GENERATION IV NUCLEAR ENERGY SYSTEMS TEN-YEAR PROGRAM PLAN

Fiscal Year 2005

Volume I

Released March 2005

Office of Advanced Nuclear Research

DOE Office of Nuclear Energy, Science and Technology

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 2005. However, the Generation IV research & development (R&D) plans continue to evolve, and this document will be updated annually or as needed. Even as this Program Plan is being released, several system R&D 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:

David W. Ostby, Technical Integrator
Generation IV program
Idaho National Laboratory
P.O. Box 1625
2525 N. Fremont
Idaho Falls, ID 83415-3865
USA

Tel: (208) 526-1288
FAX: (208) 526-2930
Email: david.ostby@inl.gov

GENERATION IV NUCLEAR ENERGY SYSTEMS TEN-YEAR PROGRAM PLAN Fiscal Year 2005

Volume I

March 2005

Idaho National Laboratory
Idaho Falls, Idaho 83415

Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

This page intentionally left blank.

EXECUTIVE SUMMARY

As reflected in the U.S. *National Energy Policy* [1], nuclear energy has a strong role to play in satisfying our nation's future energy security and environmental quality needs. The desirable environmental, economic, and sustainability attributes of nuclear energy give it a cornerstone position, not only in the U.S. energy portfolio, but also in the world's future energy portfolio. Accordingly, on September 20, 2002, U.S. Energy Secretary Spencer Abraham announced that, "The United States and nine other countries have agreed to develop six Generation IV nuclear energy concepts[2]." The Secretary also noted that the systems are expected to "represent significant advances in economics, safety, reliability, proliferation resistance, and waste minimization." The six systems and their broad, worldwide research and development (R&D) needs are described in *A Technology Roadmap for Generation IV Nuclear Energy Systems*[3] (hereafter referred to as the Generation IV Roadmap). The first 10 years of required U.S. R&D contributions to achieve the goals described in the Generation IV Roadmap are outlined in this Program Plan.

Vision

The *National Energy Policy* issued by the Bush Administration in May 2001 recommended an expansion of nuclear energy in this country and development of both advanced nuclear fuel cycles and next generation reactor technologies and advanced reprocessing and fuel treatment technologies. Recent studies by the Massachusetts Institute of Technology (MIT)[4] and National Laboratory Directors[5] have also emphasized the need for growth in nuclear power. To achieve this vision, the United States must be a worldwide leader in the development and demonstration of technical options that:

- Expand the use of nuclear energy worldwide
- Effectively manage radioactive waste
- Reduce the threat of nuclear material misuse
- Enhance national security.

To achieve this vision, the Department of Energy (DOE) Office of Advanced Nuclear Research (NE-20) has adopted an integrated strategy formulated in three mutually complementary programs: the Generation IV Nuclear Energy Systems Initiative (Generation IV), the Nuclear Hydrogen Initiative (NHI), and the Advanced Fuel Cycle Initiative (AFCI). Generation IV furthers this vision beyond previous energy systems, such as Generation III+ and NP2010 systems, through incremental improvements in economic competitiveness, sustainability[i], development of passively safe systems, and breakthrough methods to reduce the routes of nuclear proliferation.

---

i. The term sustainability denotes the ability of systems, such as nuclear energy systems, to provide their benefits indefinitely into the future without placing undue burdens on society. These burdens could arise from the generation of large quantities of nuclear waste for ultimate disposal in geological repositories, or from the depletion of indigenous uranium ore resources. Advanced systems that generate much less nuclear waste and better utilize the energy content of the uranium are more sustainable than today's generation of reactors.

Mission

The Generation IV, AFCI, and NHI combined will develop the next generation of nuclear energy systems capable of providing clean, affordable energy for generations of Americans, by:

- Developing and demonstrating advanced nuclear energy systems that meet future needs for safe, sustainable, environmentally responsible, economical, proliferation-resistant, and physically secure energy (Generation IV and NHI).

- Developing and demonstrating technologies that enable the transition to a stable, long-term, environmentally, economically, and politically acceptable advanced fuel cycle (AFCI).

Generation IV supports this mission through the development of innovative, next-generation reactor technologies. Within Generation IV, the Next Generation Nuclear Plant (NGNP) project is developing advanced high-temperature, gas-cooled reactor technology options leading to a demonstration of the capability of this technology to power the economic production of hydrogen and electricity. The Generation IV program is also investing in the development of next generation fast-neutron spectrum reactor technologies that hold significant promise for advancing sustainability goals and reducing nuclear waste generation. The national benefit of a new fleet of Generation IV reactors will far exceed that of today's reactor fleet.

Closely coupled to the Generation IV program is the NHI, which contributes to the integrated mission by demonstrating hydrogen production technologies using nuclear energy. This initiative will develop hydrogen production technologies that are shown to be compatible with nuclear energy systems through scaled demonstrations. A commercial-scale hydrogen demonstration plant could be coupled with a Generation IV demonstration facility by the middle of the next decade.

Achieving the vision of sustainable growth of nuclear energy in the U.S. will also require that our country transition from the current once through fuel cycle to an advanced fuel cycle that recycles nuclear materials. The Advanced Fuel Cycle Initiative (AFCI) is a focused R&D program whose technologies will enable this transition in the most efficient manner. AFCI will develop fuel systems for Generation IV reactors and create enabling fuel cycle technologies (i.e., fuel, cladding, separations, fuel fabrication, waste forms, and disposal technology) to significantly reduce the disposal of long-lived, highly radiotoxic transuranic isotopes while reclaiming spent fuel's valuable energy. AFCI technologies will support both current and future nuclear energy systems, including Generation IV systems, and emphasize proliferation resistant, safe, and economic operations. The AFCI is emphasizing the central role of systems analysis to define and assess the optimal deployment strategies, as well as the best possible transition from the current system to a future U.S. nuclear fuel cycle. The AFCI strategy for fuel cycle evolution is described more fully in the two 2005 AFCI reports to Congress (currently in draft)[6,7].

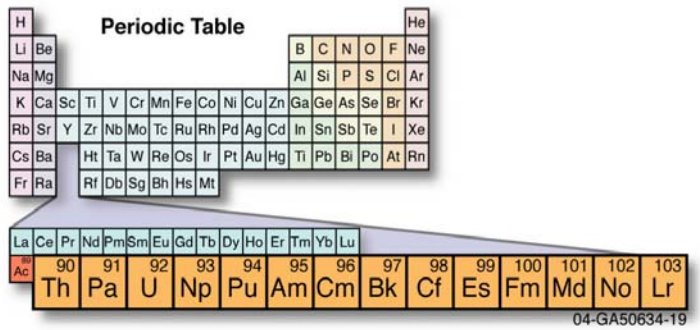
The Generation IV Roadmap identified the six most promising nuclear energy systems. The six are being pursued in the United States at varying levels based on their technology maturity and potential to meet program and national goals. Two systems employ a thermal neutron spectrum with coolants and temperatures that enable hydrogen or electricity production with high efficiency (the Supercritical Water-cooled Reactor [SCWR] and the Very High Temperature Reactor [VHTR]). Three employ a fast neutron spectrum to enable more effective management of actinides (see sidebar below) 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 and may provide an alternative to accelerator-driven systems for waste transmutation.

Strategy

As indicated above, several of the Generation IV systems are particularly well suited to meet U.S. national energy needs. The U.S. strategy includes development of reactor systems (as outlined in *The U.S. Generation IV Implementation Strategy*[8]) as well as leveraging international cooperation through the Generation IV International Forum and bi- and multi-lateral collaborations. *The U.S. Generation IV Implementation Strategy*[8] was developed by the DOE Office of Nuclear Energy, Science and Technology (NE) in FY 2003 and focuses the program on two principal goals:

Goal 1: Develop a Next Generation Nuclear Plant (NGNP) to achieve economically competitive hydrogen and electricity production in the mid-term.

What are Actinides?



Actinides are a series of radioactive metallic elements with atomic numbers from 90 to 103.

Why do they matter?

The minor actinides are neptunium (Np), plutonium (Pu), americium (Am) and curium (Cm).

Minor actinides affect repository performance by dominating long-term heat load and long-term radiotoxicity.

Minor actinides can be destroyed while producing extra energy if recycled in nuclear reactors.

The NGNP R&D is presently based on the Generation IV VHTR design, i.e., a prismatic or pebble-bed, high-temperature, gas-cooled reactor that is able to economically produce hydrogen and electricity. Use of a liquid-salt coolant is also being evaluated. The high priority on developing a capability for nuclear-generated hydrogen with the NGNP reflects the excellent potential for this system to provide a major competitive advance toward the long-standing need to diversify the energy supply of the U.S. transportation sector and to do this in a manner that is essentially emissions-free. Successful development and demonstration of an economically competitive, emissions-free, nuclear-generated hydrogen supply will be the focus of a government-laboratory-industry-international collaboration to design, develop, construct, and operate an NGNP that is dedicated to hydrogen production research and demonstration.

The NGNP program is projected to complete its key R&D by about 2012. This is partially enabled by many prior international developments in high-temperature, gas-cooled reactors. As a result, completion and startup of a demonstration NGNP is targeted for 2017. The startup test program will include an extensive integral system safety test and demonstration phase that will form part of the safety basis for future U.S. Nuclear Regulatory Commission commercial licensing. The development of an NGNP would have a number of associated benefits, including the establishment of a technical basis for development of a fast-spectrum gas reactor, as discussed in the next section.

Goal 2: Develop a fast reactor to achieve significant advances in sustainability for the long term.

The priority on fast reactors reflects their excellent potential to make significant gains in reducing the volume and radiotoxicity, and increasing the manageability, of spent nuclear fuel. With a successful fast reactor program, the United States may be able to avoid the need for a second geological repository for many decades. Fast reactors also hold the potential for extending the useful energy yield of the world's finite uranium supply many-fold for long-term sustainable nuclear energy.

The principal issues in the development of a next-generation fast-spectrum reactor for use in the United States are its economic competitiveness and management of the overall risks to workers and the public from the deployment of a closed fuel cycle. The most promising fast-spectrum Generation IV systems are the GFR, LFR, and SFR. Among these, the GFR and LFR will be given the most emphasis in resolving technical issues and uncertainties since these reactors offer strong potential benefits that have not been fully demonstrated. The SFR is already at a fairly advanced state of development with many of its technologies having been demonstrated internationally. All of these systems will be brought to a state where a down-selection can be undertaken based on demonstrated performance of their economic viability, safety and reliability, sustainability, and proliferation resistance and physical protection. The Generation IV program gives the highest priority to advancing the GFR and LFR while monitoring the progress of the SFR internationally.

Additional Generation IV Systems

The goals identified in the Implementation Strategy specify the direction of the major thrusts in the Generation IV program. However, the program also addresses those systems not in the forefront of U.S. development but which have significant international interest in their potential. The Generation IV Roadmap identified six most promising systems, four of which are mentioned above. The additional two are the SCWR and the MSR. The SCWR employs water above the critical temperature and pressure that affords a considerable increase in thermal efficiency as well as major simplifications and savings in the balance of plant. The MSR employs a circulating liquid fuel mixture that offers considerable flexibility for recycling actinides and may provide a favorable alternative to accelerator-driven systems for actinide destruction. The Generation IV program includes significant international collaborative efforts on the SCWR and exploratory collaborations on the MSR.

Organization

The Generation IV program organization was created to advance the systems as well as the many R&D needs that are common to two or more of the systems. Thus, each of the six Generation IV systems has a System Integration Manager (SIM) who is responsible for ensuring that R&D is focused on the highest priority needs of their system. In addition, National Technical Directors (NTDs) serving both Generation IV and AFCI are responsible for Systems Analysis, System Design & Evaluation Methods, Energy Conversion, Materials, Fuels, Separations, and Transmutation to focus R&D resources on needs identified by two or more systems that benefit from a common focus. In this way, R&D funds can be spent efficiently while the full scope of R&D requirements in each area can still be addressed. The Generation IV program has a Technical Integrator to plan the development of tasks and schedules to ensure that all necessary R&D projects are being performed or planned for future investigation. Full integration of the AFCI and Generation IV R&D activities are overseen by a common Systems Analysis function that guides the development of system requirements and interfaces. The emerging NHI program is also being closely integrated, primarily with the NGNP project that will demonstrate its technologies first.

Key Research & Development and International Collaboration

As described in the Generation IV Roadmap, the R&D is expected to span as much as 30 years for some of the systems. The scope of R&D found in this plan includes the outlook for the next 10 years from the date of this revision. The R&D priorities over the next 10 years are focused on four key areas of development (see Section 5 for project-specific details):

- Systems Design and Evaluation
- Fuel and Fuel Cycles
- Energy Conversion
- Materials.

This R&D provides the major building blocks necessary to support the NGNP and the preferred fast reactor concept over the next 10 years. Specific R&D milestones and activities are outlined in this Program Plan. The R&D will be performed in collaboration with GIF partner countries. The division of responsibilities for specific R&D tasks is still being negotiated, along with the enabling multilateral agreements.

This page intentionally left blank.

CONTENTS

EXECUTIVE SUMMARY iii

Vision iii

Mission iv

Strategy v

Additional Generation IV Systems vi

Organization vi

Key Research & Development and International Collaboration vi

FIGURES xii

TABLES xiii

ACRONYMS xv

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

2. GENERATION IV PROGRAM DESCRIPTION 1

2.1 Introduction 1

2.1.1 U.S. Energy Demand Outlook 2
2.1.2 The Generation IV Roadmap 3
2.1.3 Generation IV Mission Needs 4

2.2 Goals for the Generation IV program 5

2.2.1 Timelines 7

2.3 R&D Programs for Individual Generation IV Systems 7

2.4 Performance Indicators and Exit Criteria 9

2.4.1 Performance Indicator Outputs 9
2.4.2 Performance Indicator Outcomes 10
2.4.3 Exit Criteria 10

2.5 International Program Implementation 11

3. PROGRAM ORGANIZATION AND RESPONSIBILITIES 12

3.1 Organizational Structure 12

3.2 Roles and Responsibilities 13

3.2.1 DOE Office of Nuclear Energy, Science, and Technology 15
3.2.2 Integrated Generation IV, AFCI, and NHI Function Teams 15
3.2.3 Systems Analysis 16
3.2.4 System Integration Teams 17
3.2.5 National Technical Directors 17
3.2.6 Technical Integration 17
3.2.7 Project Controls 17

3.3 Generation IV Program Management Processes 18

3.4 Key Program Assumptions, Uncertainties, and Risks 18

3.4.1 Assumptions and Uncertainties 18
3.4.2 Technical Risks: Viability Phase to Performance Phase Transition 19
3.4.3 Programmatic Risks 19

4. PROGRAM INTERFACES 20

4.1 External 20

4.1.1 Nuclear Energy Research Advisory Committee 20
4.1.2 Nuclear Regulatory Commission 20
4.1.3 International Partners 20
4.1.4 University Partners 20

4.2 Internal DOE Interfaces 21

4.2.1 Nuclear Power 2010 Program 21
4.2.2 Advanced Fuel Cycle Initiative 21
4.2.3 Nuclear Hydrogen Initiative 22

5. GENERATION IV R&D PLANS 23

5.1 NGNP 23

5.1.1 System Description 23
5.1.2 Highlights of R&D 24
5.1.3 10-yr Project Budget 28

5.2 Supercritical Water Reactor 28

5.2.1 System Description 28
5.2.2 Highlights of R&D 30
5.2.3 10-yr Project Budget 31

5.3 Gas-Cooled Fast Reactor 31

5.3.1 System Description 31
5.3.2 Highlights of R&D 34
5.3.3 10-yr Project Budget 34

5.4 Lead Fast Reactor 35

5.4.1 System Description 35
5.4.2 Highlights of R&D 36
5.4.3 10-yr Project Budget 38

5.5 Sodium-Cooled Fast Reactor 39

5.5.1 System Description 39
5.5.2 Highlights of R&D 41
5.5.3 10-yr Project Budget 41

5.6 Molten Salt Reactor 41

5.6.1 System Description 41
5.6.2 Highlights of R&D 42
5.6.3 10-yr Project Budget 42

5.7 Design and Evaluation Methods 43

5.7.1 Project Description 43
5.7.2 Highlights of R&D 44
5.7.3 10-yr Project Budget 46

5.8 Energy Conversion Crosscut 46

5.8.1 Project Description 46
5.8.2 Highlights of R&D 47
5.8.3 10-yr Project Budget 49

5.9 Materials Crosscut 50

5.9.1 Project Description 50
5.9.2 Highlights of R&D 51
5.9.3 10-Yr Project Budget 52

6. SUMMARY 53

7. REFERENCES 56

FIGURES

Figure 2.1 Projected U.S. Energy Demand ... 3

Figure 2.2 Projected U.S. Transportation Energy Demand ... 3

Figure 2.3 Timelines for U.S. Goals 1 and 2 ... 7

Figure 2.4 GIF Participating Nations ... 11

Figure 3.1 DOE-NE Organizational Structure ... 12

Figure 3.2 Generation IV Program Organizational Structure ... 13

Figure 3.3 AFCI, NHI, and Generation IV program Organizational Structure ... 14

Figure 3.4 Integrated Generation IV and AFCI ... 16

Figure 5.1 Sketch of how the NGNP might be configured to produce both electricity and hydrogen. ... 23

Figure 5.2 Methods development process ... 24

Figure 5.3 Conceptual SCWR system. ... 29

Figure 5.4 Conceptual GFR system. ... 32

Figure 5.5 Conceptual LFR system. ... 36

Figure 5.6 Basic SFR power plant system configurations ... 40

Figure 5.7 Molten Salt Reactor with Brayton Power Cycle ... 42

TABLES

Table 2.1 Generation IV Objectives & Endpoints 8

Table 5.1 NGNP annual budget profile ($K). 28

Table 5.2 Required SCWR Budget ($K). 31

Table 5.3 GFR 10-year project budget ($K).* 34

Table 5.4 Known and Proposed Budget for U.S. LFR R&D ($K) 38

Table 5.5 Ten-year budget profile for SFR activities ($K). 41

Table 5.6 Ten-year budget profile for MSR activities ($K). 43

Table 5.7 Design and Evaluation Methods Funding Requirements through FY 2014 ($K) 46

Table 5.8 Total Energy Conversion Planning Level Budget FY 2005- FY 2014 ($K) 50

Table 5.9 Funding Requirements for the Generation IV Materials Crosscutting Task ($K) 52

Table 6.1 Total Required Costs for FY 2005 to FY 2014 ($M). 53

Table 6.2 FY 2005 Generation IV R&D Funding at Level 3 by Performer $(K). 54

This page intentionally left blank.

ACRONYMS

AFCI	Advanced Fuel Cycle Initiative
AGR	Advanced Gas Reactor
CFD	Computational Fluid Dynamics
D&EM	Design and Evaluation Methods
DOE	U.S. Department of Energy
-NE	Office of Nuclear Energy, Science and Technology
-NE-20	Office of Advanced Nuclear Research
-NE-ID	Idaho Operations Office
-HQ	Headquarters
-RW	Office of Civilian Radioactive Waste Management
GFR	Gas-cooled Fast Reactor
GIF	Generation IV International Forum
GPRA	Government Performance Results Act
IHX	intermediate heat exchanger
INL	Idaho National Laboratory
ISI	In-Service Inspection
LFR	Lead-cooled Fast Reactor
LWR	Light Water Reactor
MIT	Massachusetts Institute of Technology
MSR	Molten Salt Reactor
NERAC	Nuclear Energy Research Advisory Council
NERI	Nuclear Energy Research Initiative
NGNP	Next Generation Nuclear Plant
NHI	Nuclear Hydrogen Initiative
NMCP	Nuclear Materials Crosscut Program
NNSA	National Nuclear Security Administration
NRC	U.S. Nuclear Regulatory Commission
NTD	National Technical Director
ORNL	Oak Ridge National Laboratory
PCHE	printed circuit heat exchangers
PCS	power conversion system
PICS	program integration and controls system
PR&PP	proliferation resistance and physical protection
R&D	research and development
SCWR	Supercritical Water-cooled Reactor
SFR	Sodium-cooled Fast Reactor
SIM	System Integration Manager
SSTAR	Small Secure Transportable Autonomous Reactor

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 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 10 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*[3] (hereafter referred to as the Generation IV Roadmap) will guide the research and development (R&D). This plan reflects the priorities of *The U.S. Generation IV Implementation Strategy*[4] reported to Congress in September 2003. The plan also 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). Detailed plans for the systems and crosscutting R&D are given in the nine technical appendices to this document.

2. GENERATION IV PROGRAM DESCRIPTION

The Generation IV program is managed by the DOE Office of Nuclear Energy, Science and Technology (NE) with the objective of advancing nuclear energy to meet future energy needs. Through a common interest in nuclear energy, the DOE and organizations in 10 other countries formed a framework for international cooperation known as the Generation IV International Forum (GIF)[ii].

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, including 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 United States. The Generation III nuclear systems were developed in the 1990s and include a number of evolutionary designs that offer significant advances in safety and economics. A number of Generation III systems have been built, primarily in East Asia.

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 16% of world demand.

2. Nuclear energy plays a large role in the U.S. economy. In 2002, the 103 operating U.S. nuclear power plants generated 790 billion kilowatt-hours of electricity valued at $50 billion.

3. Using nuclear energy, the United States has avoided over three billion tons of air emissions since 1970.

4. U.S. nuclear plants are highly reliable and in 2001 produced electricity for 1.68 cents per kilowatt-hour on average. This low cost is second only to hydroelectric power among base load generation options.

---

ii. Argentina, Brazil, Canada, Euratom, France, Japan, the Republic of Korea, the Republic of South Africa, Switzerland, the United Kingdom, and the United States currently constitute the GIF. New members can be added by a process outlined in the GIF charter.

5. In return for access to peaceful nuclear technology, over 180 countries have signed the 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) operators 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 medium and longer 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, 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 outlook for energy demand in the United States underscores the need to increase the share of nuclear energy production. The *Annual Energy Outlook,*[9] [iii] produced by the DOE Energy Information Administration, projects an annual growth rate of 1.5% in total energy consumption to the year 2025 (see Figure 2.1). At the same time, domestic energy production will grow only 0.9% per year, creating a widening gap to be filled by energy imports. Further, most of the projected domestic energy production increase is to be provided by coal and natural gas. Thus, the outlook implies an increasing burden from carbon emissions with the potential for long-term consequences from global climate change and an increasing dependence on foreign energy sources. These projections create a strong motivation for seeking to increase the share of nuclear-generated electricity above its current 20% level.

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. The *Annual Energy Outlook* projects an annual growth of 2.0% per year for the transportation sector (see Figure 2.2), while the electricity and heating sectors will grow at 1.4% and 1.2%, respectively. Transportation is almost exclusively dependent on petroleum. This dependence has caused fluctuations in fuel prices of 30% and several "energy shocks" since the 1970s. This volatility creates a significant need for seeking 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 are specialized for hydrogen production at competitive prices need to be developed.

Two long-term technology development objectives for nuclear energy in the United States are derived from the needs identified above:

1. Develop advanced nuclear energy systems that can address the barriers to growth and 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.

---

iii. The *Generation IV Implementation Strategy* was based on the *Annual Energy Outlook 2003*, which is substantially the same as the current update. The *Annual Energy Outlook 2005* has not yet been issued. The next revision to this plan will include any updates, accordingly.

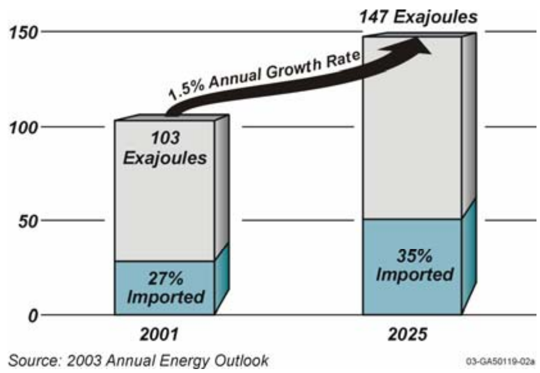


Figure 2.1 Projected U.S. Energy Demand

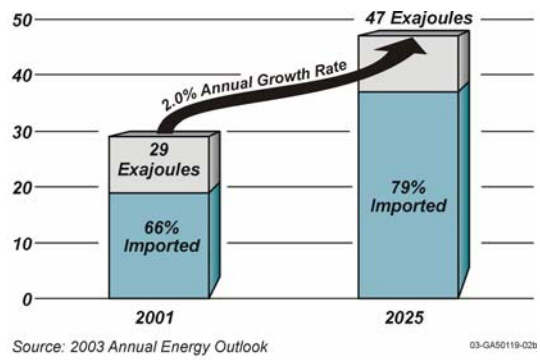


Figure 2.2 Projected U.S. Transportation Energy Demand

2.1.2 The Generation IV Roadmap

Beginning in January 2000, 10 countries and Euratom joined together to form the 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, 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 R&D necessary to support next-generation nuclear energy systems. From those discussions, a technology roadmapping effort was begun to guide the Generation IV systems. The effort was completed in two years, with the participation of over 100 experts from the GIF countries, and ended in December 2002 with the issue of the Generation IV Roadmap.[3] Especially noteworthy was the recognition gained by the United States for leading the formation of the GIF and the development of the Generation IV Roadmap. These efforts helped strengthen U.S. leadership in the peaceful uses of nuclear energy and underscore 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 scope of the R&D described in the Generation IV Roadmap 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 provides a foundation for formulating national and international program plans on which the GIF countries will collaborate to advance Generation IV systems.

As noted above, the Generation IV Roadmap identified the six most promising nuclear energy systems. Two employ a thermal neutron spectrum with coolants and temperatures that enable hydrogen or electricity production with high efficiency (the Supercritical Water-Cooled Reactor [SCWR] and the Very High Temperature Reactor [VHTR]). 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 and may provide an alternative to accelerator-driven systems for actinide destruction. Each of these systems is described in Section 5.

- Thermal-Spectrum Systems
  - Very-High-Temperature Reactor System
  - Supercritical-Water-Cooled Reactor System
- Fast-Spectrum Systems
  - Gas-Cooled Fast Reactor System
  - Lead-Cooled Fast Reactor System
  - Sodium-Cooled Fast Reactor System
- Liquid-Fuel System
  - Molten Salt Reactor System.

The Generation IV Roadmap defined a number of common, or crosscutting, R&D areas for the six selected reactor concepts. These areas included fuel cycle, fuels and materials, energy conversion, risk and safety, economics, and PR&PP. Many of the Generation IV reactor concepts share similar development needs. In total, the R&D recommended for crosscutting R&D is about equal to that for any particular concept.

2.1.3 Generation IV Mission Needs

The high-level objective of the Generation IV program is to advance the systems in accordance with DOE priorities for their deployment in the United States. The advancement of each system is measured in terms of its ability to meet the Generation IV mission needs. The mission needs have three purposes. First, they serve as the basis for developing criteria to assess and compare the systems in the Generation IV Roadmap. 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 mission needs for Generation IV (see below) are defined in the four broad areas of sustainability, economics, safety and reliability, and PR&PP. An abbreviated description of each, excerpted from the Generation IV Roadmap, is given 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 the conservation of resources, protection of the environment, preservation of the ability of future generations to meet their own needs, and the avoidance of 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 demands and long-term changes in energy use. Generation IV systems have mission needs 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 adequate, 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 such, the mission needs have been set to achieve high levels of safety and reliability through further improvements relative to current reactors. The three safety and reliability needs seek simplified designs that are safe and further reduce the potential for severe accidents and minimize their consequences. The achievement of these cannot rely only on technical improvements but they will also require 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, namely, 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 systems need to be designed from the start with improved physical protection against acts of terrorism to a level commensurate with the protection of other critical systems and infrastructure.

Mission Needs for Generation IV Nuclear Energy Systems

Sustainability-1 *Generation IV nuclear energy systems will provide sustainable energy generation that meets clean air objectives and promotes long-term availability of systems and effective fuel utilization for worldwide energy production.*

Sustainability-2 *Generation IV nuclear energy systems will minimize and manage their nuclear waste and notably reduce the long-term stewardship burden, thereby improving protection for the public health and the environment.*

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

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

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

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

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

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

The approach for achieving Generation IV mission needs is to undertake the R&D tasks outlined in the Generation IV Roadmap for the various systems and crosscutting technologies. The R&D tasks will be updated based on the key research findings that arise during the Generation IV effort over the subsequent years. Again, the tasks in the Generation IV Roadmap reflect current understanding of potential collaborative efforts by other countries and will be updated as multilateral agreements are finalized.

2.2 Goals for the Generation IV program

For each of the six systems , the Generation IV Roadmap develops the R&D needs in considerable detail and highlights the major R&D issues, benefits, and risks. The specific R&D issues and risks, identified in the Generation IV Roadmap 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. needs and technology objectives discussed above. From these studies and interactions, the following two principal priorities or goals emerged:

Goal 1: Develop an NGNP to achieve economically competitive hydrogen and electricity production in the mid-term.

The VHTR concept is considered the nearest-term reactor design that has the capability to efficiently produce hydrogen. 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 a full-scale prototype VHTR, or other commercially viable reactor technology, that is licensed by the U.S. Nuclear Regulatory Commission (NRC).
- Demonstrate safe and economical production of hydrogen and electricity using nuclear heat.

Goal 2: Develop a fast reactor to achieve significant advances in sustainability for the long term.

The high priority on fast reactors reflects their good potential to make significant gains in reducing the volume and radiotoxicity and increasing the manageability of spent nuclear fuel wastes. These advances may enable the United States to avoid a second geological repository. Fast 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 United States are its economic competitiveness and the associated deployment of a closed fuel cycle.

Three of the most promising Generation IV systems are fast-spectrum (the GFR, LFR, SFR) for enhanced sustainability, and one (the MSR) employs a reactor specialized for actinide destruction. Among these, the LFR and GFR will be given the most emphasis in resolving technical issues and uncertainties since these reactors offer strong potential benefits that have not been fully demonstrated. The SFR is already at a fairly advanced state of development, with many of its technologies having been demonstrated internationally. All of these systems will be brought 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 neutron 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.

The most direct influence of these goals for the U.S. Generation IV program is in the allocation of R&D resources among the systems in the program plan. An additional area of R&D is the crosscutting research needed by these systems. Arising from the common need for advances in fuels and materials, fuel cycle technology, and system design to achieve highly safe and reliable systems, these crosscut areas are given the most emphasis. Energy conversion technology is another important need also highlighted in the Program Plan. Specific, yet limited, activities are found in other crosscutting areas that are not as directly involved in the feasibility of these systems.

2.2.1 Timelines

Proposed timelines for the two goals are shown in Figure 2.3. The VHTR in Goal 1 shows a 12-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.

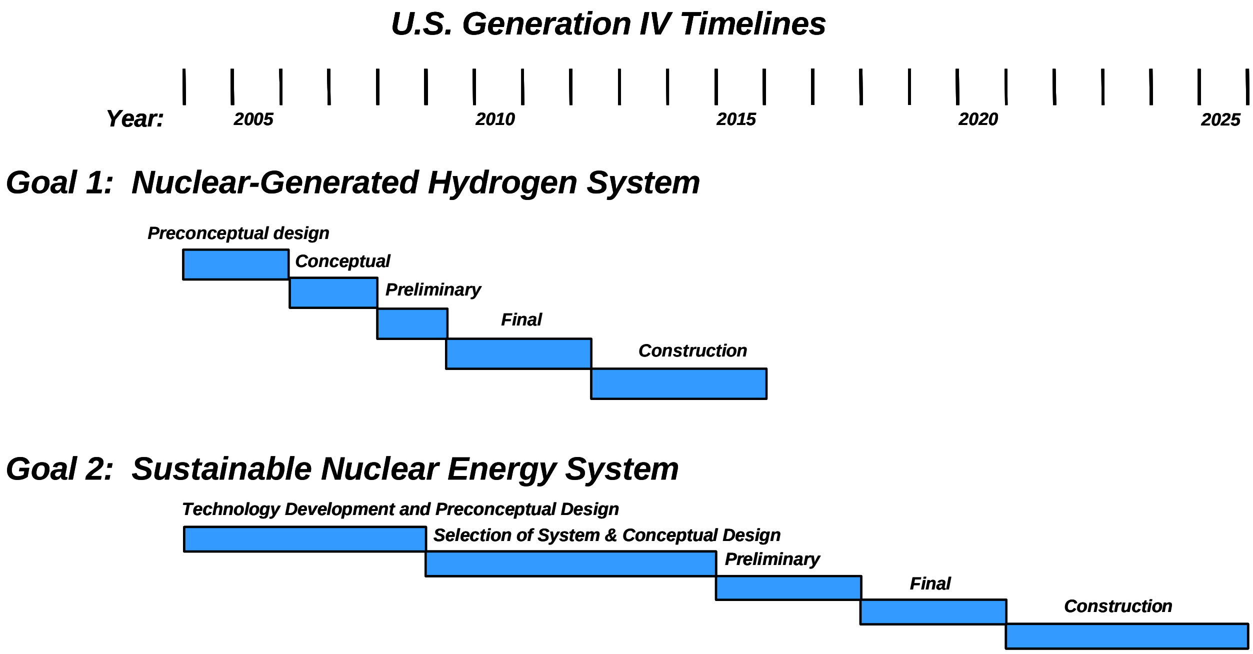


Figure 2.3 Timelines for U.S. Goals 1 and 2

The fast-spectrum reactor in Goal 2 shows a 20 to 25-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 a decade followed by a demonstration of all elements of a closed fuel cycle within a decade thereafter.

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

2.3 R&D Programs for Individual Generation IV Systems

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

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

Table 2.1 Generation IV Objectives & Endpoints

Viability Phase Objective:	**Performance Phase Objective:**
Basic concepts, technologies and processes are proven out under relevant conditions, with all potential technical *show-stoppers* identified and resolved.	Engineering-scale processes, phenomena, and materials capabilities are verified and optimized under prototypical conditions

Viability Phase Endpoints:	**Performance Phase Endpoints:**
1. Preconceptual design of the entire system, with nominal interface requirements between subsystems and established pathways for disposal of all waste streams	1. Conceptual design of the entire system, sufficient for procurement specifications for construction of a prototype or demonstration plant, and with validated acceptability of disposal of all waste streams
2. Basic fuel cycle and energy conversion (if applicable) process flowsheets established through testing at appropriate scale	2. Processes validated at scale sufficient for demonstration plant
3. Cost analysis based on preconceptual design	3. Detailed cost evaluation for the system
4. Simplified PRA for the system	4. PRA for the system
5. Definition of analytical tools	5. Validation of analytical tools
6. Preconceptual design and analysis of safety features	6. Demonstration of safety features through testing, analysis, or relevant experience
7. Simplified preliminary environmental impact statement for the system	7. Environmental impact statement for the system
8. Preliminary safeguards and physical protection strategy	8. Safeguards and physical protection strategy for system, including cost estimate for extrinsic features
9. Consultation(s) with regulatory agency on safety approach and framework issues	9. Pre-application meeting(s) with regulatory agency

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

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

Assuming the successful completion of viability and performance R&D, a *demonstration* phase of at least six years is anticipated for any system, requiring funding of several billion 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.

2.4 Performance Indicators and Exit Criteria

The high-level schedule of the Generation IV program is to develop next-generation nuclear energy systems for deployment in the 2015–2030 timeframe. To achieve this schedule, system designs must be developed to the point they are mature enough to evaluate their relative performance and select the best systems for deployment. System maturation is organized into the three phases of viability, performance, and demonstration discussed in Section 2.3. These phases coincide with the type of uncertainty reduction to be achieved by the related research.

Each successive phase of research involves larger-scale development and greater R&D costs per system. Down-selection of the number of systems will be necessary to manage total program R&D costs. During each phase, the knowledge gained from the completed research is used to update systems performance evaluations as an aid to decision makers supporting possible down selection of systems.

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.

2.4.1 Performance Indicator Outputs

R&D outputs are typically specified on an annual basis and are focused on individual technical issues or concept-specific milestones. Examples of outputs supporting the successful completion of the viability phase (the first outcome given in Section 2.4.2) include the following concept or crosscut items.

- NGNP – development of a qualified particle fuel
- NGNP – development of structural materials that can withstand sustained operational temperatures of 900 to 1000°C
- SCWR – specification of a reactor safety approach
- GFR – selection of fuel and core structural materials
- LFR – Determination of a nitride fuel fabrication method
- Energy Products – successful demonstration of a supercritical carbon dioxide cycle for electricity production.

Examples of outputs supporting the successful completion of the performance phase (the second outcome given in Section 2.4.2) 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 priorities and goals established by DOE and the budget available to the Generation IV program will drive which outputs are actively scheduled for R&D and completion.

2.4.2 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. A second outcome 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 concepts.

2.4.3 Exit Criteria

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

Upon reaching the performance phase, a specific concept has been proven viable, but construction of a prototype or a demonstration plant is still not assured. The R&D work must be directed to show that the concept can deliver on its promised potential, both technically and economically. The decision to pursue construction of a prototype or demonstration plant will be made based on favorable performance phase results.

The number of systems retained after completion of the viability phase is not guaranteed. Available R&D resources will be compared to projected performance phase costs to determine how many concepts can be carried forward. If more concepts successfully demonstrate viability than can be carried forward, only those systems with the highest performance potential will be retained, and the remainder will be dropped from further development (down selection). Currently, a down-selection for fast reactor systems is planned for 2010, with expectations of only one system being carried forward.

The process used for systems evaluation and comparison will be similar to that used during the Generation IV Roadmap 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. This documentation was summarized previously in the Viability Phase Endpoints portion of Table 2.1.

2.5 International Program Implementation

The R&D on the Generation IV systems will be implemented in an international framework with participation by the GIF members[iv]. Participation by specialists or facilities in other countries is desired and will be funded by individual member countries. The GIF established System Steering Committees for four of the six reactor systems: VHTR, GFR, SCWR, and LFR. The System Steering Committees will coordinate R&D among the member countries. Timing of R&D will also be coordinated to best leverage each country's contribution. The GIF member countries are expected to sign a framework agreement (government to government) during FY 2005, which will provide the legal agreements enabling the productive, yet protected, sharing of R&D.

Figure 2.4 GIF Participating Nations

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

iv Argentina, Brazil, Canada, Euratom, France, Japan, the Republic of Korea, the Republic of South Africa, Switzerland, the United Kingdom, and the United States.

3. PROGRAM ORGANIZATION AND RESPONSIBILITIES

3.1 Organizational Structure

The DOE Office of Nuclear Energy, Science and Technology (NE; see Figure 3.1) is responsible for leading the Federal government's investment in nuclear science and technology. DOE-NE activities help to maintain the nation's access to diverse and environmentally responsible sources of energy and advance the country's economic and technological competitiveness. 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, environmentally, economically, and politically acceptable advanced fuel cycle. 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 the NHI is to develop efficient, large-scale hydrogen production methods suitable for use with advanced nuclear reactors. By integrating the AFCI and NHI with the Generation IV program through a common systems analysis function, DOE-NE has established a structure that will facilitate the coordination of all 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. Additionally, DOE-NE established two programs to enable university and international collaborations: the Nuclear Energy Research Initiative (NERI) program enables university participation, while the International-Nuclear Energy Research Initiative (I-NERI) enables international collaboration. The NERI and I-NERI collaborations are described in Section 4.1. Figure 3.2 shows the DOE-NE Generation IV program organization.

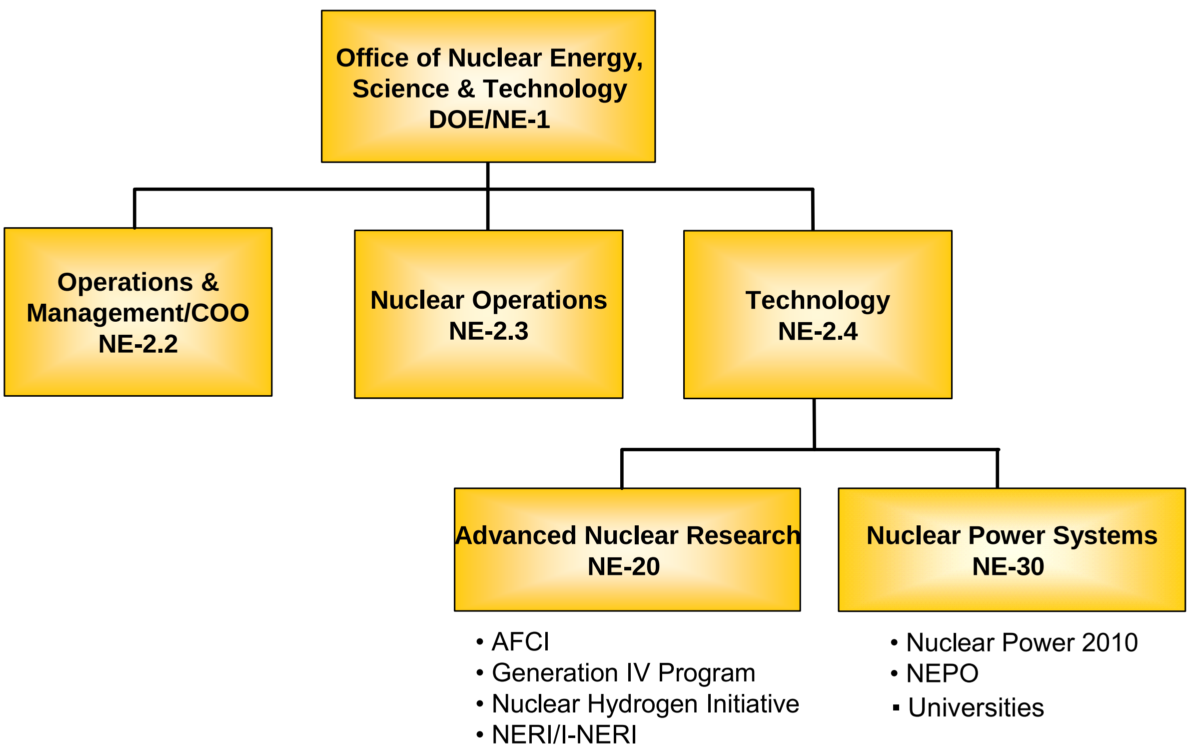


Figure 3.1 DOE-NE Organizational Structure

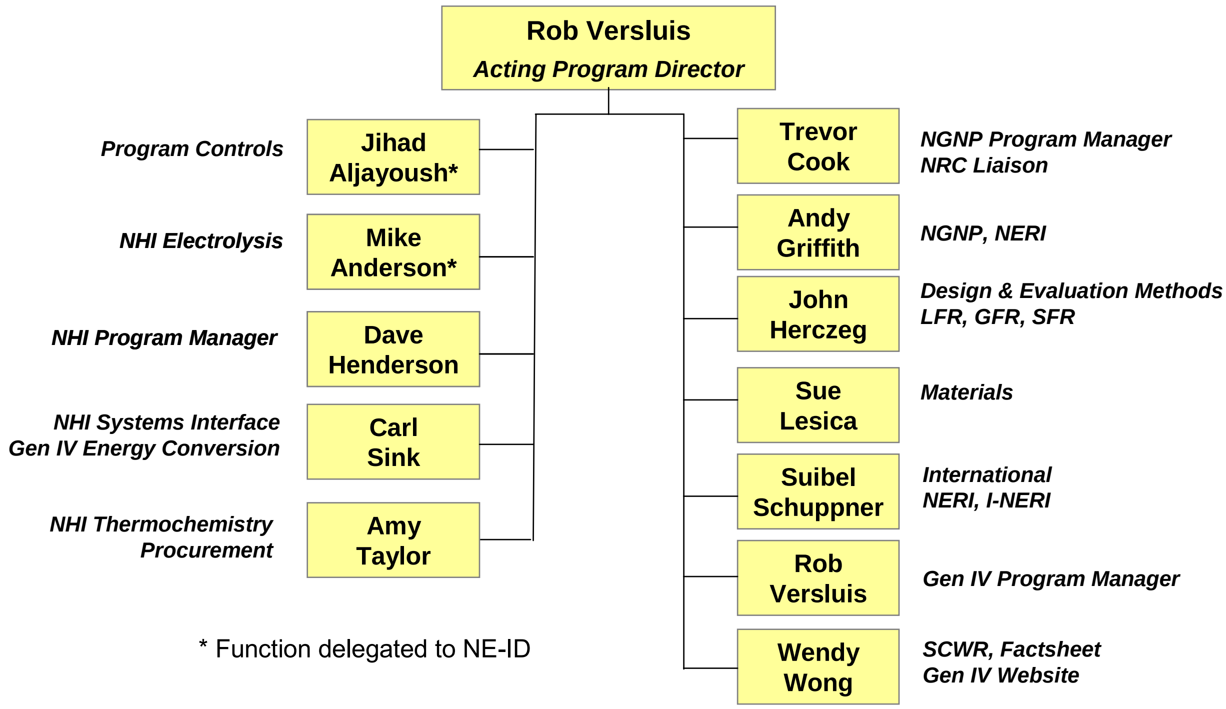


Figure 3.2 Generation IV Program Organizational Structure

3.2 Roles and Responsibilities

The AFCI and Generation IV programs have an integrated management structure that shares a common systems analysis function and National Technical Director (NTD). Roles and responsibilities for key Generation IV program functions are shared among DOE-NE headquarters (HQ), DOE-Idaho (NE-ID), Technical Integration, Program Controls, Systems Analysis, the System Integration Managers (SIMs) for the specific systems, and the NTDs for each of the primary Generation IV technology areas. Generation IV and AFCI each have primary management and funding responsibility for three NTDs. A schematic diagram of this functional structure and organization is shown in Figure 3.3. Specific roles and responsibilities for each of these functional groupings are described below.

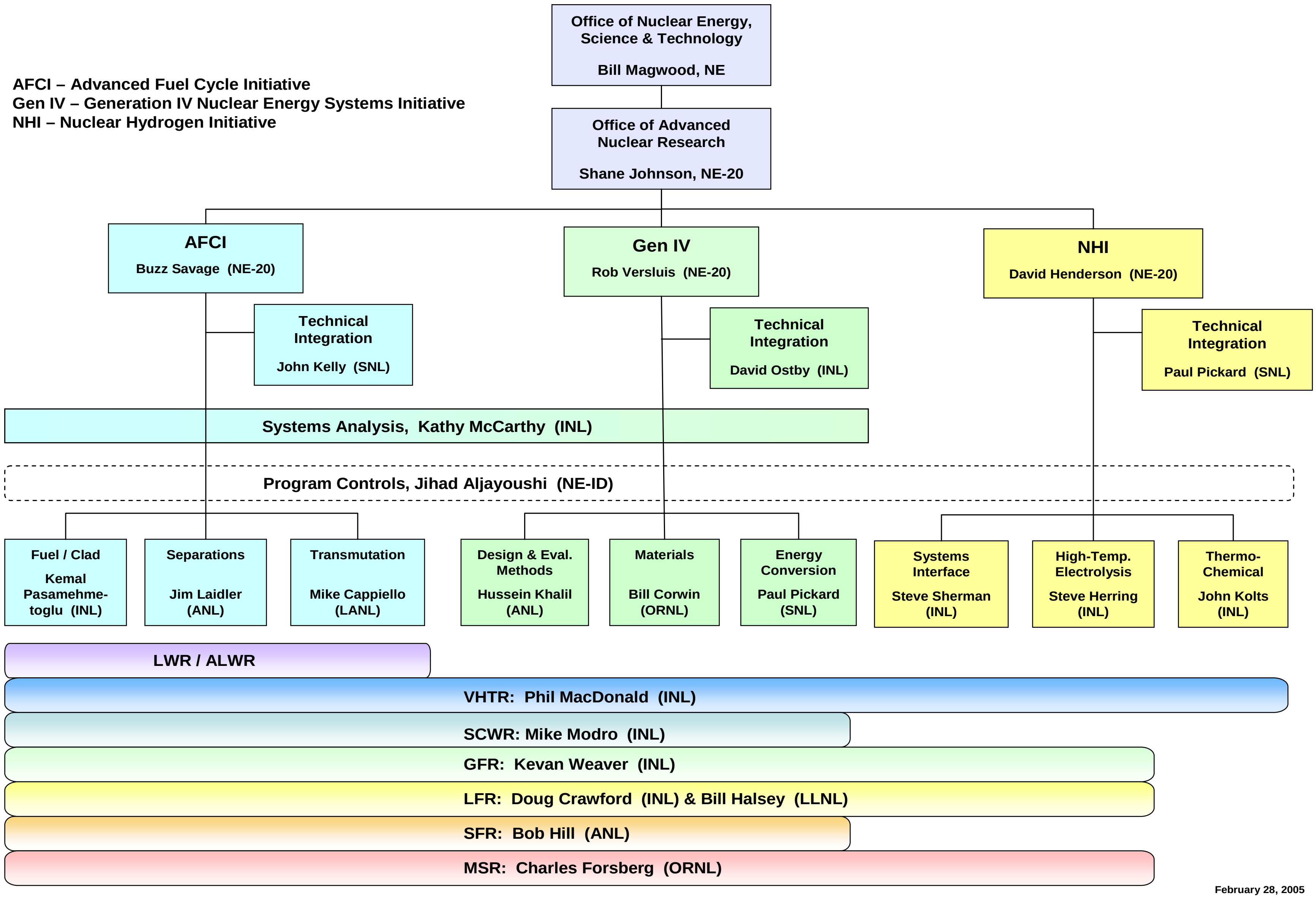


Figure 3.3 AFCI, NHI, and Generation IV program Organizational Structure

3.2.1 DOE Office of Nuclear Energy, Science, and Technology

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 (NNSA), the DOE Office of Civilian Radioactive Waste Management (RW), 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 functional disciplines specific to the important technology development and qualification R&D efforts in the AFCI and Generation IV programs are centered in six areas: design and evaluation methods, fuels and cladding, materials, separations, energy conversion, and transmutation. These six areas are headed by the NTDs, as shown in Figure 3.4, using common technology requirements to provide advanced technologies for the specific programs. The SIMs also work with the NTDs to define unique Generation IV system and AFCI R&D requirements and develop the R&D projects to meet them. The NTD-based common R&D efforts combined with the R&D efforts identified by the SIMs for the Generation IV systems comprise the total Generation IV program and AFCI R&D portfolio. The SIMs and NTDs interact as illustrated in Figure 3.4.

The NTD-based and SIM-based R&D is aimed at satisfying the viability phase and performance phase outcomes that meet the AFCI and Generation IV goals. The process is tracked and modified, as needed, by systems analysis in response to policy decisions, energy demand scenarios, and changes in requirements and strategy that arise as the AFCI and Generation IV programs evolve. 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.

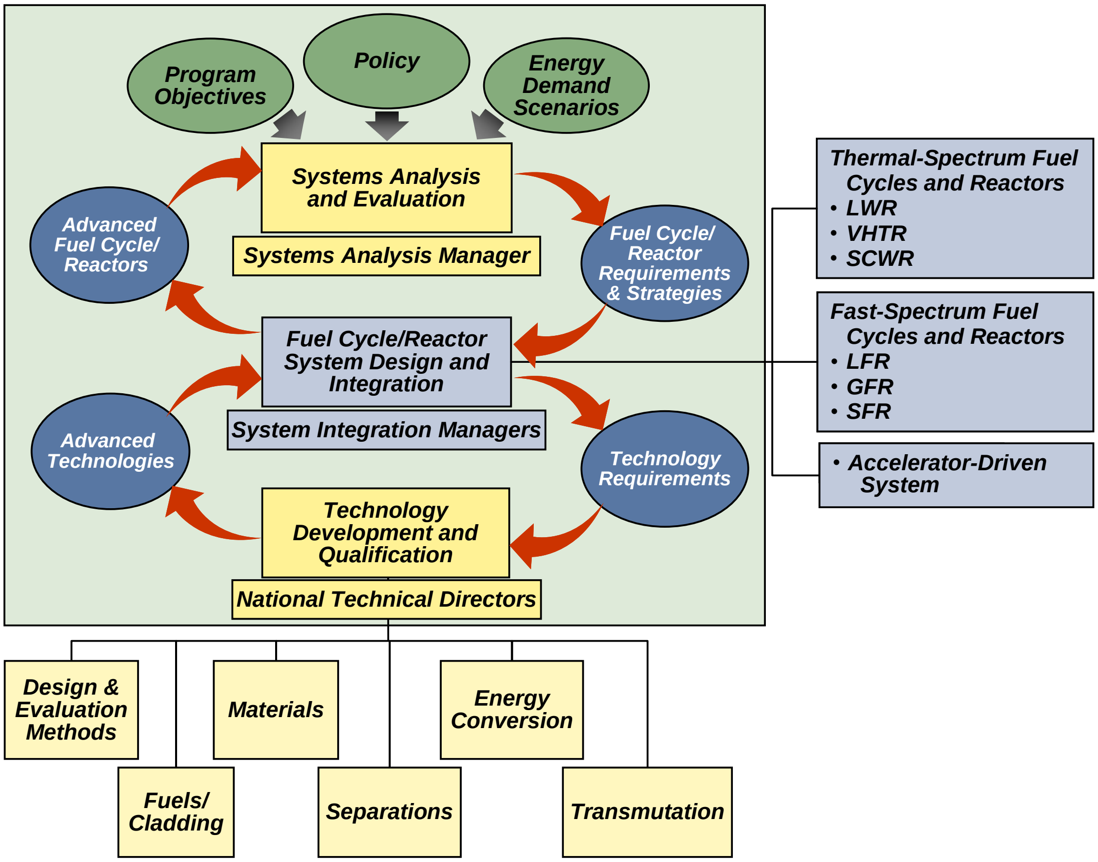


Figure 3.4 Integrated Generation IV and AFCI

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 AFCI and Generation IV
- Deploy system tools to develop recommended priorities for technology development
- Develop sustainability metrics encompassing economics, environmental, and societal aspects, capable of:
  - Evaluating nuclear 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 headed 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 product-specific R&D technology roadmaps using interdisciplinary teams
- Analyze and advance the progress of the system or facility each year
- Support the major program decisions on the selection of their system or facility.

3.2.5 National Technical Director Functions

The NTDs manage crosscut R&D activities, including:

- Develop and maintain targeted crosscut area research, including the implementation of the Generation IV 10-Year Program Plan
- Direct development of proposed tasks and manage scope, cost, and schedule of the crosscut area
- Support system integration team efforts to ensure integration of system requirements into the R&D activities.

3.2.6 Technical Integration Functions

The technical integration function integrates program technical activities, including:

- Coordinate and implement technical program guidance with the NTDs and SIMs
- Develop and update, as necessary, the Generation IV 10-Year Program Plan
- Coordinate, facilitate, and manage semi-annual meetings and all other major Generation IV program meetings
- Develop monthly reports
- Coordinate with Project Controls and track tasks to ensure that work package scope, cost, and schedule are met, including milestones, and alert DOE-NE to all potential problems or issues.

3.2.7 Project Controls Function

The Generation IV R&D program is managed according to the principles of DOE Order 413.3, *Program and Project Management for the Acquisition of Capital Assets*[10]. This Order will be fully adhered to for all capital projects developed under the Generation IV program.

On an annual basis, DOE-NE will provide draft budget guidance to the national laboratory participants based upon technical activities outlined in this 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 Work Breakdown Structure (WBS) elements consistent with this Plan. The SIMs, NTDs, and the Technical Integrator review the draft work packages for completeness and overall program integration. The draft work packages are then reviewed and revised (if necessary) by DOE-NE, who then distributes final fiscal year budget guidance for each participant. Program participants revise and finalize their work packages based upon the budget 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, they establish the cost, schedule, and technical baselines for each participant and establish the overall integrated program baseline.

A program integration and controls system (PICS) has been established to monitor the performance of work packages once they are approved. The status of each work package is evaluated monthly by the relevant SIM and/or NTD, the DOE-HQ lead, the Technical Integrator, and the Program Controls group to assess performance. For work packages where the variance from the baseline exceeds a threshold, a more in-depth evaluation is initiated and a corrective action plan developed as necessary.

3.3 Generation IV Program Management Processes

As stated in Section 3.2, the Generation IV program is managed in accordance with DOE Order 413.3, *Program and Project Management for the Acquisition of Capital Assets*. 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. Each year DOE-NE will provide draft budget guidance to the national laboratories and other participants based upon their technical capabilities and facilities as well as the input of the Technical Integrator and the SIMs/NTDs.

The Technical Integrator and the SIMs/NTDs monitor program performance against the established baseline. Changes to the baseline must be approved through the Generation IV Change 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 form the planning basis for the Generation IV program. Associated with each assumption is a degree of uncertainty, which represents some risks to the program. These risks include both technical risks and programmatic risks.

3.4.1 Assumptions and Uncertainties

- *Planning budget.* This plan is based on the $40.0 million FY 2005 Congressional appropriation enacted in December 2004. The FY 2006 budget is yet to be determined. The budgets for FY 2007 through FY 2015 represent the required levels presented in Section 5. It also assumes support for a robust AFCI Program, including sufficient funding to develop Generation IV fuels in the AFCI.

- *Major facilities 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 concept selection.* It is assumed that at least one fast spectrum Generation IV reactor concept with closed fuel cycle will be developed to achieve the AFCI and Generation IV goals. 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 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, achieving the Generation IV program goals has some technical risk associated with it. Technical risk is 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

- *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 United States 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 requirements imposed.

- *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 in all phases of the program.

4. PROGRAM INTERFACES

4.1 External

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

4.1.1 Nuclear Energy Research Advisory Committee (NERAC)

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. NERAC will periodically review DOE-NE program elements and, based on these reviews, provide 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 will provide advice on national policy and scientific aspects of nuclear energy research issues as requested by the Secretary of Energy or the DOE-NE Director. NERAC includes representatives from universities, industry, and national laboratories. Particular attention was paid to obtaining a diverse membership with a balance of disciplines, interests, experiences, points of view, and geography.

The NERAC Subcommittee on Generation IV Nuclear Energy Systems Technology has been established to advise on the conduct of the Generation IV program activities. The NERAC subcommittee on Evaluations conducts regular reviews of program plans.

4.1.2 Nuclear Regulatory Commission (NRC)

The NRC is an independent agency established by the Energy Reorganization Act of 1974 to regulate civilian use of nuclear materials. A five-member Commission heads the NRC. 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, and ensuring public and radiation worker protection, and 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.

4.1.3 International Partners

A major element of the Generation IV program is a robust cooperative program with international partners. DOE 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 United States 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 United States and collaborating countries. Under I-NERI, DOE-NE has signed bilateral agreements with Brazil, Canada, France, Eurotom, Japan, and Korea.

4.1.4 University Partners

DOE created NERI in 1999 to address the principal technical and scientific concerns affecting the future use of nuclear energy in the United States. Many NERI projects have combined the talents of U.S. universities, industry, and national laboratories to bring leading-edge 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 maintains a competitive position worldwide by advancing the state of nuclear energy technology. Starting in FY 2004, Generation IV, AFCI, and NHI program funding was reserved for NERI to fund university participation in Generation IV, AFCI, and NHI. The new incarnation of the NERI program will be continued in subsequent years and continue to attract university participation.

4.2 Internal DOE Interfaces

Internal interfaces exist with the Nuclear Power 2010 Program, AFCI, and NHI. 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 the decade to support the National Energy Policy objectives of energy security and supply diversity. The Nuclear Power 2010 Program is a joint government/industry cost-shared program to develop advanced reactor technologies and new regulatory processes, with the objective of initiating construction by 2005 and operation by 2010 of new nuclear power plants in the United States by the private sector. 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, independent expert analysis commissioned by DOE and carried out by NERAC has shown that R&D is needed on near-term advanced reactor concepts 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 Advanced Fuel Cycle Initiative

The AFCI Program is being executed in an integrated manner with the Generation IV program. The AFCI program has the responsibility of developing both reactor fuels and supporting fuel cycle technologies for both 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.

Separately from Generation IV, AFCI is responsible for providing an effective transition strategy to address the legacy of the current open fuel cycle. The technologies needed to enable the transition from the open fuel cycle are primarily focused on technical issues associated with treating LWR (and ALWR) spent nuclear fuel, such as reducing the volume and heat generation (short-term) of material requiring geologic disposal. These issues are being addressed throughout the development and demonstration of advanced separations technologies and proliferation-resistant recycled fuels. The recycle fuels would then be used in existing and advanced light water reactors, and possibly gas-cooled reactors. This approach will provide technical options that could be used to improve utilization of the nation's first repository and delay the technical need for additional repositories. Research activities include developing proliferation-resistant separations processes and fuels to harvest the energy value of these materials to be recovered, while destroying significant quantities of weapons-usable materials in light-water reactors.

The advanced fuel cycle efforts of the AFCI are also addressing the fuel cycle options required for Generation IV reactors. This part of the program will develop fuel cycle technologies to destroy actinides in fast neutron spectrum systems, greatly reducing the long-term radiotoxicity and heat load of high-level waste sent to a geologic repository. This will be accomplished through the development of a transmutation fuel cycle using Generation IV fast reactors and possibly accelerator-driven systems (ADS). The AFCI strategies that employ Generation IV fast reactors have the potential to fully optimize utilization of the geologic repository and delay the technical need for any additional repositories for a century or more. They could also eliminate weapons-usable material from waste streams while eliminating the need for uranium enrichment. Finally, they would enabling recycle of waste uranium (including depleted uranium) to provide fuel for several centuries from waste materials.[6,7]

4.2.3 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 United States, it is primarily produced by steam reforming of natural gas, which is itself a high-quality fuel. 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 United States would be equivalent to about 100 GWth of nuclear or fossil power, assuming 50% efficiency for hydrogen production. The most attractive hydrogen production options for nuclear energy are those that utilize high temperatures or efficient electricity from a VHTR to produce hydrogen from non-fossil resources (i.e., water) and are, therefore, the focus of the NHI. The NHI will collaborate, augment, and complement ongoing DOE research efforts in Generation IV, where appropriate, and initiate needed R&D in nuclear-specific areas to accomplish NHI program goals.

5. GENERATION IV R&D PLANS

5.1 NGNP

5.1.1 System Description

The DOE is conducting R&D on the VHTR design concept for the NGNP Project. The reactor design will be a graphite-moderated thermal neutron spectrum reactor that will produce electricity and hydrogen in a highly efficient manner. The NGNP reactor core could be either a prismatic graphite block type core or a pebble bed core cooled by helium. Use of a liquid-salt coolant is also being evaluated. The NGNP will use very high-burnup, low-enriched uranium, TRISO-coated fuel, and will have a projected plant design service life of 60 years.

The NGNP will produce both electricity and hydrogen. The process heat for the hydrogen production, and possibly the electricity production, will be transferred through an intermediate heat exchanger (IHX). The VHTR concept is considered the nearest-term reactor design that has the capability to efficiently produce hydrogen. The plant size, reactor thermal power and core configuration will be designed to assure passive decay heat removal without fuel damage during any hypothetical accident. Figure 5.1 provides a sample schematic of one possible design for the NGNP.

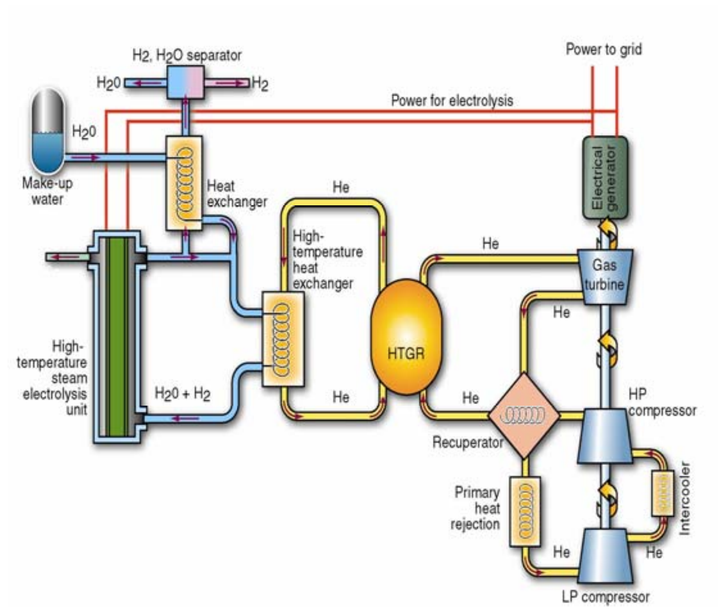


Figure 5.1 Sketch of how the NGNP might be configured to produce both electricity and hydrogen.

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.

A target schedule for the development and construction of the NGNP includes starting preconceptual designs in 2006, completing preliminary design in 2009, completing major R&D activities by 2012, and starting construction in 2012. NGNP operations are scheduled to begin in 2017.

The objectives of the NGNP Project are to:

- Demonstrate a full-scale prototype VHTR, or other commercially viable reactor technology, that is commercially licensed by the U.S. Nuclear Regulatory Commission (NRC).
- Demonstrate safe and economical nuclear-assisted production of hydrogen and electricity.

It is expected that a successful NGNP demonstration will lead to widespread deployment of VHTRs in the United States and elsewhere.

The DOE laboratories, led by the Idaho National Laboratory (INL), will perform R&D that will be critical to the success of the NGNP, primarily in the areas of:

- High-temperature gas reactor fuels behavior
- High-temperature materials qualification
- Design methods development and validation
- Hydrogen production technologies
- Energy conversion.

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

5.1.2 Highlights of R&D

5.1.2.1 System Design and Evaluation Methods. One of the great challenges of studying, designing, and licensing the NGNP is to confirm that the intended NGNP analysis tools can be used with confidence to make decisions and to assure all that the reactor systems are safe and meet their performance objectives. The R&D projects will ensure that the tools used to perform the required calculations and analyses can be trusted.

The *NGNP Design Methods Development and Validation R&D Program Plan*[11] was issued in August 2004. The R&D summarized here is based on that plan and focuses on developing tools for assessing the neutronic and thermal-hydraulic behavior of the plant. The fuel behavior and fission product transport models are discussed below. Various stress analyses and mechanical design tools will also need to be developed and validated.

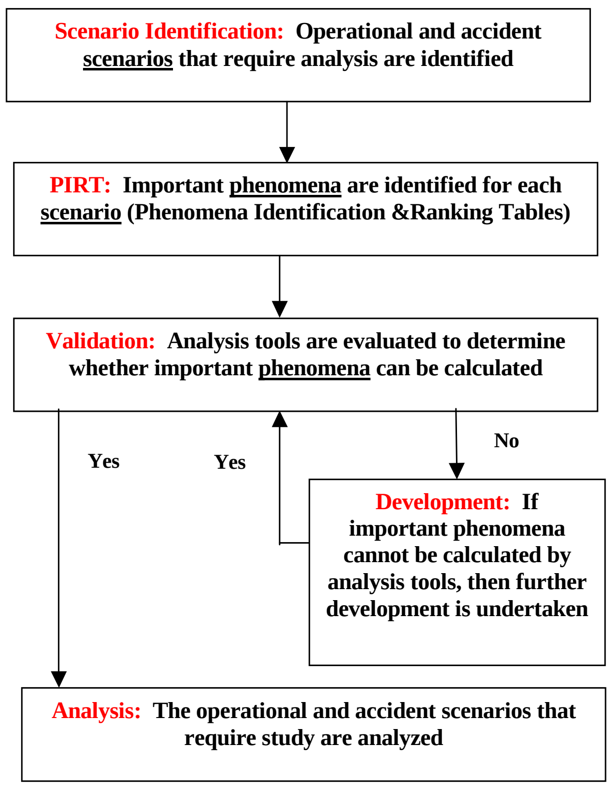


Figure 5.2 Methods development process

The overall methods development process is outlined in Figure 5.2. The requirements associated with scenario identification, defining the phenomena identification and ranking tables, completing the required development, and performing the necessary validation studies must all be completed before performing the required analyses. The NGNP design has not yet been selected; consequently, the R&D process is focused on scenarios and phenomena previously identified as important by the advanced gas-cooled reactor community.

The calculational and experimental needs, and consequently the required R&D, will be focused in eight distinct areas, based on the relative state of the software in each:

1. Basic differential and integral nuclear cross-section data measurement and evaluation, including mathematically rigorous sensitivity studies of the effects of uncertainties in the differential nuclear data and other independent design variables on key integral reactor properties

2. Reactor assembly cross-section preparation

3. Discrete ordinates transport

4. Nodal diffusion

5. Reactor kinetics

6. Thermal-hydraulics

7. Fuel behavior

8. Fission product transport.

5.1.2.2 Fuel Development and Qualification. Development and qualification of TRISO-coated, low-enriched uranium fuel is a key R&D activity associated with the NGNP Program. The work is being conducted in accordance with the *Technical Program Plan for the Advanced Gas Reactor Fuel Development and Qualification Program*[12]. The Advanced Gas Reactor (AGR) Fuel Development and Qualification Program includes work on improving the kernel fabrication, coating, and compacting technologies; irradiation and accident testing of fuel specimens; and fuel performance and fission product transport modeling. The primary goal of these activities is to successfully demonstrate that TRISO-coated fuel can be fabricated to withstand the high temperatures, burnup, and power density requirements of a prismatic block type NGNP with an acceptable failure fraction. It is assumed that TRISO fuel that is successful in a block reactor will also be successful in pebble-bed reactors since the particle packing fraction and the fuel temperatures are somewhat lower in pebble-bed reactors than in block reactors. In addition, commercialization of the fuel fabrication process, to achieve a cost-competitive fuel manufacturing capability that will reduce entry-level risks, is a secondary goal of the project.

An underlying theme for the NGNP/AGR fuel development and qualification work is the need to develop a more complete understanding of the fundamental relationship between the fuel fabrication process, key fuel properties, irradiation performance of the fuel, and release and transport of fission products in the NGNP primary coolant system. Fuel performance modeling and analysis of fission product behavior in the primary circuit are important aspects of this work. Performance models are considered essential for several reasons, including guidance for the plant designer in establishing the core design and operating limits and demonstrating to the licensing authority that the applicant has a thorough understanding of the in-service behavior of the fuel system.

The AGR Fuel Development and Qualification Program consists of five elements: fuel manufacture, fuel and materials irradiations, post-irradiation examination and safety testing, fuel performance modeling, and fission product transport and source term modeling. Each task is discussed in more detail below:

- *Fuel manufacture*. The fuel manufacture task will produce coated particle fuel that meets fuel performance specifications. This task also 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 will be fabricated for characterization, irradiation, and accident testing, as necessary, to meet the overall goals. Automated fuel fabrication technologies suitable for mass production of coated particle fuel at an acceptable cost will also be developed. That work will be conducted during the later stages of the program in conjunction with a cosponsoring industrial partner.

- *Fuels and materials irradiation*. The fuel and materials irradiation activities will provide data on fuel performance under irradiation to support fuel process development, to qualify fuel for normal operation conditions, and to support development and validation of fuel performance and fission product transport models and codes. It will also provide irradiated fuel and materials, as necessary, for post-irradiation examination and safety testing. Eight irradiation capsules have been defined to provide the necessary data and sample materials. The fuel irradiations will be conducted in the Advanced Test Reactor (ATR) located at the INL.

- *Safety testing and post-irradiation examination*. This task will provide the equipment and processes to measure the performance of AGR fuel under accident conditions. This work will support the fuel manufacture effort by providing feedback on the accident-related performance of kernels, coatings, and compacts. Data from the post-irradiation examinations and accident testing will supplement the in-reactor measurements (primarily fission gas release-to-birth ratio) as necessary to demonstrate compliance with fuel performance requirements and support the development and validation of computer codes.

- *Fuel performance modeling*. Fuel performance modeling will address the structural, thermal, and chemical processes that can lead to coated-particle failures. The release of fission products from the fuel particle will also be modeled, including the effects of fission product chemical interactions with the coatings, which can lead to degradation of the coated-particle properties. Computer codes and models will be further developed and validated as necessary to support fuel fabrication process development. Results of these modeling activities will be essential to the plant designer in establishing the core design and operation limits and will demonstrate to the licensing authority that the applicant has a thorough understanding of the in-service behavior of the fuel system.

- *Fission product transport and source term modeling*. This task will address the transport of fission products produced within the coated particles and the fuel element to provide a technical basis for source terms for AGRs under normal and accident conditions. The technical basis will be codified in design methods (computer models) validated by experimental data. This information will provide the primary source term data needed for licensing.

5.1.2.3 Energy Conversion. Planning for the Energy Conversion R&D has not yet been completed. Energy Conversion planning will be coordinated with industry participants.

5.1.2.4 Materials. The NGNP Materials R&D Program will focus on testing and qualification of the key materials commonly used in VHTRs and will address the materials needs for the NGNP reactor, intermediate heat exchanger, and associated balance of plant. Materials for hydrogen production will be addressed by NHI. Revision 1 of the *NGNP Materials Research and Development Program Plan*[13] was issued in September 2004. The R&D discussed in this document is based on that plan.

The materials R&D program is being initiated before the formal design effort to ensure that appropriate data will be available to support the NGNP design and construction process. The thermal, environmental, and service life conditions of the NGNP will make selection and qualification of some high-temperature materials a significant challenge; thus, new materials and approaches may be required. The following materials R&D areas are currently addressed in the R&D being performed or planned:

- *Qualification and testing of nuclear graphite and carbon fiber/carbon matrix composites*. 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. Most of the past work was related to a graphite known as H-451, which is no longer available. Therefore, the currently available nuclear grade graphites must be tested and qualified for use in the NGNP.

- *Development of improved high-temperature design methodologies*. The High-temperature Design Methodology project will develop the data and simplified models required by the American Society of Mechanical Engineers (ASME) B&PV Code subcommittees to formulate time-dependent failure criteria that will ensure adequate high-temperature metallic component life. This project will also develop the experimentally based constitutive models that will be the foundation of the inelastic design analyses specifically required by ASME B&PV Section III, Division I, Subsection NH. 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 by identifying the implications of time-dependent failure modes and time and rate-dependent deformation behaviors. The project will also develop data for regulatory acceptance of the NGNP designs.

- *Expansion of ASME codes and American Society for Testing and Materials (ASTM) standards to support the NGNP design and construction*. Much of this effort will provide required technological support and recommendations to the Subgroup on Elevated Temperature Design (NH) as they develop methods for using high-temperature alloys (e.g., 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 C_f/C composites structures of the core. A project team under Section III of ASME is currently undertaking these activities.

- *Improving understanding and models for the environmental effects and thermal aging of the metallic alloys*. The three primary factors that will most affect the properties of the metallic structural materials from which the NGNP components will be fabricated are the effects of irradiation, high-temperature, and interactions with the gaseous environment to which they are exposed. This work is focused on assessing the property changes of the metallic alloys as a function of exposure to the high-temperature and impure gas environments expected in the NGNP.

- *Irradiation testing and qualification of the reactor pressure vessel 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 installed and used in an appropriate material test reactor.

- *Qualification and testing of the silicon carbide fiber/silicon carbide matrix composite materials needed for the NGNP*. This program is directed at the development of C/C and SiC/SiC composites for use in selected very high temperature/very-high neutron fluence applications, such as control rod cladding and guide tubes (30 dpa projected lifetime dose) where metallic alloy are not feasible. It is believed that SiC/SiC composites have the potential to achieve a 60-year lifetime under these conditions. The usable life of the C/C composites will be less, but their costs are also significantly less. The program will eventually include a cost comparison between periodic replacement of C/C materials and use of SiC/SiC composites.

- *Assessment of fabrication and transportation issues relating to the NGNP reactor pressure vessel*. Materials issues associated with joining and inspecting heavy section forgings are covered in this task. This will initially be a scoping study to determine general transportation (e.g., transportation of large vessel sections) and fabrication (e.g., field versus shop welding) issues associated with construction of the VHTR.

- *Development of a materials handbook/database to support the Generation IV Materials Program*. This is required to collect and document in a single source the information generated in this and previous VHTR materials R&D programs.

- *NGNP reactor pressure vessel emissivity*. The emissivity and other physical and mechanical properties of layers that form either by high-temperature environmental exposure or artificially engineered layers on the exterior surface of the NGNP reactor pressure vessel will be measured. This data is needed for off-normal and accident condition assessments.

5.1.3 10-yr Project Budget

Table 5.1 shows the NGNP R&D budget required to support NGNP initial operation in 2017. The budget figures represented below are initial, predesign estimates, which may change when pre-conceptual designs are completed.

Table 5.1 NGNP annual budget profile ($K).

	FY-05	FY-06	FY-07	FY-08	FY-09	FY-10	FY-11	FY-12	FY-13	FY-14	Total
Research and Development											
Fuels Development	14,272										
Materials Selection and Qualification	6,581										
DEM	2,671										
Design and Trade Studies	6,620										
Public Outreach	200										
NGNP Subtotal	**30,344**										
Hydrogen Development	9,000										
DOE Share Subtotal	39,344										
Industry Share											
TOTAL	**39,344**										

5.2 Supercritical Water Reactor

5.2.1 System Description

Supercritical water-cooled reactors are promising advanced nuclear energy systems because of their high thermal efficiency (about 45% vs. 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 coolant 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, pressurizer, steam generators, and steam separators and dryers in current LWRs is eliminated. The main mission of the SCWR is generation of low-cost electricity. 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 concept (see Figure 5.3) is being investigated by 32 organizations in 13 countries.

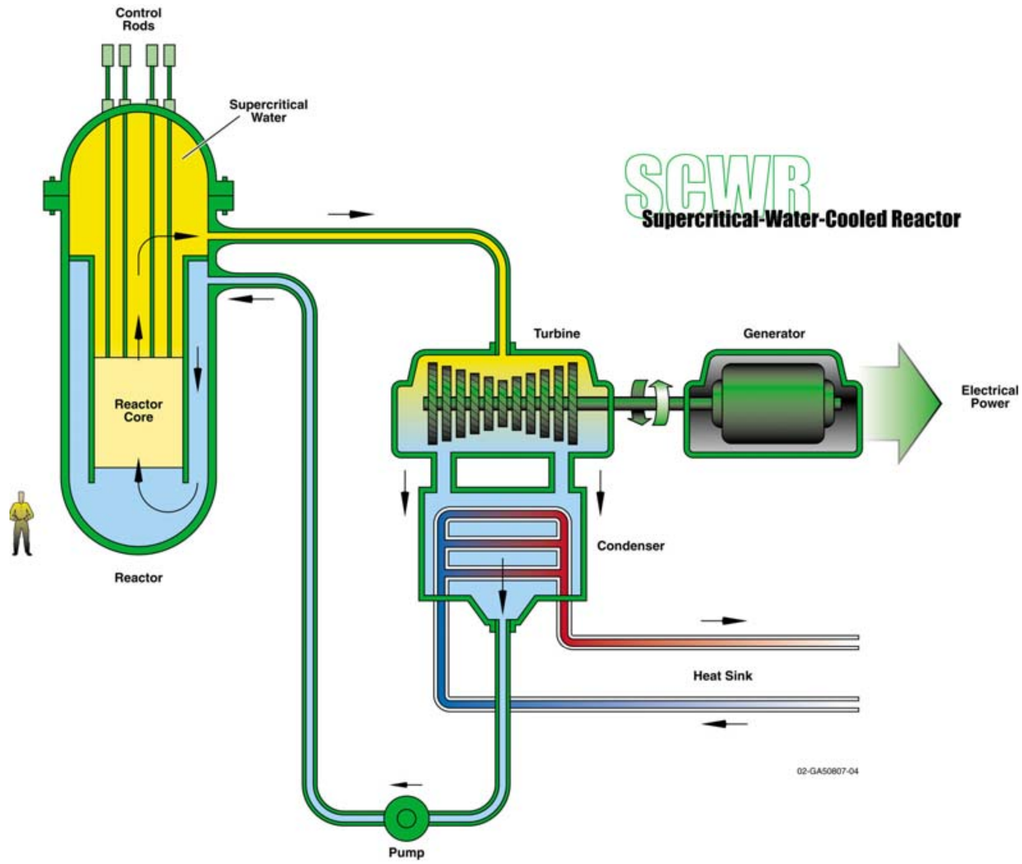


Figure 5.3 Conceptual SCWR system.

In FY 2005, the SCWR program was redirected. The current plan focuses on further assessment of SCWR viability but based on a non-U.S. concept 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 assure selection of structural and cladding materials that will maintain reliable operation of an SCWR power plant for its design life.

Current R&D programs within GIF organizations address two principal SCWR design concepts that differ in the approach to the reactor design: one utilizes a reactor pressure vessel and the other pressure tubes. From its conception, the U.S. program focused on the reactor pressure vessel concept because its roots are in the LWR technology common to all U.S. reactor vendors. Similarly, the R&D conducted in Japan, Korea, and Europe is focused on the pressure vessel concept. Canada selected a pressure tube design for its SCWR as the logical evolution of CANDU type reactors. The U.S. Generation IV SCWR program operates under the following general assumptions, 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 general assumptions 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 concept that calls for the completion of all essential R&D by 2015 and construction of a small-size (≤150 MWt) prototype SCWR by 2020.

5.2.2 Highlights of R&D

5.2.2.1 System Design. This R&D element provides for the preconceptual SCWR design needed for viability assessment and for guidance of materials, thermal-hydraulic, and system research. In general, this task establishes a baseline design and addresses safety systems, control and startup, system and comparative analyses, basic thermal-hydraulic phenomena, safety, stability, and methods. During 2003–2004, most of the issues identified were addressed and resolved in the context of basic SCWR viability. The work during 2005–2013 will be focused on cooperation with GIF partners and identification of the most promising design.

- *System and comparative analyses.* The objective of this activity is to perform, in cooperation with GIF partners, performance and comparative analyses of proposed SCWR concepts. Comparative analysis of these various core designs will be conducted to evaluate the relative merits and shortcomings of each and their potential to meet the Generation IV goals. The objective is to converge on a design that can be jointly developed and eventually demonstrated in cooperation with other GIF countries. The analyses will include operational analyses, safety analyses, and economic assessment.

- *Basic thermal-hydraulic phenomena, safety, stability and methods.* This R&D program element addresses current basic knowledge gaps in areas such as 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.

5.2.2.2 Fuels. The SCWR concept is based on standard LWR fuel; therefore, no specific fuel R&D is planned. The cladding issues are addressed in the materials research.

5.2.2.3 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, and 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 required special consideration. However, initial studies and consultation with engineering and vendor firms have shown that the balance of plant and turbine issues can be resolved and are not a viability problem.

5.2.2.4 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 economics 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 some sort of thermal and/or corrosion-resistant barrier. Based on the available data for other alloy classes, there is currently no single alloy that has been studied enough to unequivocally ensure its viability in an 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 10-yr Project Budget

Table 5.2 shows the SCWR required budget.

Table 5.2 Required SCWR Budget ($K).

Functional Area	FY-05	FY-06	FY-07	FY-08	FY-09	FY-10	FY-11	FY-12	FY-13	FY-14	Total
Systems Design*	460										
Fuels	0										
Energy Conversion	0										
Materials	466										
TOTAL	**926**										

* Budgets for 2009-2012 include funding for U.S. participation in an international integral facility program.

5.3 Gas-Cooled Fast Reactor

5.3.1 System Description

The gas-cooled fast reactor (GFR; see Figure 5.4) 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 is possible with the current designs being considered, thus 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 economical and efficient fuel cycle processes.

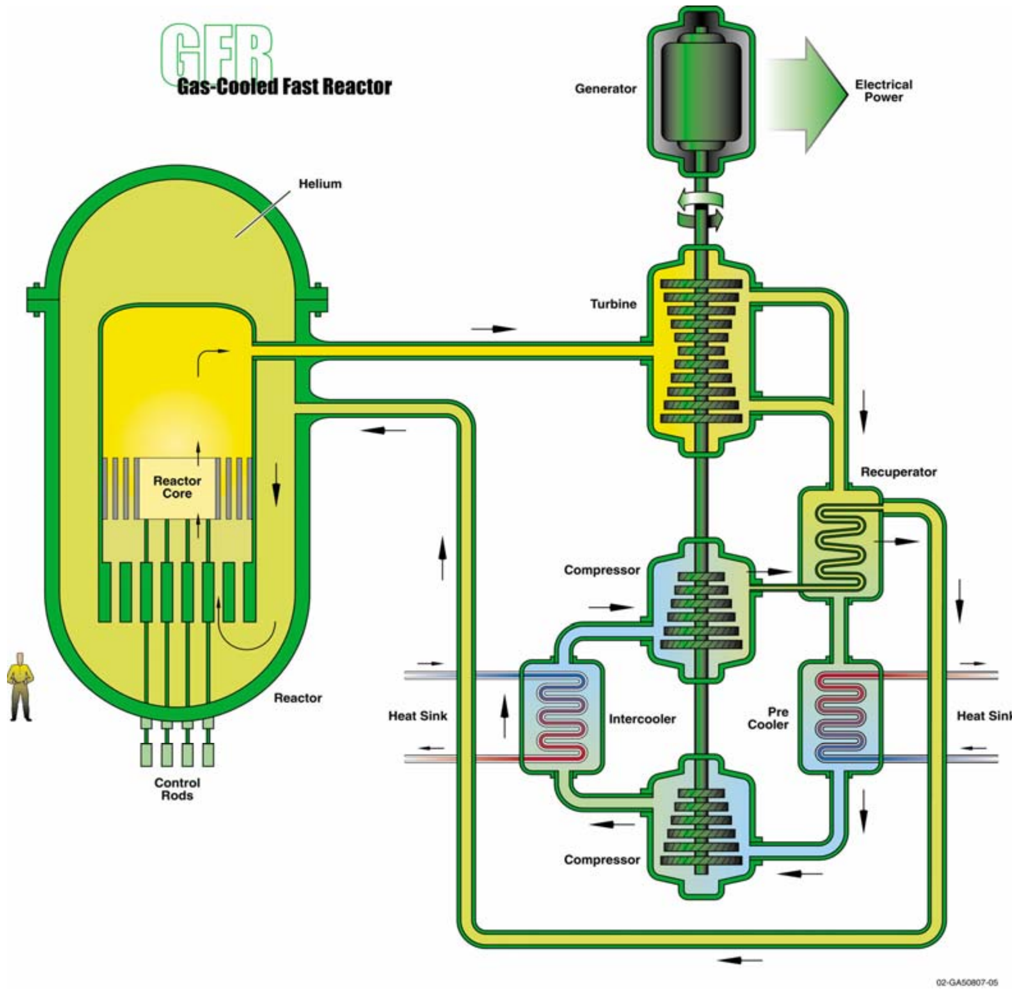


Figure 5.4 Conceptual GFR system.

The main characteristics of the reference GFR are a self-generating core (i.e., CR = 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 VHTR, and thus its ability to utilize as much VHTR material and balance-of-plant technology as possible. Like thermal-spectrum helium-cooled reactors such as the GT-MHR and the PBMR, 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 thermochemical production of hydrogen.

While the United States has a 2010 down-select criterion, the international community has issued a detailed R&D plan to establish the viability of the GFR by 2010, complete a conceptual design by 2019, and 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 concept is deemed feasible for further study. This second phase will be the start of the 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 includes conceptual studies of a reference GFR system, assessment of options, analyses of the safety approach and of specific safety features, and the 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 actinides and be recyclable in an economic manner.

The broad Generation IV goals translate into specific goals and work scope for the GFR. This includes:

- Definition of a GFR reference conceptual design and operating parameters that meet the requirements

- Identification and assessment of alternative design features regarding the Generation IV goals and criteria (e.g., lower temperatures, indirect cycle)

- Safety analysis for the reference GFR system and its alternatives

- Assessment of economics, including the impact on investment and operating costs of the simplified and integrated fuel cycle and the modularity of the reactor (series production, in-factory prefabrication, and sharing of on-site resources)

- Development and validation of computational tools needed for the design and analysis of operating transients (design basis accidents and beyond), including benchmarking and validation against experimental data and identification of required test facilities to obtain missing experimental data for the qualification of calculation tools.

5.3.2 Highlights of R&D

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

5.3.2.1 System Design and Evaluation Methods. 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, AFCI will perform all research in this area. However, the direction and results of the 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 refabrication viability studies

5.3.2.3 Energy Conversion. The major activities within the Energy Conversion research 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 research include screening and testing of high-temperature materials (including welding and fabrication) and possible corrosion studies using supercritical CO_2.

5.3.3 10-yr Project Budget

The proposed U.S. budget is shown in Table 5.3.

Table 5.3 GFR 10-year project budget ($K).*

	FY-05†	**FY-06**	**FY-07**	**FY-08**	**FY-09**	**FY-10**	**FY-11**	**FY-12**	**FY-13**	**FY-14**	**Total**
System Design and Evaluation	528										
Materials	606										
Energy Conversion	20										
Fuels and Fuel Cycle‡	20										
TOTAL	**1174**										

* The overall estimated budget for GFR through 2025 is approximately $940 M (this includes funding from other GIF participants).

† FY-05 budget includes carryover

‡ Fuels research to be funded from AFCI (assumes contribution of ~$3M per year, with $50K for Generation IV/AFCI integration).

5.4 Lead-Cooled Fast Reactor

5.4.1 System Description

The Lead-Cooled Fast Reactor (LFR) is proposed to advance 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. Lead does not interact vigorously with air, water/steam, or carbon dioxide, thus eliminating concerns about exothermic reactions. It has a high boiling temperature (1740°C) such that the prospect of boiling or flashing of the ambient pressure coolant is realistically eliminated. It is also noted that two land prototypes and eight submarine reactors utilizing lead-bismuth eutectic coolant were operated as part of the Russian Navy and provide approximately 80 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 (see Figure 5.5) is the Small Secure Transportable Autonomous Reactor (SSTAR) concept, which is a small, modular, fast reactor. The main mission of the 20 MWe (45 MWt) 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, island nations of the Pacific Basin, and elsewhere. This may be a niche market within which costs that are higher than those for large-scale nuclear power plants are competitive. Design features of the reference SSTAR include a 20-to-30-yr-lifetime sealed core, a natural circulation primary autonomous load following without control rod motion, and use of a supercritical CO_2 (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.

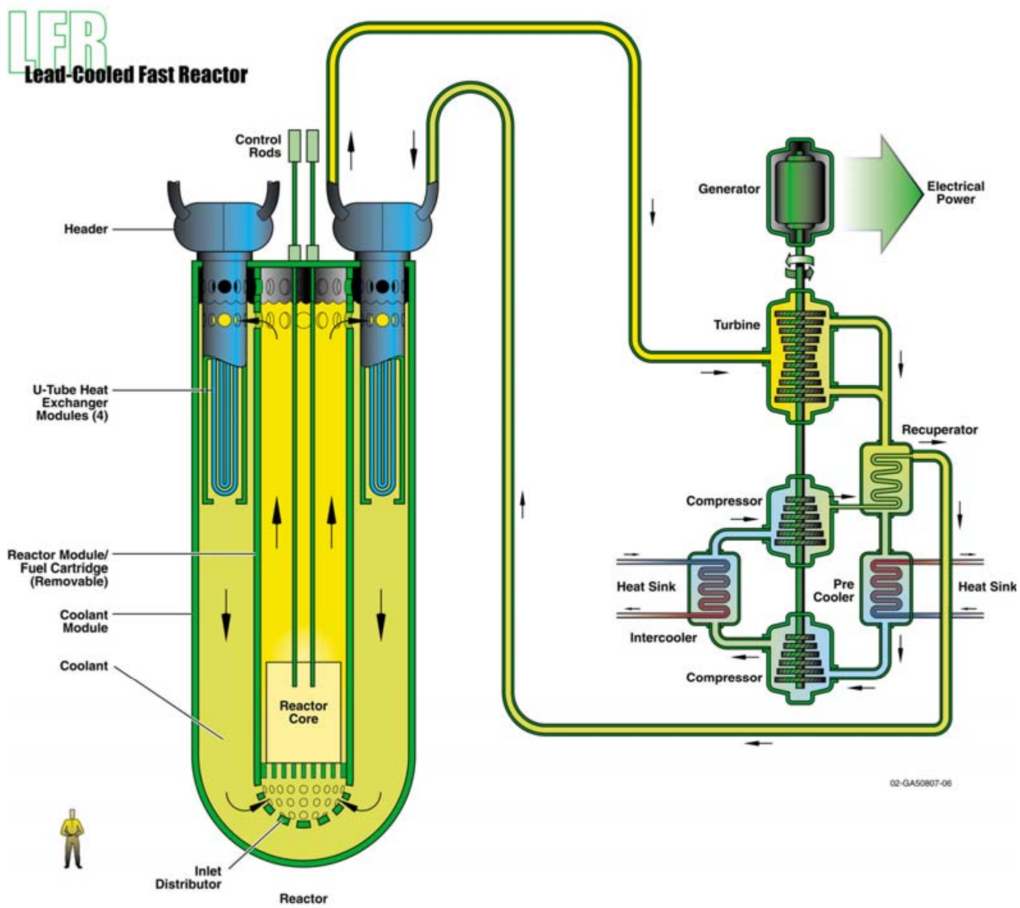


Figure 5.5 Conceptual LFR system.

This R&D plan addresses viability issues associated with the LFR leading to the Generation IV fast 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 preconceptual design. Conceptual design will begin in 2009 and continue, given a decision for pursuing the LFR in 2010, to 2014. R&D tasks that support conceptual design will be defined in more detail later in the viability R&D program, but will include analysis and experiments intended to reduce design uncertainty and establish conceptual limiting conditions of operation.

5.4.2 Highlights of R&D

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 eliminating the intermediate heat transport system, startup using natural circulation, and the emergency heat removal concept.

Viability of the long-life core and passive safety under all upset 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 (up to 650°C peak cladding) must be identified to provide requirements for potential materials and determine that such material performance can be achieved within an engineering development program.

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 and experiments. 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 decay heat during postulated accidents. Additionally, calculations will be run to demonstrate that core and Pb-to-CO_2 heat exchangers remain covered by ambient pressure that single-phase primary coolant inside the reactor vessel and single-phase natural circulation removes the core power under all operational and postulated accident conditions.

Experience with LWRs and previous fast 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 to ensure that the LFR 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 design.

Concepts for inspecting and verifying key safety structures and boundaries of the LFR concept 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 long core lifetime.

Because the envisioned LFR concept 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 at %) under operating conditions and transient testing, including accident conditions, to verify acceptable fuel behavior.

If the LFR system as envisioned is to be viable, 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 acceptable efficiencies with lower Pb coolant outlet temperatures, which reduces the challenges for materials in an economically acceptable system. 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. These include determining whether there is information available regarding commercial-scale S-CO_2 Brayton cycle operation; evaluating innovative design concepts for compressors, turbine, printed circuit heat exchangers (PCHEs), and other components; demonstrating long-term operation of components with small channels (e.g., PCHEs) without fouling or corrosion; and demonstrating operation of an integral cycle at 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 concept 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-martenistic steels, 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 10-yr Project Budget

The known and proposed budget for the LFR R&D described herein is provided in Table 5.4.

Table 5.4 Known and Proposed Budget for U.S. LFR R&D ($K).

Technology	**FY-05**	**FY-06**	**FY-07**	**FY-08**	**FY-09**	**FY-10**	**FY-11**	**FY-12**	**FY-13**	**FY-14**	**TOTAL**
System Design & Evaluation	536										
Materials	754										
Energy Conversion	0										
Fuels & Licensing	0										
Total	**1290**										

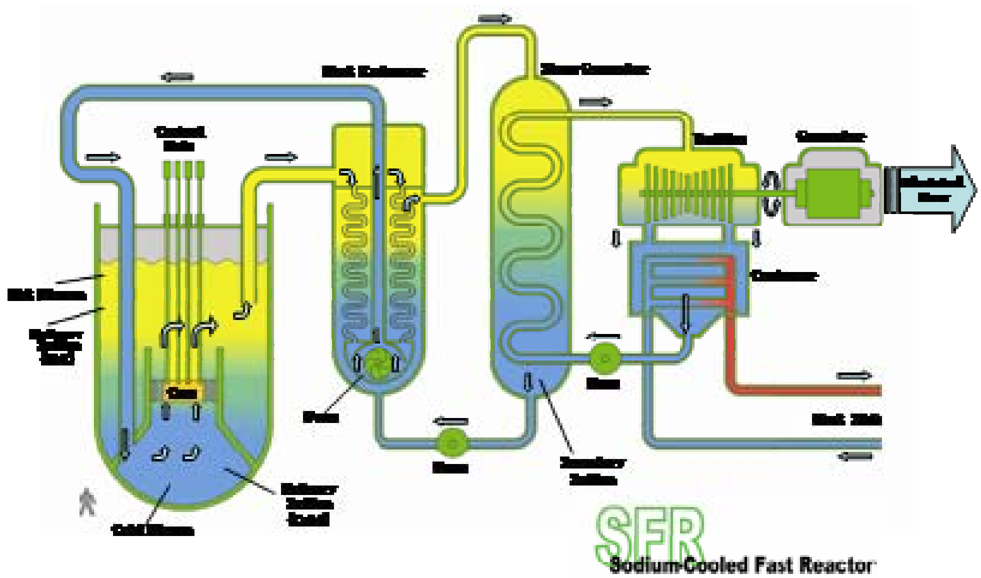
5.5 Sodium-Cooled Fast Reactor

5.5.1 System Description

The sodium-cooled liquid metal reactor system features a fast-spectrum reactor and closed fuel recycle system. The primary mission for the SFR is the management of high-level wastes and, in particular, management of plutonium and other actinides. 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 the natural uranium.

A variety of plant size options is available for the SFR, ranging from modular systems of a few hundred MWe to large monolithic reactors of about 1500 MWe. Sodium core-outlet temperatures are typically 550ºC. The primary coolant system in a SFR can either be arranged in a pool layout (a common approach, where all primary system components are housed in a single vessel) or in a compact loop layout, favored in Japan (see Figure 5.6). 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 achieve the overall performance targets discussed in the next paragraph 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. A GIF R&D Plan has been developed to cover the R&D needed to resolve viability and performance questions to complete the development of the SFR system.



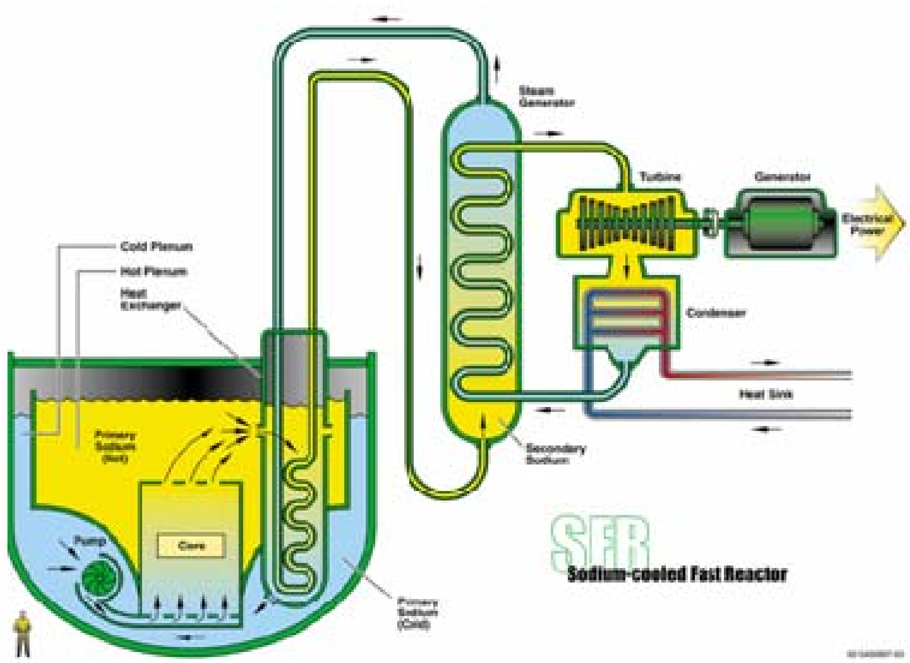


Figure 5.6 Basic SFR power plant system configurations

The performance targets affecting the SFR development, in collaboration with GIF, include completion of the preconceptual reference design by 2007 and the initial phase of materials research and reactor design by 2010 to facilitate selecting 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 to interact with GIF countries to ensure that the GIF R&D Plan addresses the needs and goals of the program, maintain awareness of the R&D progress and accomplishments under the GIF Plan, and contribute to the GIF SFR R&D, with relevant activities being performed under the AFCI and Generation IV programs in the United States.

5.5.2 Highlights of R&D

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 to demonstrate the design and safety characteristics, especially with fuels containing transurancis, and to optimize the design with innovative approaches to meet the objectives of the specific Generation IV missions, primarily waste management.

5.5.3 10-yr Project Budget

The budget projection for the 10-yr period starting in FY 2005 is shown in Table 5.5. The current plan does not address the resolution of the remaining viability issues discussed under System Design and Safety. Only the GIF interaction is currently funded under this 10-yr program plan.

Table 5.5 Ten-year budget profile for SFR activities ($K).

Task	**FY-05**	**FY-06**	**FY-07**	**FY-08**	**FY-09**	**FY-10**	**FY-11**	**FY-12**	**FY-13**	**FY-14***	Total
Interaction with GIF	40										
TOTAL	**40**										

* Amounts and scope for System Design and Safety will need to be determined after system selection in FY 2010, if applicable.

Note that if the SFR technology were selected in FY 2010, a design activity would be started in preparation for the construction phase. This is not included in the current plan.

5.6 Molten Salt Reactor

5.6.1 System Description

Molten Salt Reactors (MSR; see Figure 5.7) are liquid-fueled reactors that can be used for burning of actinides and production of electricity, hydrogen, and fissile fuels. Fissile, fertile, and fission products are dissolved in a high-temperature, molten-fluoride salt with a very high boiling point (1400°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 molten 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.

In the 1950s and 1960s, two experimental MSRs built at the Oak Ridge National Laboratory (ORNL) established the basic technology for the MSR. In addition, there are overlaps between the MSR and the technologies being developed for the NGNP, which would provide the basis for an Advanced Molten Salt Reactor (AMSR) with major improvements in economics and reductions in R&D requirements. Lastly, MSR research is ongoing in Europe. The MSR program is organized to develop an AMSR by integrating the NGNP technology, the historical ORNL MSR technology, and the European technology with its emphasis on fuel cycles.

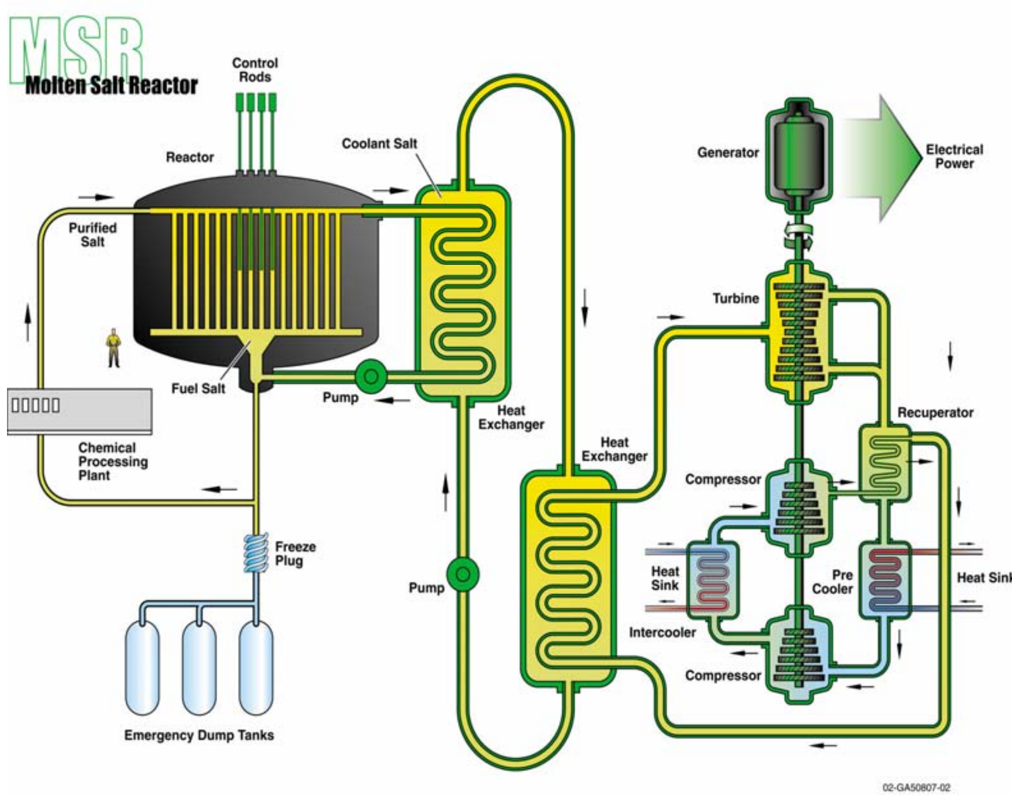


Figure 5.7 Molten Salt Reactor with Brayton Power Cycle

The overall systems timeline is to determine viability by 2014. Because the basic technology of the MSR has been demonstrated, viability is defined as sufficient information to make a credible determination on the commercial viability of a MSR that meets the defined design goals.

The scope of the activities are to (1) develop a conceptual design of an AMSR to provide an understanding of the economics, (2) develop the technologies to the point that there is a reasonable confidence that a MSR could be fully developed, and (3) assess and develop the associate fuel cycle technologies to understand the capabilities of MSRs for multiple missions, such as burning of actinides. Due to limited funding, the scope described here is being performed under related projects, including the GIF, NGNP, AFCI, NHI, and crosscutting programs.

5.6.2 Highlights of R&D

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 (i.e., burning of actinides and production of electricity, hydrogen, and fissile fuel), and issues associated with a modern MSR, thus providing the basis for a decision on whether to initiate a large-scale developmental program with the goal of deployment. The U.S. scope of work associated with the MSR effort includes interaction with GIF in support of the R&D planning and coordination activities.

5.6.3 10-yr Project Budget

The budget projection for the 10-yr period starting in FY 2005 is shown in Table 5.6.

Table 5.6 Ten-year budget profile for MSR activities ($K).

Task	FY-05	FY-06	FY-07	FY-08	FY-09	FY-10	FY-11	FY-12	FY-13	FY-14	Total
Interaction with GIF	40										
TOTAL	**40**										

5.7 Design and Evaluation Methods

5.7.1 Project 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 design and evaluation methods (D&EM) R&D activities are as follows:

- 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.

Design and Evaluation Methods R&D addresses the need for validated analysis tools for designing Generation IV systems and confirming 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 additional phenomena (e.g., fuel behavior, fission gas release, materials damage, chemical reactions, etc.) developed within other elements of the Generation IV, AFCI, and NHI programs.

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

The overall timeline for this research conforms with and supports the timelines for developing the Generation IV systems. Accordingly, the first five years are devoted to providing the capabilities needed for (a) resolution of viability issues for Generation IV systems, (b) development of a high-performance

NGNP design, and (c) down-selection among fast reactor systems. Additionally, there is early emphasis on establishing the evaluation methodologies so that they can 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 NGNP 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 D&EM in a coordinated and cost-effective manner.

5.7.2 Highlights of R&D

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

5.7.2.1 Modeling Improvement. Although Computational Fluid Dynamics (CFD) 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 R&D programs that increase the accuracy of CFD, 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 simulation tool for consistent assessment of concepts is also needed. A planned activity is 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 actinides are significant, and they impact 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 need to be incorporated into inventory tracking tools to ensure that they give accurate results.

The recent and continuing growth in computer power motivates 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 spectral changes 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 & III nuclear power plants. In addition, the existing economic models were not designed to compare nuclear energy systems featuring innovative fuel cycles; energy conversion technologies; and the capability for generating electricity, hydrogen, and other energy products nor 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 systems.

Methodologies currently available for evaluating proliferation resistance and physical protection (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 Methodology Working Group 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. This program is coordinated with NNSA, who also provides funding support.

5.7.2.3 D&EM Program Coordination. This D&EM program component provides for coordination and oversight of R&D activities; maintaining cognizance of related R&D activities conducted in other national and international programs; periodic reporting of results to DOE, GIF, and their advisory review committees; and participation in conferences, workshops, and educational forums.

5.7.3 10-yr Project Budget

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

Table 5.7 Design and Evaluation Methods Funding Requirements through FY 2014 ($K)

Task	**FY-05**	**FY-06**	**FY-07**	**FY-08**	**FY-09**	**FY-10**	**FY-11**	**FY-12**	**FY-13**	**FY-14**	**Total**
Coordination of Design and Evaluation R&D	150										
Improvement of Design and Safety Analysis Capabilities	805										
Development and Application of Evaluation Methodologies	932										
TOTAL	**1887**										

5.8 Energy Conversion

5.8.1 Project Description

Energy Conversion Crosscut R&D focuses on the energy conversion technologies that support implementation of Generation IV reactor systems, through either improved efficiency, reduced costs, or enabling new energy products. Energy conversion technologies that optimally couple to the performance characteristics of Generation IV reactors will result in more efficient and cost effective nuclear electricity, which is an important metric for determining NGNP viability. The cost of electricity from an NGNP is proportional to capital and operating cost recovery 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, directly increase plant output. If the associated incremental costs for the more efficient power conversion cycle are 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. Thus, there is significant motivation to investigate power conversion system approaches that have the potential to maximize the power output of Generation IV systems.

Energy Conversion crosscut involves research on advanced power conversion options for two major categories of Generation IV reactors:

- High-temperature systems (up to 1000°C – NGNP)
- Intermediate outlet temperature systems (550 to 700°C range – GFR, LFR, SFR and MSR).

The development of power conversion options for the intermediate-temperature systems is focusing on the supercritical CO_2 Brayton cycle, which has potential for optimal system efficiency in the 550 to 700°C temperature range. The assessment of high-temperature power conversion options for NGNP addresses both near-term cycle and configuration options that influence cost and performance and longer-term advanced technology options. These studies are intended to provide a basis for evaluation of future power conversion system design studies to be performed as part of the NGNP project. Initially, these studies focus on engineering analyses to determine performance potential and cost implications but will ultimately lead to scaling demonstration experiments for selected options to provide a validated technology basis for next generation technology decisions.

Information on efficiency and cost of power conversion systems for Generation IV reactors will be an important component of system and technology selection decisions. The selection of a sustainable nuclear energy system is currently scheduled for 2010. Energy Conversion Crosscut needs to provide information on supercritical CO_2 Brayton cycle cost and performance by that time to support the selection decision. The Energy Conversion studies also need to address high-temperature Brayton cycle technology options for the NGNP to support the evaluation and selection of proposed power conversion system designs for the NGNP. The stages of this assessment are generally coordinated with the conceptual, preliminary, and final design stages of the NGNP.

To provide the necessary power conversion cost and performance information needed to support technology selection and implementation decisions, the R&D effort will proceed in the following general sequence:

- 2005 – 2007. Power conversion cycle assessments and analyses to address viability issues and performance potential for the range of promising power conversion cycles

- 2007 – 2010. Laboratory-scale demonstrations of components and key technologies to validate analytical assessments

- 2009 – 2014. Pilot-scale demonstrations of selected technologies to confirm engineering approaches and performance.

This sequence of analyses, component development, and small-scale experiments leading to pilot scale experiments for selected power conversion options will demonstrate system performance potential and refine estimates of power conversion system costs.

5.8.2 Highlights of R&D

Previous Energy Conversion Program studies evaluated the cost benefit of Brayton cycle options for improved efficiency for Generation IV outlet temperature ranges. These preliminary studies concluded that several cycle variations, such as interstage heating/cooling, bottoming cycles, or non-ideal gas working fluids, could provide increased efficiency at the cost of additional complexity. The Brayton cycle cost-benefit study (FY-04) also evaluated major component cost implications and concluded that supercritical CO_2 cycles at intermediate temperatures and interstage heating/cooling options at higher temperatures merited further investigation. The Energy Conversion Program is also continuing the evaluation of S-CO_2, including turbomachinery design, plant configuration, and cost estimation, and system control approaches. During FY-04, the Program also initiated a technology assessment for high-temperature He Brayton cycles to provide a basis for comparing and evaluating future power conversion system designs for NGNP. Brief summaries of these activities are given below.

5.8.2.1 Brayton Cycle Cost Benefit Study. The Brayton Cycle Cost Benefit Study (FY-04) evaluated a range of Brayton cycle technology options that could increase the efficiency and, potentially, the cost effectiveness of candidate power conversion cycles. The study provided perspective on the value of these modifications and on the R&D effort that would be required to implement such a system. Several possible Brayton cycle modifications were analyzed to determine the potential efficiency improvement and estimate the incremental cost of the required component changes. A relative cost-benefit approach that was based on changes from a reference recuperated helium Brayton cycle was developed using costs from previous high-temperature gas reactor design studies to provide a baseline for modified cycle cost comparisons. Efficiency improvements were calculated, and the relative costs of the associated modifications were then estimated to define a figure of merit, which was defined as the relative reduction in the cost of electricity generated.

All of the cycle modifications identified below showed potential for efficiency improvement over the reference recuperated Brayton cycle. However, the cost of the cycle modifications in some cases negated any potential performance improvement. The cost of electricity generated for the Brayton cycles evaluated range from 20% cost reductions to net cost increases of up to 30 %, depending on conditions. Some of the key observations included:

- *Interstage heating and/or cooling*. At the higher temperature (1173 K), multiple stage interstage heating and cooling cycles resulted in a reduction of 10 to 15% in the cost of electricity – with significant improvement noted for as few as 2 to 4 stages.

- *Split flow, or recompression*. At the lower temperature (873 K), several cycle modifications showed potential cost benefit. The CO_2 split-flow cycle provides significant efficiency improvement with relatively little increase in system complexity. Both the interstage heated and cooled system and the Rankine bottoming cycle showed significant potential for improvement in this 873 to 1173 K temperature range.

- *Combined cycles*. The combined Brayton-Rankine cycle showed improvement at the lower temperatures, but the improvement was not as much at the higher temperatures. Although the bottoming cycle results in increased efficiency in the 873 to 1173 K range, the positive overall cost-benefit for this approach is notable since it was the most complex system examined. Further analyses based on more detailed designs will be required to confirm these positive results.

- *Alternate working fluids*. Nitrogen or CO_2 working fluids in a standard recuperated Brayton cycle were not cost effective. The reduced heat transfer capability of these working fluids increases heat exchanger costs significantly, which outweigh any calculated higher efficiency.

Although reductions in the cost of power generation of 10 to 20% appear modest, these savings are significant. Achieving the same magnitude of savings from improvements in nuclear system construction costs or operation and maintenance costs is even more challenging. More efficient power conversion systems facilitate the implementation of next generation reactors.

5.8.2.2 Supercritical CO_2 Brayton Cycle. The supercritical CO_2 Brayton cycle has been the focus of Energy Conversion research for the intermediate temperature systems due to the potential for very high efficiency in the temperature range of 550 to 700°C. The very compact turbo-machinery also has the potential for reduced power conversion system capital costs. Work at Massachusetts Institute of Technology has developed preliminary turbine and compressor designs for S-CO_2 systems based on NASA design codes adapted for S-CO_2 working fluid properties. Designs for 300-MWe turbines and compressors that are very compact (approximately 0.8 meters diameter) and very efficient (93%) have been developed. 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 extrapolations from current supercritical steam turbine designs.

Preconceptual designs for a 300 MWe S-CO_2 plant were developed as a basis for preliminary cost and configuration evaluations. These system designs take advantage of the compact turbomachinery and address the heat transfer issues associated with the lower conductivity CO_2. This results in relatively compact power conversion systems for S-CO_2 in comparison with similar sized (300 MWe) supercritical steam or He Brayton 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 steam Rankine system coupled to a high-temperature gas reactor. Work is currently underway to assess the system control issues associated with an S-CO_2 system and the possibilities of demonstrating of key technologies and operations at a cost-effective scale.

5.8.2.3 NGNP Technology Options Study. In anticipation of procuring of an advanced power conversion system for the NGNP, this study was initiated to identify the major design and technology options and tradeoffs that must be considered in the evaluation of a high-temperature He Brayton power conversion system (PCS). These PCS technology options affect cycle efficiency, capital cost, system reliability, maintainability, and technical risk and, therefore, the cost of electricity. This study showed that the key PCS design and configuration choices have a large effect on PCS power density and nuclear island size, making careful and detailed analysis of design tradeoffs important in selection of PCS options. It was also observed that high-temperature reactors appear to be able to achieve lower materials requirements (e.g., steel and concrete) at smaller unit sizes. For high-temperature reactors, a much larger fraction of total construction inputs goes into the nuclear island.

Power conversion system technology options also include variations on the cycle operating conditions and cycle type, which can have an important impact on performance and cost. These options included working fluid choices (He, N_2, CO_2), system pressures, direct vs. indirect cycles, and interstage cooling (or heating).

The PCS configuration and physical arrangement of the system components influences structure sizes, pressure boundary, volume and mass, gas inventories and storage volume, uniformity of flow to heat exchangers, pressure losses, and maintainability. The major factors considered in this study included distributed vs. integrated PCS design approach, shaft orientation (vertical/horizontal), single vs. multiple shafts, and pressure boundary design. These configuration design choices were found to strongly influence both the size and cost of the PCS system and the technology requirements for key components. This study also identified the implications and interdependencies of these features to illuminate the basis for particular choices when evaluating future designs. Current design studies on closed, high-temperature, Brayton-cycle systems have made significantly different choices in these areas. These observations illustrate the complex interactions of the many design choices that will be considered in the NGNP PCS. It is clear that detailed and integrated design efforts must be performed on candidate designs before quantitative evaluations are reliable.

5.8.3 10-yr Project Budget

For FY-05 through FY-14, the Generation IV Energy Conversion Program will complete technology assessments for Generation IV power conversion options, perform preliminary design studies to confirm performance potential and cost implications, perform key technology development experiments, and initiate laboratory- or pilot-scale demonstrations necessary to support technology selections. The major Energy Conversion tasks are the development and scaled demonstration of the supercritical CO_2 cycle for intermediate outlet temperature Generation IV systems, and the evaluation and development of advanced technologies for performance improvement of high-temperature He Brayton cycles for very high-temperature Generation IV systems. The budgets associated with these major activities are summarized in Table 5.8.

Table 5.8 Total Energy Conversion Planning Level Budget FY 2005- FY 2014 ($K)

FY-05	FY-06	FY-07	FY-08	FY-09	FY-10	FY-11	FY-12	FY-13	FY-14	Total
729										

5.9 Materials

5.9.1 Project Description

An integrated R&D program 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 National Materials Crosscut Program (NMCP) is to ensure that the 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 concepts.

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 by 2017 and adequate data to assess the viability of the other Generation IV reactor systems by 2010.

The NMCP explicitly includes the following materials R&D generally considered crosscutting: (1) qualification of materials for service that must withstand radiation-induced challenges; (2) qualification of materials for service that must withstand high-temperature challenges; (3) the development of validated models for predicting long-term, physically based microstructure-property relationships for Generation IV reactors; and (4) the 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. Additionally, it contains the overall management and coordination function for the Generation IV Integrated Materials Program that also addresses materials issues specific to individual reactor and energy-conversion systems. An extensive summary of the overall Generation IV Integrated Materials Program is contained in the draft report *Updated Generation IV Reactors Integrated Materials Technology Program Plan*, Revision 1, ORNL-TM-2003/244 (R1), August 31, 2004.

5.9.2 Highlights of R&D

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 United States 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 concept, it will be necessary to work with the SIMs for each individual reactor concept to examine the range of requirements for its major components to ascertain what the materials challenges and solutions to those will be. It will then be necessary to establish an appropriate breakdown of responsibilities for the widely varying materials needs within the Generation IV Initiative. It is expected that there will be two primary categories for materials research needs:

- Materials needs that crosscut two or more specific reactor system and

- Materials needs specific to one particular reactor concept or energy conversion technology.

Where 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 concept has unique materials challenges, it will be appropriate to address those activities in conjunction with that particular reactor system's R&D. The National Materials Program within the Generation IV Initiative 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.

Reactor-specific materials research that has been identified for the individual reactor and energy-conversion concepts includes materials compatibility 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 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 VHTR as the NGNP by 2017 will strongly drive much of the materials research during the next 10 years of the program. Accordingly, though the four crosscutting activities identified above will include materials of interest to all the reactors, where possible, the emphasis will be on materials that meet the needs of the NGNP while at the same time supporting the other reactor concepts. Where the NGNP materials needs clearly outstrip those of the other reactor systems, they will be addressed independently, and the other reactor systems will be able to utilize relevant results.

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

5.9.3 10-Yr 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 concepts and NHI will be funded by those activities and are delineated elsewhere.

Table 5.9 Funding Requirements for the Generation IV Materials Crosscutting Task ($K)

Task	FY-05	FY-06	FY-07	FY-08	FY-09	FY-10	FY-11	FY-12	FY-13	FY-14	TOTAL
Materials for Radiation Service	391										
Materials for High-Temp Service	195										
Microstructural Modeling	80										
High-Temp Design Methodology (a)	278										
System-Specific Materials (b)	119										
National Materials Program Management	500										
TOTAL	**1,563**										

(a) Detailed required materials database development to be provided under Materials for High-Temperature Service task

(b) Primary funding included in specific system and NTD budgets, only coordination funding shown

6. SUMMARY

The total costs for concept and crosscut R&D are summarized in Tables 6.1 and 6.2. Table 6.1 shows the total required costs for FY 2005 to FY 2014.

Table 6.1 Total Required Costs for FY 2005 to FY 2014 ($M).

	FY-05*	FY-06	FY-07	FY-08	FY-09	FY-10	FY-11	FY-12	FY-13	FY-14	TOTAL
NGNP	30.34**										
SCWR	0.93										
GFR	1.17										
LFR	1.29										
SFR	0.04										
MSR	0.04										
D&EM	1.89										
Energy Conversion	0.73										
Materials	1.56										
TOTAL	**37.99**										

* Includes FY-04 carryover.

** Includes AGR funding.

Table 6.2 FY 2005 Generation IV R&D Allocated Funding at Level 3 by Performer $(K).

WBS Element		ANL-W	ANL-E	BNL	INL	LANL	LLNL	ORNL	SNL	ID	HQ	Total
1.0	**Program**			60	500					2,102	2,398	**5,060**
	1.01 Technical Integration			60	500							560
	1.02 Program Control									200		200
	1.03 Program (Tax & Reserve)										2,398	2,398
	1.04 University									1,902		1,902
2.0	**NGNP**		450		10,292			8,240		6,018		**25,000**
	2.01 Project Integrator									5,320		5,320
	2.02 NGNP Fuels				5,502			4,750		100		10,352
	2.03 NGNP Materials				3,140			3,290				6,430
	2.04 NGNP Methods Validation		450		1,450			200				2,100
	2.05 University									598		598
	2.06 NGNP Other				200							200
3.0	**SCWR**		50		800							**850**
	3.01 Reactor Design		50		410							
	3.02 Materials				390							
	3.03 Energy Conversion											
4.0	**GFR**	100	150	80	295			75		300		**1,000**
	4.01 Reactor Design		150	80	185							
	4.02 Materials	100			70			75		300		
	4.03 Energy Conversion				20							
	4.05 Fuels				20							
5.0	**LFR**	50	293		18	229	410					**1,000**
	5.01 Reactor Design	50	200				170					
	5.02 Materials		93		18	229	240					
	5.03 Energy Conversion											
6.0	**SFR**		40									**40**
	6.01 Reactor Design		40									
7.0	**MSR**							40				**40**
	7.01 Reactor Design							40				
8.0	**Design & Evaluation Methods**		625		175			150				**950**
	8.01 Program Coordination		150									
	8.02 Model Improvement		475		175							
9.0	**Materials**							1,300				**1,300**
	9.01 Program Coordination							400				
	9.02 Radiation Service							350				
	9.03 High-Temp Service							195				
	9.04 Microstructural Modeling							80				
	9.05 HT Design Methodology							200				
	9.06 Reactor-Specific							75				

WBS Element		ANL-W	ANL-E	BNL	INL	LANL	LLNL	ORNL	SNL	ID	HQ	Total
10.0	**Energy Conversion**		70		55			30	445			**600**
	10.01 Program Coordination								75			
	10.02 Adv Electrical Conversion								80			
	10.03 SC CO2 Turbomach		70						270			
	10.04 Adv Heat Transport				55			30	20			
11.0	**Systems Analysis**				100							**100**
12.0	**Bi-Lateral & Multi-Lateral Agreements**	632	745	180	1,067			275		1,111	50	**4,060**
	12.01 Program Admin				50							50
	12.02 GIF Secretariat				253					200	50	503
	12.03 GIF Evaluation Groups											
	12.03.01 Economic Method							75		175		250
	12.03.02 PR&PP Method		100	180						125		405
	12.03.03 Risk & Safety Method				50							50
	12.03.04 GIF Support		40		220							260
	12.05 INTD	357	605		494			200		611		2,267
	12.06 University Sum	275										275
TOTAL (by Lab)		**782**	**2,423**	**320**	**13,302**	**229**	**410**	**10,110**	**445**	**9,531**	**2,448**	**40,000**

7. REFERENCES

1 *National Energy Policy*, National Energy Policy Development Group, May 2001, available at http://www.whitehouse.gov/energy/National-Energy-Policy.pdf, accessed December 2004.

2 Nuclear News, November 2002, pp. 20–26.

3 *A Technology Roadmap for Generation IV Nuclear Energy Systems*, Generation IV International Forum, GIF-002-00, December 2002, available at http://www.inel.gov/initiatives/generation.shtml, accessed January 2004.

4 *The Future of Nuclear Power*, Interdisciplinary MIT Study, 2003, available at http://web.mit.edu/nuclearpower/, accessed December, 2004.

5 *Nuclear Energy: Power for the 21st Century—An Action Plan*, Six DOE Lab Action Plan, April 30, 2003, Executive Summary at: http://nuclear.inel.gov/papers-presentations/default.shtml, accessed December 2004.

6 *Report to Congress – Advanced Fuel Cycle Initiative: Objectives, Approach, and Technology Summary* (Draft), U.S. Department of Energy, January 27, 2005

7 *Advanced Fuel Cycle Initiative (AFCI) Report to Congress*, U.S. Department of Energy, February 2, 2005.

8 *The U.S. Generation IV Implementation Strategy*, U.S. Department of Energy, September 2003, available at http://nuclear.gov/Generation IV/gen-ivstrategy.html, accessed December 2004.

9 *The Annual Energy Outlook 2004*, Energy Information Administration, available at http://www.eia.doe.gov/oiaf/aeo/, accessed December 2004.

10 *Program and Project Management for the Acquisition of Capital Assets,* DOE Order 413.3, U.S. Department of Energy,

11 Schultz, Richard R., et al., *Next Generation Nuclear Plant – Design Methods Development and Validation Research and Development Program Plan,* INEEL/EXT-04-002293, Idaho National Engineering and Environmental Laboratory, September 2004.

12 Bell, G. L., et al., *Technical Program Plan for the Advanced Gas Reactor Fuel Development and Qualification Program,* ORNL-TM-2002/262, Oak Ridge National Laboratory, 2003.

13 Hayner, G. O., et al., *Next Generation Nuclear Plant Materials Research and Development Program Plan*, INEEL/EXT-04-02347, Idaho National Engineering and Environmental Laboratory, September 2004.