codes, a lattice physics code, and nodal diffusion codes, that can be used for efficient and accurate design of the NGNP.

- ***Nuclear Data Measurements, Integral Evaluations, and Sensitivity Studies:*** Accurate differential nuclear data libraries and well-characterized and accurate integral benchmark information are required for all computational reactor physics tasks associated with NGNP design and operation. Differential nuclear cross section data for all materials used in the reactor are required as input to the physics codes. Furthermore, integral benchmark experiment data for relevant existing critical configurations are required for physics code validation. Finally, rigorous sensitivity studies for representative NGNP core designs are required for prioritizing data needs and for guiding new experimental work in both the differential and integral regimes.

5.1.3 Fiscal Year 2006 Project Budget

The FY 2006 budget for NGNP is shown in Table 5.1

Table 5.1. FY 2006 budget profile for NGNP activities ($K).

Task	FY-06[a]
R&D	42,150[b]
Nuclear hydrogen R&D/Demo	25,000
Total	67,150

a. FY 2006 funding includes FY 2005 carryover funds.
b. Additional NGNP funding is included in the crosscutting section.

5.2 Supercritical-Water-Cooled Reactor

5.2.1 System Description

SCWRs are promising advanced nuclear systems because of their high thermal efficiency (i.e., about 45% versus about 33% efficiency for current LWRs) and considerable plant simplification. SCWRs are basically LWRs operating at higher pressure and temperatures with a direct, once-through cycle. Operation above the critical pressure eliminates coolant boiling, so the coolant remains single-phase throughout the system. Thus, the need for recirculation and jet pumps, pressurizers, steam generators, and steam separators and dryers in current LWRs is eliminated.

The main mission of the SCWR is generation of low-cost electricity (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). It is built upon two proven technologies: LWRs, which are the most commonly deployed power-generating reactors in the world, and supercritical fossil-fired boilers, a large number of which are also in use around the world. The SCWR system (Figure 5.4) is being investigated by 32 organizations in 13 countries. General information about the SCWR system and its technical challenges is widely available in the literature so it will not be repeated here.

In FY 2005, the SCWR program was redirected. The current plan focuses on further assessment of SCWR viability independent of a specific system design. Due to the potential economic benefits as an efficient electricity generator, reliable tools need to be developed to assess the viability of a variety of potential SCWR designs. In addition, materials research needs to be conducted to establish the optimal operational parameter range for SCWR from a materials point of view and ensure selection of structural and cladding materials that will maintain reliable operation of a SCWR power plant for its design life.

Current R&D programs within GIF organizations address two principal SCWR design concepts that differ in their approach to the reactor design: one utilizes a RPV and the other utilizes pressure tubes. The main difference between these pressure vessel concepts lies in the core layout and the moderators. From its conception, the U.S. program focused on the RPV concept because its roots are in the LWR technology common to all U.S. reactor vendors. Similarly, the R&D conducted in Japan, the Republic of Korea, and Europe is focused on the pressure vessel concept. Canada selected a pressure tube design for its SCWR as the logical evolution of Canada deuterium uranium (CANDU)-type reactors. The U.S. Generation IV SCWR Program operates under the following system characteristics, which are consistent with the SCWR's focus on electricity generation at low capital and operating costs:

- Direct cycle
- Thermal-spectrum
- Light-water coolant and moderator

- Low-enriched uranium oxide fuel
- Base load operation.

These system characteristics are essentially common to all SCWR systems in consideration by the GIF, except for the moderator; the Canadian system utilizes heavy water and the Korean system uses solid moderator. The GIF SCWR Steering Committee has generated a schedule for the demonstration of the SCWR system that calls for the completion of all essential R&D by 2015 and construction of a small-size (≤150 MW_t) prototype SCWR by 2020.

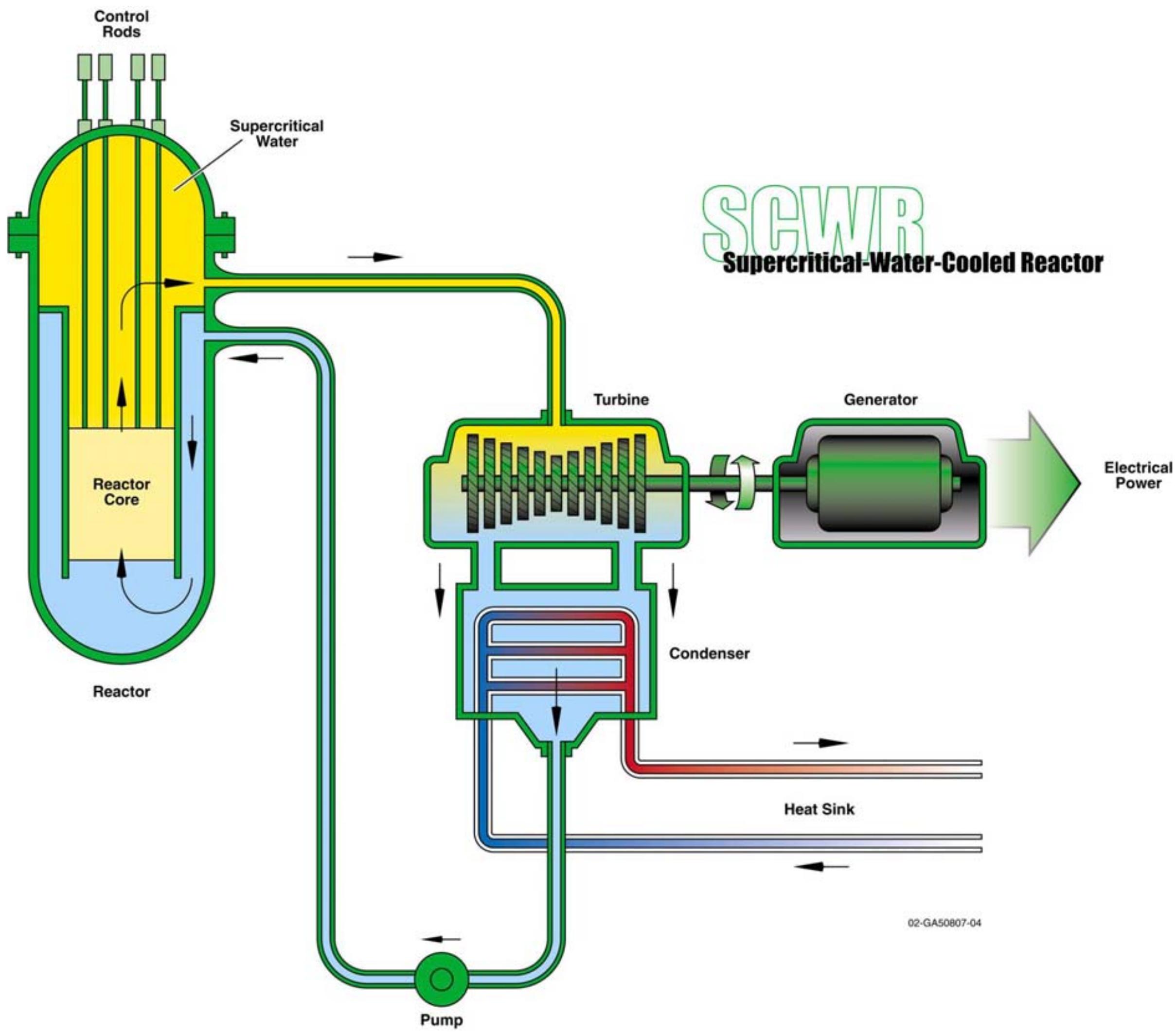

Figure 5.4. Conceptual SCWR system.

5.2.2 Highlights of Research and Development

5.2.2.1 System Design and Evaluation. This R&D element provides the pre-conceptual SCWR design needed for the viability assessment and guidance for materials and chemistry, thermal-hydraulic, and system research. In general, this task addresses baseline design, safety systems, control and startup, system and comparative analyses, basic thermal-hydraulic phenomena, safety, stability, and methods.

Work performed by the GIF partners from 2006 to 2014 will focus on identification of the most promising design. Since 2005, the U.S. has not actively participated in this activity.

- ***System and Comparative Analyses:*** The objective of this GIF activity is to converge on a design that can be developed jointly and demonstrated cooperatively by the other GIF countries. It will include operational analyses, safety analyses, and economic assessment.

5.2.2.2 Basic Thermal-Hydraulic Phenomena, Safety, Stability, and Methods. This R&D program element addresses current basic knowledge gaps in areas such as the thermal-hydraulic phenomena expected during normal operation and accidents, system performance under a variety of conditions, and analytical methods needed for safety and system performance assessment. In collaboration with GIF partners, the necessary experiments will be conducted, databases will be developed, and analytical models and codes will be assessed and improved where necessary. Codes will be validated against available and planned experimental data, and benchmarked against other codes developed by the GIF partners or elsewhere.

5.2.2.3 Fuels. The SCWR system is based on standard LWR fuel. It is not clear at this time if in-pile fuel testing will be required or not. The SCWR Steering Committee sponsored an expert's workshop in March 2006 at Nuclear Energy Agency Headquarters in Paris, France to address this issue. The conclusion of the workshop was that in-pile fuel testing would be necessary for any combination of cladding material and fuel composition if a SCWR was to ever be licensed.

5.2.2.4 Energy Conversion. The major components of the power conversion cycle are external to the reactor vessel and include the steam turbine and associated valving, the condenser, the demineralizer/condensate polisher, the feedwater preheaters, and the deaerator. There do not appear to be any special needs for alloy selection for the condenser, the demineralizer/condensate polisher, the feedwater preheaters, or the deaerator in the SCWR design, as long as the water chemistry guidelines developed for the control of corrosion in supercritical fossil plants can be followed. On the other hand, the turbine requires special consideration. However, initial studies and consultation with engineering and vendor firms have shown that the BOP and turbine issues can be resolved and are not a viability problem.

5.2.2.5 Materials. This section describes, in general terms, the R&D needs for SCWR materials. The actual R&D needed to select and/or develop materials that meet these requirements is described in Appendix 9.0, Materials.

For any of the proposed SCWR designs, R&D on materials will need to focus on the following key areas:

- Oxidation, corrosion, and stress corrosion cracking
- Radiolysis and water chemistry
- Strength, embrittlement, and creep resistance
- Dimensional and microstructural stability.

In addition to these performance factors, the cost of the material and its effect on fuel utilization must also be considered to meet the economic and sustainability requirements of Generation IV designs.

For any SCWR core design, materials for reactor internals and fuel cladding will need to be evaluated and identified. Zirconium-based alloys, so pervasive in conventional water-cooled reactors, will not be a viable material for most of the proposed SCWR core designs without a thermal and/or corrosion-resistant barrier.

Based on the available data for other alloy classes, no alloy has currently received enough study to unequivocally ensure its viability in a SCWR. A variety of potential materials have been identified that should be given consideration for both fuel cladding and core internal components.

5.2.3 Fiscal Year 2006 Project Budget

The FY 2006 budget for SCWR is shown in Table 5.2.

Table 5.2. FY 2006 budget profile for SCWR activities ($K).

Task	FY-06[a]
Systems Design	403
Materials	440
Total	843

a. FY 2006 funding includes FY 2005 carryover funds.

5.3 Gas-Cooled Fast Reactor

5.3.1 System Description

The GFR is primarily envisioned for missions in electricity production and actinide management, although it may be able to support hydrogen production as well. The GFR (Figure 5.5) was chosen as one of the Generation IV nuclear reactor systems to be developed based on its excellent potential (1) for sustainability through reduction of the volume and radiotoxicity of both its own fuel and other spent nuclear fuel, and (2) for extending/utilizing uranium resources orders of magnitude beyond what the current open fuel cycle can realize. In addition, energy conversion at high thermal efficiency and cogeneration is possible with the current designs being considered, increasing the economic benefit of the GFR. However, R&D challenges include the ability to use passive decay heat removal systems during accident conditions, survivability of fuels and in-core materials under extreme temperatures and radiation, and economic and efficient fuel cycle processes.

The main characteristics of the GFR are: a self-generating core (i.e., conversion ratio = 1) with a fast neutron spectrum, robust refractory fuel, high operating temperature, direct energy conversion with a gas turbine, and full actinide recycling (possibly with an integrated, on-site fuel reprocessing facility).

The reference GFR system features a fast-spectrum, helium-cooled reactor and closed fuel cycle. This was chosen as the reference design due to its close relationship with the NGNP, and, thus, its ability to utilize as much NGNP material and BOP technology as possible. Like thermal-spectrum, helium-cooled reactors such as the Gas-Turbine Modular Helium Reactor and the Pebble Bed Modular Reactor, the high outlet temperature of the helium coolant makes it possible to deliver electricity, hydrogen, or process heat with high conversion efficiency. The GFR reference design will utilize a direct-cycle, helium turbine for electricity (42% efficiency at 850°C) and process heat for thermo-chemical production of hydrogen.

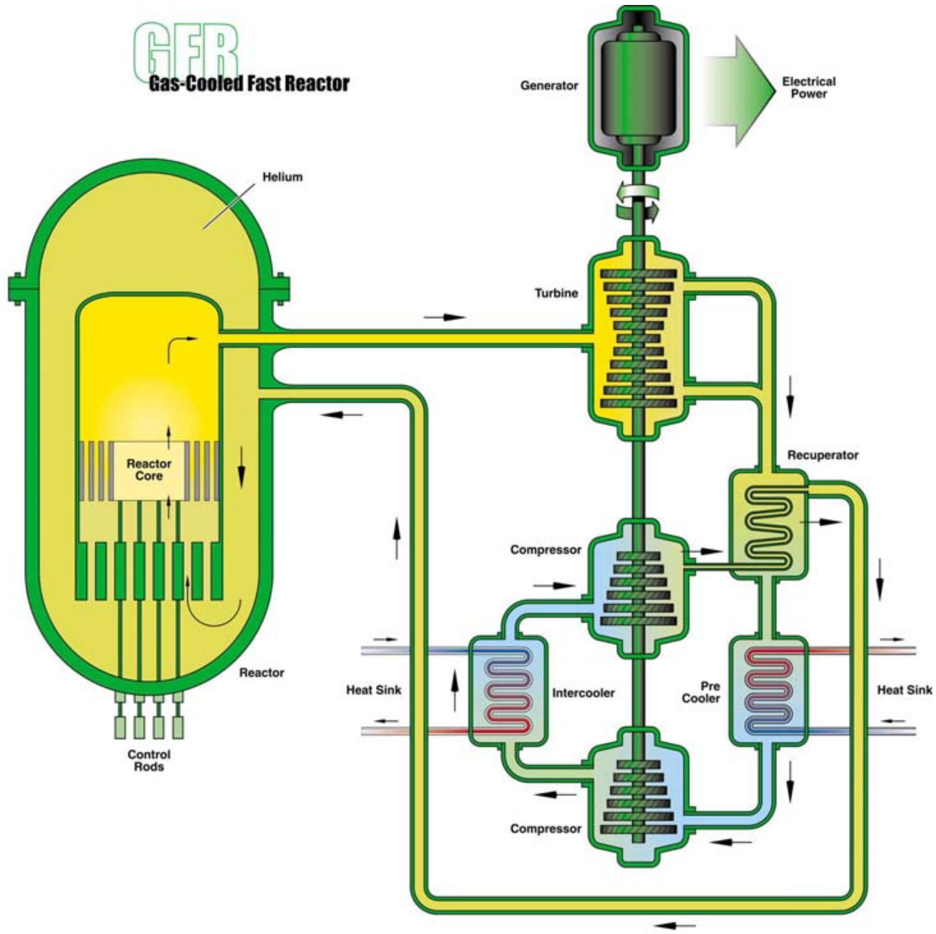

Figure 5.5. Conceptual GFR system.

The international community has issued a detailed R&D plan to establish the viability of the GFR by 2012, to complete a conceptual design by 2019, and to build a prototype by 2025. The first phase of research will deal with the viability and feasibility of the system. This research is mainly focused on those items that are critical to the initial advancement of the GFR. The second phase of the research will begin once the main viability phase is complete, and the reactor system is deemed feasible for further study. This second phase will be the start of performance phase research where phenomena, processes, and capabilities are verified and optimized under prototypical conditions.

The specific GFR research objectives include:

1. System design and safety research, which involves conceptual studies of a reference GFR system, assessment of options, analyses of the safety approach and of specific safety features, and development of computational tools for these studies
2. Materials research, which includes the identification and/or development of materials that can withstand the high temperatures and high fluence that will be encountered within the core region, and the development of out-of-core materials that will withstand the high temperatures
3. Energy conversion research that offers the best in power conversion systems for both direct and indirect cycles

4. Fuel and fuel cycle research, which will identify and fabricate those fuels that will perform well under extreme temperature and radiation conditions, handle the addition of minor actinides, and be recyclable in an economic manner.

5.3.2 Highlights of Research and Development

The specific R&D goals and work scope for the GFR are to:

- Define a GFR reference conceptual design meeting requirements for self-breeding cores, multi-recycling, power density and coupling between the reactor and process heat applications
- Identify and assess alternative design features (e.g., lower temperatures, indirect cycle)
- Perform a safety analysis for the reference GFR system and its alternatives
- Assess the impact on investment and operating costs of the simplified and integrated fuel cycle and the modularity of the reactor
- Develop and validate computational tools to design and analyze operating transients (design basis accidents and beyond)
- Ensure the core has:
  - High heavy metal content in the dedicated fuel volume
  - Use of refractory materials with low neutron absorption and moderation effects
  - Geometries allowing efficient cooling (pressure drop in the core, etc.)
  - High level of fission product confinement
  - Resistance to impurities in the helium coolant
  - Plutonium content in the range of 15 to 20%, with the ability to incorporate minor actinides
  - Potential for high burnups (target of 15% fissions of initial metal atoms)
  - Ability to reprocess (grouped actinide management)
  - Ability to sustain high temperatures and doses.
- Assess fabrication and welding capabilities, initial properties and properties under irradiation, microstructure and phase stability under irradiation, and initial and in-pile compatibility with helium for candidate materials
- Develop several small technological facilities devoted to coolant quality and inventory, tribology, leak tightness, thermal insulation, and instrumentation qualification
- Develop multi-purpose helium loops (~ 1 MW) for small component and system qualification, pressure drop studies, and sub-assembly hydro-dynamic characterization
- Develop a demonstration helium loop (~ 20 MW) for large component qualification, reactor system studies, code qualification, safety studies, and operation training.

To this point, all research needed for the development of the GFR has been described. Those portions that the U.S. intends to participate in are outlined in the sections that follow.

5.3.2.1 System Design and Evaluation. The major activities within the System Design and Evaluation research include safety system design and evaluation of passive and active safety systems for decay heat removal, system control and transient analysis, design and construction of experiments for thermal-hydraulic/safety tests and coolant chemistry control, and code development/adaptation for neutronic and thermal-hydraulic analysis.

5.3.2.2 Fuels and Fuel Cycle. Per direction from DOE, the AFCI will no longer perform research in this area. However, the direction and results of the international fuels and fuel cycle research will need to be tightly integrated with the GFR system design and safety task and correlated with the materials work that is being performed.

The major activities within the fuels and fuel-cycle research include fuels feasibility, fabrication, and testing; recycle process feasibility studies; and studies on the viability of refabrication.

5.3.2.3 Energy Conversion. The major activities within Energy Conversion R&D include feasibility studies of a direct Brayton cycle (including component testing) and development of the turbomachinery for helium and CO_2 systems.

5.3.2.4 Materials. The major activities within the Materials R&D include screening and testing of high-temperature materials (including welding and fabrication) and possible corrosion studies using supercritical CO_2 (S-CO_2).

5.3.3 Fiscal Year 2006 Project Budget

Given the overall budget of ~$940M required for development of the GFR and the participation of six GIF members (the European Union, France, Japan, Switzerland, the United Kingdom, and the U.S.), an initial assumption was made that the U.S. contribution will be approximately 16.5% (or 1/6th) of the total, or ~$157M. This gives a rough yearly budget of $9M per participant (or a total budget of ~$55M per year for the project). The FY 2006 U.S. budget is shown in Table 5.3.

Table 5.3. FY 2006 budget profile for GFR activities ($K).

Task	FY-06[a]
System Design and Evaluation	829
Materials	607
Energy Conversion[b]	10
Fuels and Fuel Cycle[b]	35
Total	1,481

a. FY 2006 budget includes FY 2005 carryover funds.
b. Monitoring of other programs for design integration.
AFCI is no longer providing funds for fuels research.

5.4 Lead-Cooled Fast Reactor

5.4.1 System Description

The LFR has the potential to meet many of the Generation IV mission interests. The LFR is mainly envisioned for electricity and hydrogen production, and actinide management. Options for the LFR also include a range of plant ratings and sizes from small modular systems to monolithic plants.

The LFR (Figure 5.6) is proposed to meet all of the Generation IV goals of non-proliferation, sustainability, safety and reliability, and economics. Two key technical aspects of the envisioned LFR that offer the prospect for achieving these goals are the use of lead (Pb) coolant and a long-life, cartridge-core architecture in a small, modular system intended for deployment with small grids or remote locations. The Pb coolant is a poor absorber of fast neutrons and enables the traditional sustainability and fuel cycle benefits of a liquid metal-cooled fast-spectrum core to be realized. Pb does not interact vigorously with air, water/steam, or CO_2 eliminating concerns about exothermic reactions. It has a high boiling temperature (1,740°C) so the prospect of boiling or flashing of the ambient pressure coolant is realistically eliminated. Two land prototypes and ten submarine reactors utilizing lead-bismuth eutectic coolant were operated in Russia, providing about eighty reactor years of experience together with the supporting development of coolant technology and control of structural material corrosion.

The LFR envisioned in the Generation IV Program is the Small Secure Transportable Autonomous Reactor (SSTAR) concept, which is a small modular fast-spectrum reactor. The main mission of the 20 MW_e (45 MW_t) SSTAR is to provide incremental energy generation to match the needs of developing nations and remote communities without electrical grid connections such as those that exist in Alaska or Hawaii, Ulung Island in the Republic of Korea, island nations of the Pacific Basin (e.g., Indonesia), and elsewhere. This gives early LFR designs a unique niche market where costs for competitive systems are high and large-scale nuclear power plants are not competitive. Evolution of the LFR technology to larger sizes may broaden the market. Design features of the reference SSTAR include a 20- to 30-year-lifetime sealed core, a natural circulation primary, autonomous load following without control rod motion, and use of an innovative S-CO_2 energy conversion system. The incorporation of inherent thermo-structural feedbacks imparts walk-away passive safety, while the use of a sealed, cartridge core with a 20-year or longer cycle time between refueling imparts strong proliferation resistance. If these technical innovations can be realized, the LFR will provide a unique and attractive nuclear energy system that meets Generation IV goals.

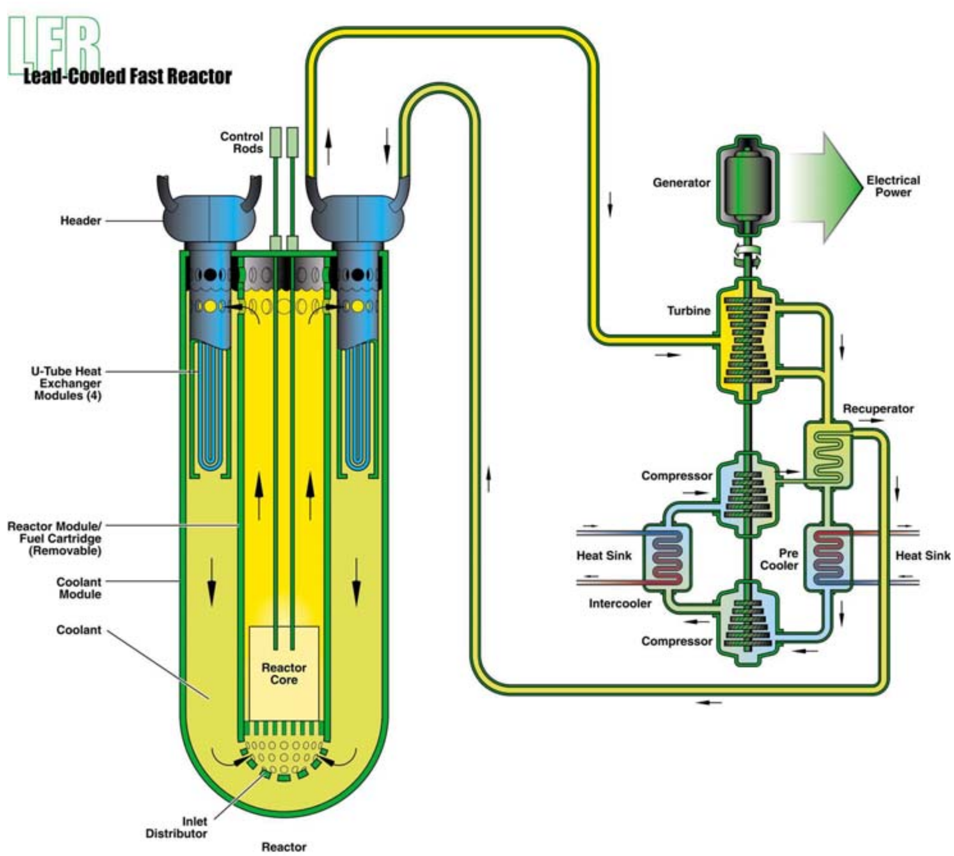

Figure 5.6. Conceptual LFR system.

This R&D plan addresses viability issues associated with the LFR leading to the Generation IV fast-spectrum reactor selection in 2010 and a follow-on decision in 2014 to proceed with design and construction of the LFR demonstration plant. The plan described in this section reflects 10 years of a 20-year development program leading to startup of a LFR demonstration unit. Viability will be established through focused viability R&D tasks and with formulation of a technically defensible pre-conceptual design. Conceptual design will begin in 2009 and continue, given a decision for pursuing the LFR in the 2010 to 2014 timeframe. R&D tasks that support conceptual design will be defined in more detail at a later time in the viability R&D program, but will include analysis and experiments intended to reduce design uncertainty and to establish conceptual limiting conditions of operation.

5.4.2 Highlights of Research and Development

5.4.2.1 System Design and Evaluation. R&D tasks for System Design and Evaluation will address the areas of core neutronics, system thermal-hydraulics, passive safety evaluation, containment and building structures, in-service inspection, and assessing cost impacts.

Core design is essential to establishing the necessary features of a 20- to 30-year-life core and determining core parameters that impact feedback coefficients. R&D tasks associated with this work include further optimization of the core configuration, establishing a startup/shutdown rod and control rod strategy, and calculating reactivity feedback coefficients.

System thermal-hydraulic studies are essential to establishing the parameters for potential natural circulation cooling in the primary system, identifying any safety issues to be addressed in subsequent design, and establishing parameters for ensuring passively-safe response. R&D tasks associated with this work include (1) an autonomous load following evaluation for the reactor using the calculated reactivity feedback coefficients and (2) establishing the viability of startup using natural circulation, the emergency heat removal concept, and eliminating the intermediate heat transport system.

Viability of the long-life core and passive safety under all abnormal conditions (including seismic events that might unacceptably reconfigure a core) requires materials that can withstand stresses at high temperature and, for some components, contact with liquid lead. The range of expected stresses and temperatures and potential materials must be identified. Establishing actual materials and conditions of operation are design functions to be accomplished later in a development program. However, ranges of conditions must be identified to provide requirements for materials and to determine that such material performance can be achieved within an engineering development program. The preconceptual structural design must be evaluated to ensure viability at projected system temperatures up to 650°C peak cladding.

Passively safe response can be designed into the reactor core and plant based on current experience and passive safety design principles. However, the magnitudes of feedback coefficients for a given design and integral behavior of a reactor plant must be verified through further analysis. R&D tasks associated with this work include evaluating operational transients and postulated accidents, the potential for flow instability, the potential for flow reversal, and removal of afterheat during postulated accidents. Additionally, calculations will be run demonstrating that core and Pb-to-CO_2 heat exchangers remain covered by ambient pressure, single-phase, primary coolant inside the reactor vessel, and single-phase natural circulation removes the core power under all operational and postulated accident conditions with the exception of extraordinarily low probability postulated beyond design basis accidents.

Experience with LWRs and previous fast-spectrum reactor plants and concepts indicates that large containments, necessary to contain a fair amount of gaseous reaction and fission products, drove such plants to large economies of scale. This must be avoided if the LFR is to be financially viable. Therefore, the factors that would drive containment design must be evaluated as part of a viability R&D program to ensure that the design, if technically achievable, can avoid large-size containment requirements. R&D tasks associated with this work include evaluating the requirements for containment, including configuration, size, and capability; considering industrial health aspects of operation with Pb and CO_2; and identifying decontamination and decommissioning issues that would impact the design.

Concepts for inspecting and verifying key safety structures and boundaries of the LFR system must be identified during the viability R&D phase for subsequent engineering development. R&D tasks associated with this work include identifying In-Service Inspection (ISI) approaches for operation over core lifetimes of 20 years or more, proposing and evaluating approaches that significantly reduce or minimize the requirements for ISI, and assessing the capability to operate with failed cladding over a long core lifetime.

Because the envisioned LFR system will not have the benefit of economy of scale, the identified opportunities to reduce capital and operating costs below those of larger, base-load plants must be evaluated. In particular, additional design features with strong cost impacts must be identified and considered for subsequent changes to design requirements. R&D tasks associated with this work include establishing a basis for a credible estimate of plant costs and evaluating economic conditions for niche market applications.

5.4.2.2 Fuel and Fuel Cycle. Viability of both nitride fuel and whole-core cassette refueling will be addressed in the fuel and fuel-cycle R&D.

Achieving long core life, walk-away passive safety, and reliable operation will require robust and predictable fuel performance for long durations under service conditions. Nitride fuel has many properties and characteristics that render it well suited for LFR application; however, there is very little data on nitride fuel performance to confirm the designer’s current assumptions regarding this fuel type. R&D tasks associated with this work include irradiation testing and demonstration to projected burnups (>13 atomic weight %) under operating conditions, and transient testing, including accident conditions, to verify acceptable fuel behavior.

If the proliferation-resistant LFR system is to be viable as envisioned, with refueling occurring only at 20- to 30-year intervals and with equipment that is brought onsite temporarily rather than maintained onsite, then credible concepts for emplacing and exchanging fueled core cartridges must be proposed and considered. R&D tasks associated with this work include determining the viability of cooling the spent cassette during retrieval and shipment following a short cool down period, identifying spent-fuel-cassette shielding concepts, evaluating in-cask cassette cooling concepts and safeguards considerations, and assessing the impact upon plant containment and building structures.

5.4.2.3 Energy Conversion. Use of an S-CO_2 Brayton cycle for energy conversion offers the prospect of significantly higher efficiencies at the reference LFR core outlet temperature and acceptable efficiencies with lower Pb coolant outlet temperatures, which reduces the challenges for materials in a near-term demonstration. Furthermore, the economic viability of the LFR may depend on reduction of capital cost achieved by incorporation of an S-CO_2 Brayton cycle rather than a steam Rankine cycle. Therefore, several R&D tasks associated with S-CO_2 Brayton cycle conversion are identified as viability tasks. These include evaluating innovative design concepts for compressors, turbines, printed circuit heat exchangers (PCHEs), and other components, then designing, testing, and demonstrating them. Additional tasks include demonstrating long-term operation of components with small channels (e.g., PCHEs) without fouling or corrosion, and demonstrating operation of an integral cycle at a sufficiently large scale.

5.4.2.4 Materials. Viability of long core lifetime, passive safety, and economic performance (both capital and operating costs) of the LFR system will depend on identifying materials with the potential to meet service requirements. R&D tasks associated with this work include identifying candidate Si-enhanced ferritic-martensitic (F/M) steels, oxide dispersion strengthening F/M steels, carbides, amorphous materials, and other candidate materials; testing the compatibility of candidate materials with heavy liquid metal coolants; demonstrating control of corrosion to ensure adequate thickness of cladding and structural elements at operating temperatures over long core and reactor lifetimes; and preparing code cases for selected cladding and structural materials throughout the operating temperature range.

5.4.3 Fiscal Year 2006 Project Budget

The FY 2006 budget to begin the LFR R&D described in the previous sections is provided in Table 5.4.

Table 5.4. FY 2006 budget profile for LFR activities ($K).

Task	FY-06[a]
System Design and Evaluation	575
Materials	775
Total	1,350

a. FY 2006 funding includes FY 2005 carryover funds.

5.5 Sodium-Cooled Fast Reactor

5.5.1 System Description

The SFR system features a fast-spectrum reactor and closed fuel-recycle system. The primary mission for the SFR is to produce electricity, burn transuranics and produce fissile material. With innovations to reduce capital cost, the mission can extend to electricity production, given the proven capability of sodium reactors to utilize almost all of the energy in natural uranium.

A range of plant size options is available for the SFR, ranging from small modular systems of 100 MW_e to large monolithic reactors of about 1,500 MW_e. Sodium core outlet temperatures are typically 550ºC. The primary coolant system in a SFR can either be arranged in a pool layout (Figure 5.7)–a common approach where all primary system components are housed in a single vessel–or in a compact loop layout (Figure 5.8) favored in Japan. For both options, there is a relatively large thermal inertia of the primary coolant. A large margin to coolant boiling is achieved by design and is an important safety feature of these systems. Another major safety feature is that the primary system operates at essentially atmospheric pressure. A secondary sodium system acts as a buffer between the radioactive sodium in the primary system and the energy conversion system in the power plant.

The objective of the R&D program is to establish the viability of the SFR system and to achieve the overall performance targets discussed under the program schedule to provide sufficient information to support the selection of the preferred fast-spectrum system by 2010. The R&D activities are conducted in collaboration with other GIF countries interested in SFR technology. There is a GIF R&D Plan intended to cover the R&D to resolve viability and performance questions to complete the development of the SFR system.

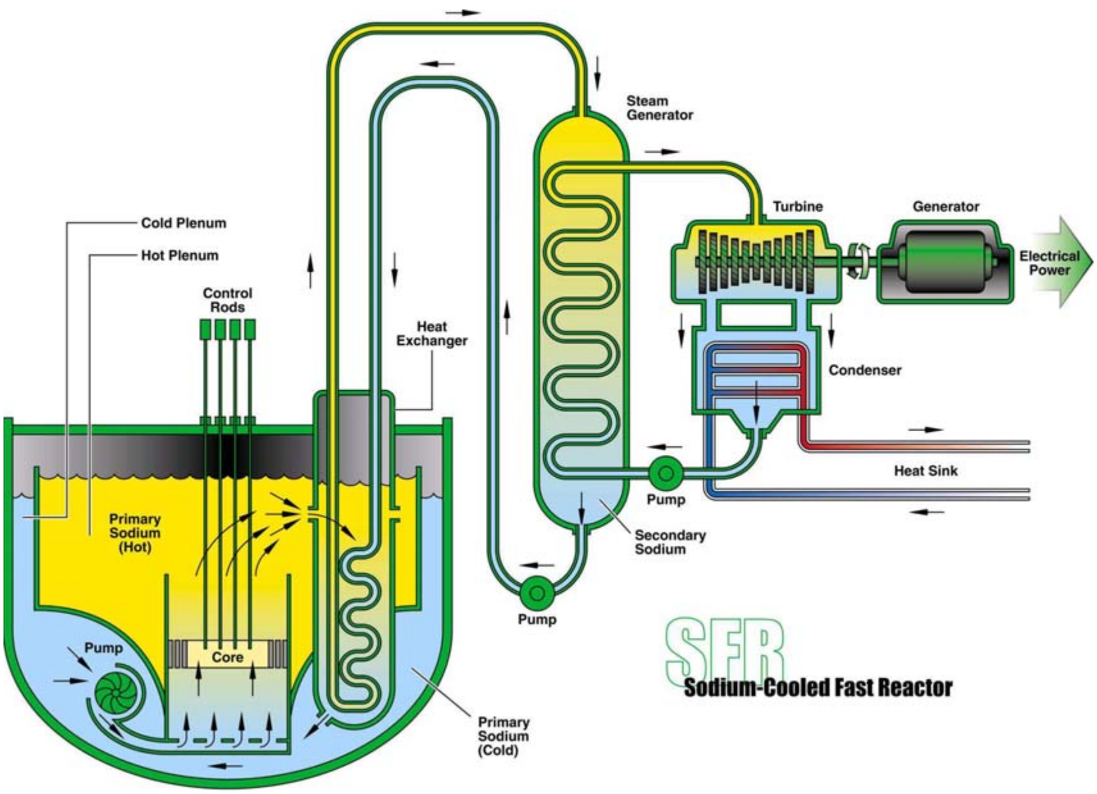

Figure 5.7. Pool layout SFR power plant system configuration.

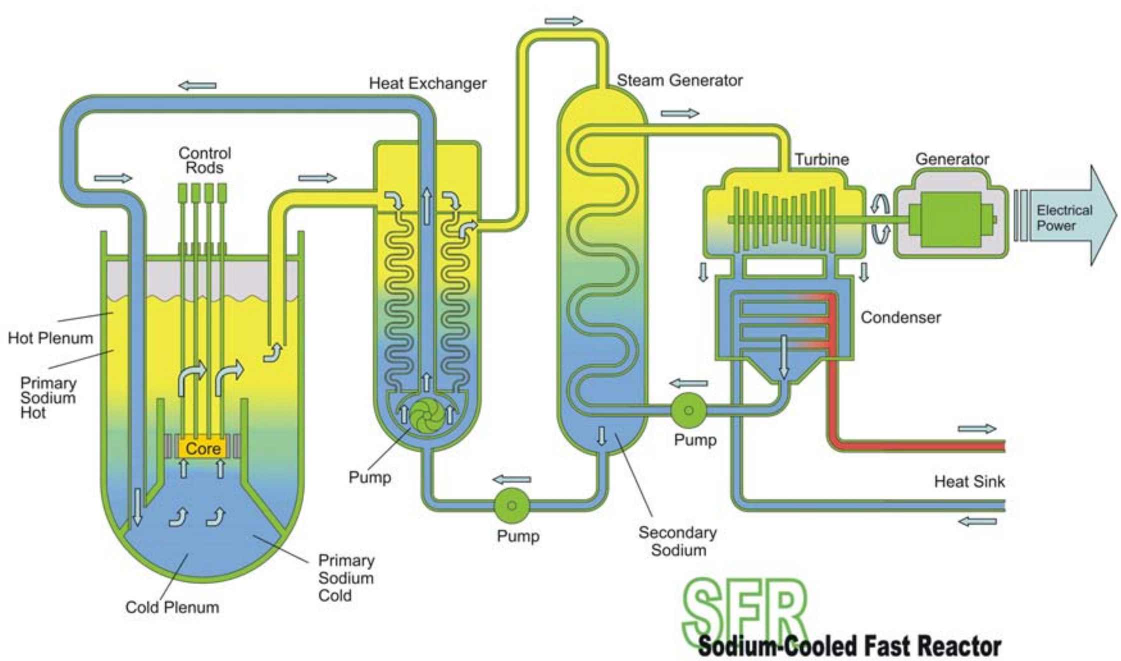

Figure 5.8. Compact loop SFR power plant system configuration.

The performance targets affecting the SFR development, in collaboration with GIF, include completion of the preconceptual reference design by 2007 and completion of the initial phase of materials research and reactor design by 2010 in order to select the preferred fast-spectrum system by the end of 2010.

The scope of the current SFR R&D Plan is to maintain the collaboration with GIF countries in the development of the system to meet the overall program goals of fast-spectrum system selection by 2010. The activities included under this R&D Plan are (1) interacting with GIF countries, (2) ensuring that the GIF R&D Plan addresses the needs and goals of the program, (3) maintaining awareness of the R&D progress and accomplishments under the GIF Plan, and (4) contributing to the GIF SFR R&D with relevant activities being performed under AFCI and Generation IV Programs in the U.S.

5.5.2 Highlights of Research and Development

Sodium-cooled systems have been significantly developed and may not require as much system design R&D as other Generation IV systems. R&D is nevertheless needed for demonstration of the design and safety characteristics, especially with fuels containing minor actinides, and to optimize the design with innovative approaches to meet the objectives of the specific missions of Generation IV, primarily actinide management and improved economics.

5.5.2.1 System Design and Evaluation. Overall R&D activities in this area are conducted under the GIF SFR R&D Plan.

Innovations for the SFR systems include means to reduce capital cost. Both economy of scale and economy of modular factory fabrication and just-in-time capacity additions are proposed. Recommended R&D also includes operations and maintenance items, such as the development of under-sodium viewing and/or ultrasonic testing in sodium, development of high-reliability steam generators, and development or selection of materials for components and structures. In reactor safety, the technology gaps center around three general areas: (1) basic properties, (2) assurance of passive safety response, including the modeling and validation of the models through experimentation, and (3) the technology for evaluation of bounding events.

5.5.2.2 Fuels and Fuel Cycle. SFR fuels will contain a relatively small fraction of minor actinides (MAs) and a small amount of fission products. The reactor systems based on mixed uranium-plutonium oxide fuel are primarily under development in Japan, and their preferred recycle option is an advanced aqueous process. R&D will be needed to demonstrate high actinide recoveries (99.9%) and the proliferation resistance features of the process, as well as remote fabrication processes for ceramic fuels.

Metal-fueled reactor systems under development in the U.S. use a pyroprocessing recycle process as the preferred fuel cycle option. R&D is needed to conduct large-scale plutonium and MA extraction experiments from electrorefiners, work on electrorefiner salt cleanup and high-level waste form production in order to achieve high actinide recoveries (~99.9%), develop any secondary waste stream treatment, and complete certification of the two high-level waste forms (metal and ceramic) for repository disposal.

The GIF countries leading the development of the SFR will develop the draft strategy for PR&PP. Studies carried out under the AFCI program, related specifically to pyroprocessing of metal fuels, can complement the draft strategy.

Viability items for pyroprocessing, such as studies in the fuel cycle options for actinide management, are functionally part of the AFCI program and are not included in the SFR development plan under Generation IV.

A significant technology gap for fast-spectrum reactor systems using recycled fuel is the need for performance data and transient safety testing of fuel that has been recycled using prototypic processes.

5.5.2.3 Energy Conversion. The basic energy conversion R&D needed for SFR systems is (1) to establish the technical basis for coupling S-CO_2 Brayton cycles to SFRs and (2) to develop revolutionary steam generator technologies to minimize plant cost. The first activity, coupling to an S-CO_2 cycle, has been supported as part of Crosscutting Energy Products R&D before FY 2007. This work will be more directly focused on SFR application and supported directly by the U.S. Generation IV SFR option starting in FY 2007.

Brayton cycle development for application to the SFR is addressed in the GIF R&D Plan. SFR systems will also benefit from innovative BOP simplifications pursued under crosscutting activities in the U.S. Generation IV Program, as discussed under the Energy Conversion section of the Program Plan.

5.5.2.4 Materials. Materials issues include (1) fuel-cladding constituent interdiffusion behavior for MA-bearing fuels, (2) development of high-strength steels for use in structures and piping to improve economics and (3) improved materials for recycle systems. The FUTURIX-Materials Irradiation (MI) experiments that are part of the SFR scope in FY 2007 are also relevant to advanced materials development for SFR applications.

5.5.3 Fiscal Year 2006 Project Budget

The FY 2006 budget for SFR activities is shown in Table 5.5.

Table 5.5. FY 2006 budget profile for SFR activities ($K).

Task	FY-06
Integration and Design	60
Total	60

5.6 Molten Salt Reactor

5.6.1 System Description

MSRs are liquid-fueled reactors that can be used for production of electricity, actinide burning, production of hydrogen, and production of fissile fuels (Figure 5.9). Electricity production and waste burndown are envisioned as the primary missions for the MSR. Fissile, fertile, and fission isotopes are dissolved in a high-temperature molten fluoride salt with a very high boiling point (1,400°C) that is both the reactor fuel and the coolant. The near-atmospheric-pressure molten fuel salt flows through the reactor core that contains graphite moderator. In the core, fission occurs within the flowing fuel salt that is heated to ~700ºC, which then flows into a primary heat exchanger where the heat is transferred to a secondary molten salt coolant. The fuel salt then flows back to the reactor core. The clean salt in the secondary heat transport system transfers the heat from the primary heat exchanger to a high-temperature Brayton cycle that converts the heat to electricity. The Brayton cycle (with or without steam bottoming cycle) may use either nitrogen or helium as a working gas.

The R&D strategy for the MSR is driven by three factors: (1) the MSR programs of the 1950s and 1960s that provided the technological foundation, (2) the technological overlap between the development needs for the MSR and other DOE programs, particularly the Generation IV NGNP and the NHI, and (3) the European Community MSR programs. The technologies being developed for the NGNP provide the basis for an Advanced Molten Salt Reactor (AMSR) with improvements in economics and reductions in R&D requirements for the MSR.

The overall MSR timeline includes determining viability by 2015. Because the basic technology of the MSR has been demonstrated, viability is defined as sufficient information to make a credible determination on the commercial feasibility of an MSR for power generation or viability to meet one of the new missions proposed for the MSR such as actinide burning.

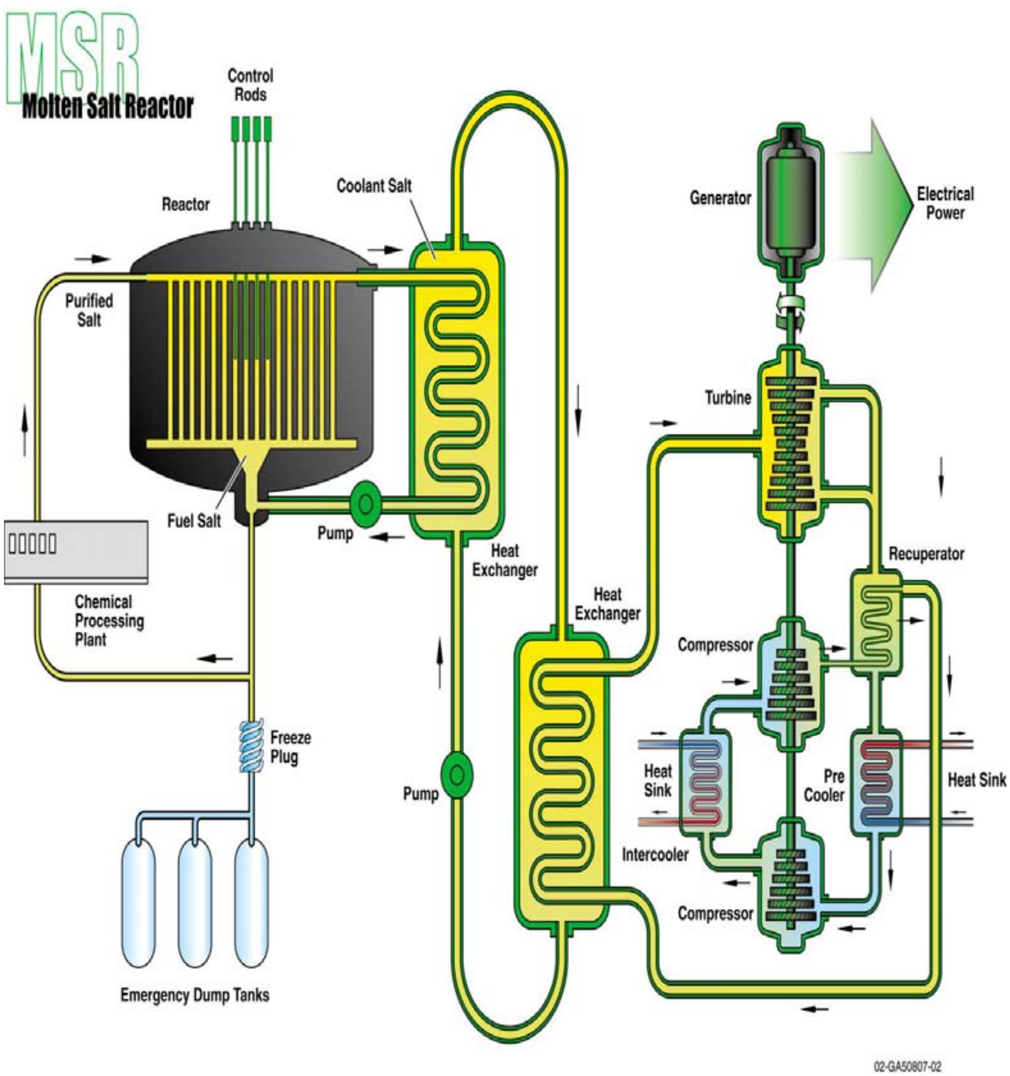

Figure 5.9. MSR with Brayton power cycle.

The scope of the MSR includes: (1) developing a conceptual design of an AMSR to provide an understanding of the economics, (2) developing the technologies to the point that there is a reasonable confidence that an MSR could be fully developed, and (3) assessing and developing the associate fuel-cycle technologies to understand the capabilities of MSRs for multiple missions, such as actinide burning.

5.6.2 Highlights of Research and Development

Because of ongoing synergistic programs, major advances in development and understanding of MSRs are expected to occur within the next decade with a modest investment of resources. This should enable the program to develop a credible understanding of the economics, capabilities to perform alternative missions (electricity, hydrogen, actinide burning, and fuel production), and issues associated with a modern MSR and, thus, provide the basis for a decision on whether to initiate a large-scale developmental program with the goal of deployment.

5.6.2.1 System Design and Evaluation. The goal of the system design and evaluation studies is to optimize system design for a modern MSR. Since development of detailed conceptual designs for large MSRs in the 1960's, major changes in goals, regulatory requirements, and technologies have occurred that have not yet been integrated into the conceptual design approach for a next generation MSR.

The objective of the design optimization work is to determine the characteristics and design parameters of a modern, optimized MSR. Three major changes must be incorporated into a modern MSR design.

1. The new high-temperature NGNP technologies (such as Brayton cycles)
2. Advances in non-NGNP technologies, such as remote operations, robotics, and controls
3. Changing mission requirements (from fuel production to actinide burner and hydrogen missions) that will simplify the plant design.

The current regulatory structure was developed with the concept of solid-fuel reactors, but liquid fueled reactors use different approaches to reactor safety than solid fueled reactors. The comparable regulatory requirements for this system must be defined. Using current tools, appropriate safety analysis is required followed by appropriate research on the key safety issues.

The critical safety requirement for an MSR is that the radionuclides remain dissolved in the molten salt under all conditions. The reactor size, design, and safety systems are dependent upon this property. There are two basic R&D tasks: (1) determine the limits of the solubility of trivalent actinides in candidate molten salts and (2) assure control of noble metal fission products in the primary system.

5.6.2.2 Fuels and Fuel Cycle. Development of an MSR involves multiple fuel cycle challenges that are currently being coordinated in the AFCI program at the systems level. More detailed efforts will be required in the future.

5.6.2.3 Energy Conversion. The goal of the energy conversion R&D is to establish the technical basis for coupling Brayton cycles for electricity production and thermochemical water cracking cycles for hydrogen production to MSRs. These activities are expected to take place as part of an effort on Crosscutting Energy Conversion R&D. Development of Heat Exchangers for Coupling to Energy Conversion Systems R&D will be coupled to that of the Crosscutting Energy Conversion R&D. Development of Multi-reheat Brayton Power Cycles R&D will be coupled to that of the NGNP program.

5.6.2.4 Materials. The major goal of the materials R&D is to identify and qualify materials with properties appropriate for MSR operating conditions, including corrosion resistance, mechanical performance, and radiation performance. The primary materials of interest are the moderator (graphite) and the reactor vessel/primary loop alloy (presently a Ni-based alloy). It is also necessary to develop corrosion control and coolant monitoring strategies for protecting the reactor vessel and primary piping alloys.

Candidate salts and materials will be selected and materials testing will take place over the range of temperatures, flows, and stresses expected in the MSR system. Candidate materials and salts will be irradiated under expected neutron spectrum conditions to screen them for adequate mechanical performance, dimensional stability, and corrosion resistance. Advanced, mechanistically-based models for radiation performance will be developed as a crosscutting activity.

5.6.3 Fiscal Year 2006 Project Budget

The ten-year budget projection includes two classes of activities. The first is activities that support GIF R&D planning and coordination. As shown in table 5.6, this is the only class of activities included in the Fiscal Year (FY) 2006 budget. The second is those associated with the R&D program. Funding requirements are being defined. The program is based upon input from European GIF activities and the relevant U.S. NGNP activities aimed at providing a basis for an advanced MSR.

Table 5.6. FY 2006 budget profile for MSR activities ($K).

Task	FY-06
GIF R&D Planning and Coordination	40
Total	40

5.7 Design and Evaluation Methods

5.7.1 Crosscut Description

The design of Generation IV systems will require simulation capabilities that provide accurate predictions of system performance. Viability of new technologies and design features will require confirmation by credible analyses verified with experimental data. Credible analyses will also be required as the basis for regulatory reviews and licensing of Generation IV designs of choice. The required simulation capabilities include computer codes and databases for simulating neutronic, thermal-hydraulic, and structural behavior in steady-state and transient conditions. For each system and type of analysis, the adequacy of existing analysis tools will need to be assessed and the required enhancements to their capabilities implemented and qualified. Many of the required analytical capabilities are crosscutting in that they are applicable to multiple Generation IV systems.

The objectives of the Generation IV D&EM R&D activities are to:

- Enable cost-effective development of high-performance Generation IV systems by providing capabilities for system design development, safety enhancement, and performance optimization
- Provide methodologies for measuring the performance of Generation IV systems against Generation IV technology goals
- Support R&D prioritization based on results of system design analyses and performance evaluations
- Form the groundwork for safety review, licensing, and regulation of Generation IV systems.

D&EM R&D addresses the need for validated analysis tools for design of Generation IV systems and confirmation of their safety. These analysis tools include modeling approaches, computer codes, and databases used to represent neutronic, thermal, fluid-flow, and structural phenomena in steady state and transient conditions. They also represent the mutual coupling among these phenomena and their coupling with additional phenomena (e.g., fuel behavior, fission gas release, materials damage, and chemical reactions) developed within other elements of the Generation IV, AFCI, and NHI programs.

A second major D&EM R&D area is to advance methodologies for evaluating overall system performance against Generation IV technology goals. This is accomplished through participation in the Methodology Working Groups (MWGs) established by the GIF.

The overall timeline for D&EM research conforms to the timelines currently foreseen for developing the Generation IV systems. Accordingly, the first five years are devoted to providing the capabilities needed for (1) resolution of viability issues for Generation IV systems, (2) development of high-performance NGNP and SFR designs, and (3) down-selection among reactor systems and options. Additionally, there is early emphasis on establishing the evaluation methodologies, so that they may be used in evaluating progress toward the Generation IV goals and in choosing among system design alternatives.

In the second five-year phase of the program, the analysis methods will be increasingly focused on the specific designs adopted for the NGNP and SFR systems and on the development of other Generation IV systems. These methods will be formally qualified for use in design development and licensing. Moreover, in this second phase the evaluation methodology efforts will be directed to supporting the application of the methodologies for evaluating the performance of selected system designs.

Work scope for D&EM consists of the following three components:

- ***Modeling Improvement:*** Planning, implementation, and qualification of analysis capabilities (computer codes and data) for designing Generation IV systems and confirming their safety
- ***Evaluation Methodologies:*** Development of methodologies for evaluating overall system performance and measuring progress toward the Generation IV technology goals
- ***D&EM Program Coordination:*** Work with Generation IV Program participants and international partners to advance design and evaluation methods in a coordinated and cost-effective manner.

5.7.2 Highlights of Research and Development

Highlights of the R&D directed toward improving modeling capabilities and evaluation methodologies are summarized below.

5.7.2.1 Modeling Improvement. Although CFD software has so far proven to be a useful design tool for LWR systems under normal operating conditions, its applicability for different types of coolants or for simulation of accident conditions remains to be established. To accomplish the Generation IV safety assurance objectives, creation of programs that increase the accuracy of CFD software, extend its range of applicability, and experimentally validate its predictions as an engineering simulation tool will be important. The initial focus will be on verifying the applicability of commonly used CFD software for different types of coolants, distinct heat transfer regimes, and a wide range of flow phenomena.

A crosscutting systems dynamics tool for consistent assessment of systems is needed. Planned activities include the evaluation, enhancement, and integration of modules from various system dynamics code versions that were previously developed for diverse reactor plant types. The proposed activity will advance such codes by integrating and validating existing capabilities and extending them for analysis of Generation IV systems.

The uncertainties in nuclear data for higher actinides are significant and affect predictions of isotopic inventories, decay heat, and radiation emission characteristics. Data requiring additional assessments include energy release per fission, spontaneous fission model parameters, fission product yields, half-lives, decay energies, decay branching ratios, and radiotoxicity factors. Improved data needs to be incorporated into inventory tracking tools to ensure that they give accurate results.

The recent and continuing growth in computer power motivate the assessment and further development of Monte Carlo-based analysis capabilities applicable to multiple reactor types. Enhancement of these codes will also be investigated, including the propagation of errors as a function of depletion, provision of temperature interpolation capability, and modeling of thermal-hydraulic feedback.

An integrated neutronic and depletion capability is needed for modeling non-equilibrium and equilibrium cycle operations of Generation IV systems, with representation of both their in-core and ex-core fuel cycle segments. Accurate modeling of systems with significant spectral gradients and changes of spectrum with depletion is a key requirement. The tool would employ advanced modules suitable for analysis of different Generation IV systems.

Uncertainties in reactor physics data lead to uncertainties in predictions of depletion-dependent system characteristics. By using sensitivity analysis methods, it is possible to avoid explicit recalculation of the effects for each data variation and at the same time to obtain information on additional data needs. This activity will develop an analytical tool for burnup-dependent sensitivity evaluation and models for evaluating the uncertainties in predicted performance characteristics for different Generation IV designs.

5.7.2.2 Evaluation Methodologies. An integrated nuclear energy economics model is central to standard and credible economic evaluation of Generation IV nuclear energy systems. The innovative nuclear systems considered within Generation IV require new tools for their economic assessment since their characteristics differ significantly from those of current Generation II and III nuclear power plants. In addition, the existing economic models were not designed to compare nuclear energy systems featuring innovative fuel cycles and capability for generation of electricity, hydrogen and other energy products and energy conversion technologies, or to evaluate economics of deployment in different countries or world regions. The GIF Economics Modeling Working Group is charged with developing an integrated economics model applicable to the comprehensive evaluation of the economic performance of Generation IV nuclear energy system.

Methodologies currently available for evaluating PR&PP of nuclear energy systems are limited by the lack of accepted figures of merit that provide a sufficient representation of system performance in these areas. A PR&PP MWG has been formed to develop an improved methodology for assessing Generation IV systems. This group is charged with developing a systematic method for evaluating and comparing the PR&PP of these systems, including their fuel cycle facilities and operations. To the maximum extent possible, a quantitative and standardized methodology is targeted as is the ability to identify system features that contribute to the overall resulting assessment of the comparative PR&PP of the system.

The approach for evaluating risk and safety of Generation IV systems and the technical basis for their future regulation need to be established. There is considerable incentive to define an evaluation methodology that is independent of system/technology and that can support safety and licensing reviews of Generation IV systems deployed in different countries or world regions. The GIF Risk and Safety Working Group was formed to support this aim and, in particular, to (1) specify safety and quality goals, and the methodology for evaluating system performance relative to these goals, (2) facilitate integrated consideration of safety and PR&PP goals, (3) provide recommendations to GIF on interactions with the nuclear safety regulatory community and other issues relevant to safety and regulation, and (4) interact with the Generation IV SSCs and project management boards to provide insights for the definition of the R&D that advances safety, reliability, and quality goals.

5.7.2.3 Design and Evaluation Methods Program Coordination. This D&EM program component provides for coordination and oversight of R&D activities directed to improve modeling capabilities and evaluation methodologies. It also provides for maintaining cognizance of related R&D activities conducted in other national and international programs, so that the benefits of those activities may be realized to the greatest extent possible by the Generation IV Program. Finally, it provides for periodic reporting of results to DOE, GIF, and their advisory review committees, and for participation in conferences, workshops, and educational forums.

5.7.3 Fiscal Year 2006 Project Budget

Major D&EM program components are supported by FY 2006 funding as shown in Table 5.7.

Table 5.7. FY 2006 budget profile for D&EM activities ($K).

Task	FY-06[a]
Coordination of Design and Evaluation R&D	160
Improvement of Design and Safety Analysis Capabilities	1,090
Development and Application of Evaluation Methodologies	1,107
Total	2,357

a. FY 2006 funding includes FY 2005 carryover funds.

5.8 Energy Conversion

5.8.1 Crosscut Description

Generation IV Energy Conversion R&D is investigating more efficient and cost effective energy conversion technologies for Generation IV reactors. Energy conversion technologies that optimize the use of the thermal output of advanced reactors will result in more efficient and cost effective nuclear electricity, a key metric for determining Generation IV system viability. The cost of electricity from a Generation IV reactor is proportional to capital cost recovery and operating costs divided by the net electrical output, or:

Cost ($/kW-hr) = (Capital Cost Recovery + Operating Costs)/(Electrical Output).

Improvements in plant efficiency, derived from improvements in the power conversion cycle, increase plant output directly. If the associated incremental cost for the more efficient power conversion cycle is relatively small compared to total plant capital costs, improvements in cycle efficiency have essentially the same result as direct reductions in plant construction and operating costs. There is significant motivation to develop power conversion systems (PCSs) that maximize the power output of Generation IV reactors.

The current suite of Generation IV reactors encompasses a wide range of thermal output conditions, and the type of power conversion cycle that is most appropriate depends on these thermal characteristics—primarily outlet temperature, system pressure, and working fluid characteristics. The Energy Conversion studies have focused on the PCSs for high-priority Generation IV reactor types:

- Metal-cooled or intermediate temperature reactor systems with outlet temperatures in the range of 500 to 700°C (SFR, LFR, and GFR)
- VHTR systems (i.e., the NGNP) with an inert gas coolant at outlet temperatures up to 1,000°C.

The primary focus of Energy Conversion R&D is the development of Brayton cycles for the metal-cooled, intermediate-temperature reactor systems. The S-CO_2 Brayton cycle provides high efficiency with relatively little increase in complexity and the potential for reduced capital cost. A smaller effort will address options for the NGNP to optimize efficiency and understand cost/efficiency trade offs. These studies are intended to provide a basis to evaluate future PCS design decisions for high-temperature Helium Brayton cycles for temperatures up to 1,000°C.

To provide the necessary power conversion cost and performance information needed the R&D effort will proceed in the following general sequence:

- 2006–2007

  Power conversion cycle analyses and conceptual designs to address viability issues and performance potential for S-CO_2 and Helium Brayton cycles

- 2008–2011

  Laboratory scale demonstrations of small-scale components and systems to demonstrate key technologies to validate performance potential

- 2011–2015

  Construction and demonstration of pilot scale systems to confirm engineering approach and performance, and refine cost estimates.

This sequence of power cycle analyses and small-scale component and system experiments will address key technology issues and uncertainties, and provide the basis for validated models to support the design of pilot scale experiments for selected systems. The pilot scale experiments will demonstrate engineering approaches, confirm performance potential, and refine estimates of PCS costs.

5.8.2 Highlights of Research and Development

Energy Conversion research activities to date addressed three primary areas:

1. S-CO_2 system and component issues, design, and performance
2. High-temperature Helium Brayton cycle efficiency improvement
3. Advanced heat transport configuration options for NGNP.

5.8.2.1 Supercritical Carbon Dioxide Brayton Cycle Research and Development

Status. The S-CO_2 Brayton cycle has been the focus of Energy Conversion research for the intermediate temperature reactors (500 to 700°C) due to the potential for very high efficiency and very compact turbomachinery, which has the potential for reduced PCS capital costs. Work at Massachusetts Institute of Technology (MIT) has developed preliminary turbine and compressor designs for S-CO_2 systems based on National Aeronautics and Space Administration design codes adapted for S-CO_2 working fluid properties. Designs for 300 MW_e turbines and compressors have been developed that are very compact (approximately 0.8 meters in diameter) and are also very efficient (~90%). A particularly unique requirement is the operation of the main compressor near the critical point of CO_2. Recent industry review studies have suggested radial compressors or mixed radial-axial stages for this application. Investigation of radial units for S-CO_2 compressors will be a priority for FY 2006. The initial assessment is that these components will require significant design efforts to accommodate the CO_2 working fluid conditions, but that these designs are feasible based on adaptations of current technology.

Conceptual designs for a 300 MW_e S-CO_2 plant have also been developed as a basis for preliminary cost and configuration evaluations. These system designs take advantage of the compact turbo-machinery and address the heat transfer issues associated with the lower thermal conductivity of CO_2, resulting in relatively compact PCSs for S-CO_2 in comparison with similar sized conventional Rankine or supercritical steam systems. Preliminary cost estimates, which will be revised as the design matures, indicate as much as a 20% reduction in the cost of an S-CO_2 plant in comparison with a similar sized supercritical steam system coupled to a high-temperature gas reactor. The key remaining issues requiring further analysis and experimental demonstration are associated with the main compressor, which operates very near the critical point of CO_2, and the related issue of overall system control strategy with the split flow, two-compressor configuration. These issues are currently being addressed in analytic studies, but will ultimately require experimental validation in scaled S-CO_2 system or component tests.

Evaluation of the dynamic response of the S-CO_2 cycle is a key issue for system viability. Work has been initiated at Argonne National Laboratory (ANL) to investigate control strategies for this cycle, and work is underway at both ANL and MIT to develop improved models for simulating the dynamic response of these systems. The goal of power cycle control is to adjust the cycle conditions such that in steady state, heat removal from the reactor matches the load demand from the electric grid. There are several approaches to decreasing the generator power which involve either reducing the power produced by the turbine, increasing the power consumed by the compressors, or decreasing the heat addition to the cycle. Initial studies examined several possible approaches: in-reactor heat exchanger bypass, turbine inlet throttle valve, turbine bypass, inventory control, and flow split control. Analysis of S-CO_2 control strategies will continue to be a priority for FY 2006.

5.8.2.2 High-Temperature Helium Brayton Cycle Studies. High-temperature Helium Brayton cycle studies have examined the cost and efficiency implications of interstage heating/interstage cooling modifications to the standard recuperated Brayton cycle. The added complexity results in some increased capital cost, but the efficiency improvements are significant and effectively leverage the cost of the nuclear system as well as the PCS.

Observations from the current studies show that for closed recuperated Brayton cycles, the use of multiple expansion and reheat stages can:

- Increase cycle efficiency by 8 to 12% over the single-stage compression recuperated Brayton and 5 to 8% over the two-stage compression recuperated Brayton cycle (for the same turbine inlet temperature)
- Reduce the size of the input heat exchanger by 10 to 20%, the rejection heat exchanger by 15 to 25%, and the recuperator heat exchanger by a factor of 2
- Increase the PCS energy density by a factor of 1.5.

Systems with similar efficiency and power density are possible with most of the major PCS design options (vertical versus horizontal, single versus multiple shaft, distributed versus integrated layout, and working fluid choices). Maintenance implications, accessibility and reliability, etc. may end up being the differentiating considerations. PCS technology options also include variations on the cycle operating conditions and the cycle type that can have an important impact on performance and cost. Some of the observations from this assessment of these factors include:

- Direct/Indirect—Efficiency loss can be 2 to 4%, depending on design, and the intermediate heat exchanger becomes a critical component at high temperatures. Maintainability is a key issue.
- Differences between helium and nitrogen working fluids were not considered critical for turbomachinery design. The primary difference is in the heat exchanger size to compensate for the lower nitrogen thermal conductivity.
- Nitrogen allows 3,600-rpm compressor operation at thermal powers at and below 600 MW_t, while helium compressors must operate at higher speeds requiring reduction gears, asynchronous generators, or multiple-shaft configurations. Turbomachinery tolerances for helium systems do not appear to be a key issue.

5.8.2.3 Advanced Heat Transport–Intermediate Loop. Coupling high-temperature reactor heat sources to hydrogen production systems or advanced electrical generation requires both efficient heat transfer and, in the case of hydrogen production, adequate separation of the facilities to assure that off normal events in the production facility do not impact the nuclear power plant. An intermediate heat transfer loop will be required for both hydrogen production and indirect electrical cycles. The proposed NGNP facility is a dual-purpose facility that demonstrates both hydrogen and efficient electrical generation. Later plants could be single-purpose facilities, but at this stage of development, both single- and dual-purpose facilities need to be understood.

Several possible configurations for an intermediate heat transport system that transfers heat between the reactor primary system and the hydrogen and/or electrical generation plant were evaluated, including both direct and indirect cycles for the production of electricity. Both helium and liquid salts were considered as the working fluid in the intermediate heat transport loop. Thermal-hydraulic and cycle-efficiency evaluations of the different configurations and coolants estimated the sizes of components as an indication of the associated capital costs.

5.8.3 Fiscal Year 2006 Project Budget

The major Energy Conversion tasks are the development and scaled demonstration of the S-CO_2 cycle for intermediate outlet temperature Generation IV systems, and the evaluation and development of advanced technologies for performance improvement of high-temperature Helium Brayton cycles for very-high-temperature Generation IV systems. The FY 2006 budget associated with these major activities are summarized in Table 5.8.

Table 5.8. FY 2006 budget profile for Energy Conversion activities ($K).

Energy Conversion	FY-06[a]
Total	1,322

a. FY 2006 funding includes FY 2005 carryover funds.

5.9 Materials

5.9.1 Crosscut Description

The National Materials Crosscut Program (NMCP) is an integrated R&D program which will be conducted to study, qualify, and, in some cases, develop materials with properties required for the Generation IV advanced reactor systems. The objective of the NMCP is to ensure that the required Generation IV materials R&D program will comprise a comprehensive and integrated effort to identify and provide the materials data and its interpretation needed for the design, codification, licensing, and construction of the selected advanced reactor systems.

For the range of service conditions expected in Generation IV systems, including possible accident scenarios, sufficient data must be developed to demonstrate that the candidate materials meet the following design objectives:

- Acceptable dimensional stability including void swelling, thermal creep, irradiation creep, stress relaxation, and growth
- Acceptable strength, ductility, and toughness
- Acceptable resistance to creep rupture, fatigue cracking, creep-fatigue interactions, and helium embrittlement
- Acceptable chemical compatibility and corrosion resistance (including stress corrosion cracking and irradiation-assisted stress corrosion cracking) in the presence of coolants and process fluids.

Additionally, it will be necessary to develop validated models of microstructure-property relationships to enable predictions of long-term materials behavior to be made with confidence and to develop high-temperature materials design methodology for materials use, codification, and regulatory acceptance. The integrated Generation IV Materials R&D program is planned to provide materials data needed to design, license, and construct the NGNP soon after 2020 and to provide adequate data to assess the viability of the other Generation IV reactor systems by 2010.

The NMCP within the Generation IV Program will have responsibility for establishing and executing an integrated plan that addresses crosscutting, reactor-specific, and energy-conversion materials research needs in a coordinated and prioritized manner. Four interrelated areas of materials R&D are generally considered to crosscut all of the Generation IV reactor systems. They include:

1. Qualification of materials for service within the vessel and core of the reactors that must withstand radiation-induced challenges
2. Qualification of materials for service in the BOP that must withstand high-temperature challenges
3. Development of validated models for predicting long-term, physically-based microstructure-property relationships for the high temperatures, extended operation periods, and high irradiation doses that will exist in Generation IV reactors
4. Development of an adequate high-temperature-materials design methodology to provide a basis for design, use, and codification of materials under combined time-independent and time-dependent loadings.

5.9.2 Highlights of Research and Development

To make efficient use of program resources, the development of the required databases and methods for their application must incorporate the extensive results from both historic and ongoing programs in the U.S. and abroad that address related materials needs. These would include, but not be limited to, DOE, NRC, and industry materials research programs on liquid-metal, gas, and light-water-cooled reactors; fossil-energy and fusion materials research programs; and similar foreign efforts.

Since many of the challenges and potential solutions will be shared by more than one reactor system, it will be necessary to work with the SIMs for each individual reactor system. The range of requirements for each reactor's major components needs to be examined to ascertain what the materials challenges and solutions to those will be and to establish an appropriate disposition of responsibilities for the widely varying materials needs within the Generation IV Program. It is expected that there will be two primary categories for materials research needs:

- Materials needs that crosscut two or more specific reactor systems
- Materials needs specific to one particular reactor system or energy conversion technology.

When there are commonly identified materials needs for more than one system, it will be appropriate to establish a crosscutting technology development activity to address those issues. Where a specific reactor system has unique materials challenges, it will be appropriate to address those activities in conjunction with that particular reactor system's R&D.

Reactor-specific materials research that has been identified for the individual reactor and energy-conversion concepts includes materials that are compatible with a particular coolant or heat-transfer medium, as well as materials expected to be used only within a single reactor or energy conversion system, such as graphite, selectively permeable membranes, catalysts, etc. A special category of reactor-specific materials research will also include research that must be performed at a pace that would significantly precede normal crosscutting research in the same area (e.g., NGNP reactor system materials R&D).

While the current plan addresses materials issues for all the reactors currently being examined within the Generation IV Program, there is recognition that the plans to build a NGNP by about 2020 will strongly drive much of the materials research during the next ten years.

A final category of materials R&D that is recognized within the Generation IV Program is the materials needs for the development of fuels and reprocessing technology within AFCI and for the chemical processing equipment for NHI. While both AFCI and NHI are independent programs with their own research objectives and funding, their applications will contain many of the same conditions that exist for reactor systems and their components in the Generation IV Program, and hence, they may utilize a common set of structural materials. A special collaboration between these programs has been developed and is being maintained to help ensure that the materials R&D being conducted within them is coordinated to minimize duplication of effort and costs and to maximize mutually beneficial materials technology development and qualification.

5.9.2.1 Materials Crosscutting Tasks. This R&D area focuses on four key areas, described below.

- ***Materials for Radiation Service:*** In general, the performance of structural materials is limited by the degradation of physical and mechanical properties as a result of exposure to energetic neutrons or by exposure to the chemical environment provided by the primary coolant medium. Although there are very significant differences in operating environments between the various systems under consideration, it is possible to identify a number of common environmental features. Combining the evaluation of materials as a function of neutron exposure offers an opportunity for addressing the development and qualification of materials for multiple systems within a coordinated set of irradiation experiments. Evaluation of candidate materials that are applicable to multiple systems offers both an improved overall database and the potential for significant cost savings compared to conducting separate irradiation programs for each reactor system.
- ***Materials for High-Temperature Service:*** In the Generation IV Program, although the operating conditions vary significantly from one reactor system to the next, analysis indicates that significant commonality exists with regard to the selection of materials for their high-temperature structural

components. Even though many of the materials that will be required for construction of high-temperature, out-of-core components will be the same as those used for some in-core applications, the focus of this crosscutting technology development task will be on their unirradiated, high-temperature qualification. Short-term tensile and fatigue properties will be evaluated for these materials. Time-dependent creep and creep-fatigue will also be addressed since they are the primary limitations for materials use. To take full advantage of the potential of the reactor systems in the Generation IV Program, it will be necessary to utilize the advances made in structural materials technology, select the most promising candidate materials for higher temperature service, and move forward toward acceptance of these materials into the appropriate construction codes.

- ***Development of Microstructure-Properties Models:*** The development and evolution of the fundamental microstructural features that establish materials performance need to be understood to further improve material performance and/or ensure the very long operational life envisioned for Generation IV reactor systems. This will require a combination of theory and modeling activities tied to detailed microstructural characterization and mechanical property measurements. The models must be developed using the best current materials science practice in order to provide a sound basis for interpolating and extrapolating materials performance beyond experimental databases, as well as providing the fundamental understanding needed to make designed changes in material compositions and processing to achieve improved properties.
- ***Development of Improved High-Temperature Design Methodology:*** The objective of the HTDM task is to establish the improved and expanded structural design technology necessary to support the codification and utilization of structural materials in high-temperature Generation IV reactor system components. The temperatures and materials requirements of most Generation IV components exceed the time/temperature coverage currently provided by Subsection NH of Section III of the ASME B&PV, which governs the design and construction of elevated-temperature, Class 1 nuclear components. This task will provide the data and models required by ASME Code groups to formulate time-dependent failure criteria and assessment rules and procedures that will ensure adequate life for components fabricated from the metallic alloys chosen for Generation IV systems. The task will also provide the material behavior (constitutive) models for the detailed inelastic design analysis methods required by Subsection NH for accessing critical structural regions and will provide the simplified inelastic design analysis methods that are allowed for less critical regions and are used for preliminary design.

5.9.2.2 Reactor-Specific Materials. Reactor-specific materials research includes materials-compatibility with a particular coolant or heat-transfer medium used in a single reactor system, as well as structural materials expected to be used only within a single reactor or energy conversion system. Additionally, where research must be performed at a pace that would significantly precede cross-cutting research in the same area, it has also been classified as being reactor-specific. Reactor-specific research identified to date is described for each reactor system in Appendix 9.0 of this document (Volume II).

5.9.3 Fiscal Year 2006 Project Budget

Only the costs associated with the Materials Crosscut tasks are include in Table 5.9. Costs for materials activities associated with the specific reactor systems and NHI will be funded by those activities and are delineated elsewhere.

Table 5.9. FY 2006 budget profile for Materials activities ($K).

Task	FY-06[a]
Materials for Radiation Service	364
Materials for High-Temp Service	742
Microstructural Modeling	108
High-Temp Design Methodology[b]	326
System-Specific Materials[c]	147
National Materials Program Mgmt.	420
Total	2,107

a. FY 2006 funding includes FY 2005 carryover funds.
b. Detailed required materials database development to be provided under Materials for High-Temperature Service task.
c. Primary funding included in specific system and NTD budgets. Only coordination funding is shown above.

6. BUDGET SUMMARY

The FY 2006 budget profiles for the Generation IV nuclear energy systems and crosscut activities are displayed in Table 6.1. Table 6.2 shows the Generation IV Program FY 2006 budget.

Table 6.1. FY 2006 budget profile for Generation IV systems and crosscut activities ($M).

System or Crosscut	FY-06[a]
NGNP[b]	42.15
SCWR	0.83
GFR	1.48
LFR	1.35
SFR	0.06
MSR	0.04
D&EM[c]	2.36
Energy Conversion	1.32
Materials	2.11
Total	51.70

a. FY 2006 funding includes FY 2005 carryover funds
b. Includes AGR funding
c. Includes GIF evaluation methodology funding

Table 6.2. FY 2006 budget profile for Generation IV Program activities ($K)[a].

Work Breakdown Structure Element		ANL	BNL	INL	LANL	LLNL	ORNL	SNL	ID	HQ	Total
1.0	1.0 Technical Integration										
	1.01 Program Integration			978							978
	1.02 Program Controls								252		252
	1.03 Management Reserves									3,334	3,334
										Subtotal	4,564
2.0	NGNP [b]										
	2.01 Project Management			4,632							4,632
	2.02 Fuels			11,515					634		12,149
	2.03 Materials	500		6,056			6,552		1,000		14,108
	2.04 Design Development	1,006		3,729			6,512				11,247
	2.05 Other			14							14
										Subtotal	42,150
3.0	SCWR										
	3.01 Reactor Design	51		352							403
	3.02 Materials			410			30				440
										Subtotal	843
4.0	GFR										
	4.01 Reactor Design	442	100	237					95		
	4.02 Materials			207					400		874
	4.03 Fuels										607
										Subtotal	1,481
5.0	LFR										
	5.01 Reactor Design	304		52		229					585
	5.02 Materials	125		101	257	282					765
										Subtotal	1,350
6.0	SFR										
	6.01 Reactor Design	60									60
										Subtotal	60
7.0	MSR										
	7.01 Reactor Design						40				40
										Subtotal	40
8.0	Design & Evaluation Methods										
	8.01 Program Coordination	160									160
	8.02 Model Improvement	765		179			76				1,020
	8.03 RSICC						70				70
										Subtotal	1,250

Work Breakdown Structure Element		ANL	BNL	INL	LANL	LLNL	ORNL	SNL	ID	HQ	Total
9.0	Materials										
	9.01 Program Coordination						420				420
	9.02 Radiation Service						364				364
	9.03 High-Temp Service						742				742
	9.04 Microstructural Modeling						108				108
	9.05 HT Design Methodology						326				326
	9.06 Reactor-Specific						147				147
										Subtotal	2,107
10.0	Energy Conversion										
	10.01 Program Coordination							118			118
	10.02 Adv Electrical Conversion							150			150
	10.03 SC CO_2 Turbomach	241						623			864
	10.04 Adv Heat Transport			160				30			190
										Subtotal	1,322
11.0	Systems Analysis										
	Systems Analysis			112							112
										Subtotal	112
12.0	I-NERI										
	12.01 I-NERI Admin. Support	90		294			436		2,694		3,514
	12.02 I-NERI Research Projects									820	820
										Subtotal	4,334
13.0	13.01 NERI										
	13.01 NERI Research Projects								7,033		7,033
										Subtotal	7,033
14.0	GIF										
	14.01 GIF Support	46		331					400		777
	14.02 GIF Working Groups										0
	14.02.01 Economic Method						81		250		331
	14.02.02 PR&PP Method	126	220						348		694
	14.02.03 Risk & Safety Method			82							82
										Subtotal	1884
Total		3,916	319	29,445	257	511	15,903	920	13,106	4,154	68,531

a. FY 2006 funding includes FY 2005 carryover funds
b. Includes AGR funding

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