Battelle
The Business of Innovation

Nuclear Energy for the Future

Required Research and Development Capabilities

An Industry Perspective

Final – September 2008

Participant Organizations

A total of 35 organizations (including industry, universities, regulators, national laboratories and others) participated in the development of this analysis by offering input, ideas, and/or draft reviews.

Industry

AREVA NP
Bechtel Corporation
Dominion
Electric Power Research Institute
Entergy
Exelon Corporation
FirstEnergy Nuclear Operating Company
General Electric Hitachi Nuclear Energy
Global Nuclear Fuel, LLC
Nuclear Energy Institute
Southern Nuclear Operating Company, Inc.
The Babcock & Wilcox Company – Technical Services Group
UniStar Nuclear Energy
URS Corporation – Washington Division
Westinghouse Electric Company, LLC

Universities

Georgia Institute of Technology
Idaho State University
Massachusetts Institute of Technology
North Carolina State University
Oregon State University
The Ohio State University
University of California, Berkeley
University of Florida
University of Idaho
University of Michigan
University of New Mexico

National Laboratories

Argonne National Laboratory
Idaho National Laboratory
Los Alamos National Laboratory
Oak Ridge National Laboratory
Pacific Northwest National Laboratory
Savannah River National Laboratory

Others

Battelle
Marston Consulting

This analysis is intended to represent the synthesis of data provided and should not be viewed as representing any particular organization's interest nor does organizational participation indicate endorsement.

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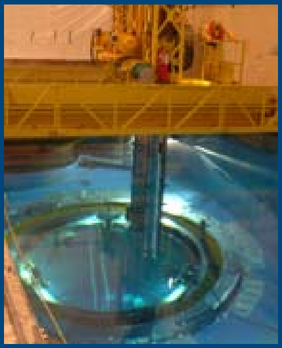
Acronym List

ALWR	Advanced Light Water Reactor
ANL	Argonne National Laboratory
ATR	Advanced Test Reactor
˚C	Degree Celsius
CFR	Code of Federal Regulations
CO_2	Carbon Dioxide
DBT	Design Basis Threat
DOE	Department of Energy
DOE NE	DOE Office of Nuclear Energy
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
FFTF	Fast Flux Test Facility
GNEP	Global Nuclear Energy Partnership
GWd/MTU	Gigawatt Days per Metric Ton of Uranium
HFEF	Hot Fuel Examination Facility
HFIR	High Flux Isotope Reactor
HLW	High-Level Waste
HTGR	High-Temperature Gas-cooled Reactor
HTR	High-Temperature Reactor
HTTR	High-Temperature Test Reactor
I&C	Instrumentation and Control
IAEA	International Atomic Energy Agency
IHX	Intermediate Heat Exchange(r)
IMET	Irradiated Materials Examination and Testing Laboratory

INL	Idaho National Laboratory
INPO	Institute of Nuclear Power Operations
K-12	Kindergarten Through 12th Grade
kWh	Kilowatt Hour
LMR	Liquid Metal Reactor
LTA	Lead Test Assembly
LWR	Light Water Reactor
MC&A	Material Control and Accountability
MMBTU	Million British Thermal Units
MOX	Mixed Oxide
MWth	Megawatt Thermal
NANTeL	National Academy for Nuclear Training e-Learning
NE	Nuclear Energy
NEAC	Nuclear Energy Advisory Committee
NEI	Nuclear Energy Institute
NGNP	Next-Generation Nuclear Plant
NGR	Next-Generation Reactors
NRC	Nuclear Regulatory Commission
NSF	National Science Foundation
ORNL	Oak Ridge National Laboratory
PBMR	Pebble Bed Modular Reactor
PIE	Post-Irradiation Examination
ppm	Parts Per Million
R&D	Research and Development
REU	Research Experience for Undergraduates Program
S&S	Safeguards and Security
SFC	Sustainable Fuel Cycle
SSC	Systems, Structures, and Components
UCO	Uranium Oxycarbide
U.S.	United States
USD	U.S. Dollars
V&V	Validate and Verify

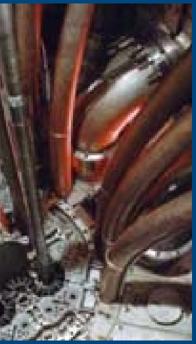


Executive Summary

Nuclear energy has been proven safe, reliable, and affordable. Nuclear energy is poised to play an ever-increasing role in meeting future energy demand and in managing carbon emissions. In response to this opportunity, the nuclear energy industry, together with the U.S. Department of Energy (DOE), is extending the service life of the currently operating reactors, deploying advanced light water reactors (ALWRs), exploring applications beyond electricity production, developing next-generation reactors, and taking steps to close the nuclear fuel cycle. Essential research and development (R&D) capabilities and facilities are required to achieve these goals. Only a portion of the required capabilities and facilities are currently available.

Recognizing these needs, the DOE Office of Nuclear Energy (DOE NE) requested Battelle to coordinate with the domestic nuclear energy industry and the academic community to identify the capabilities and facilities required to support the achievement of the nuclear energy industry's goals. Battelle designed and led a four-step process to identify the required capabilities and facilities. The first step obtained extensive input from the industry and academic communities to define goals for the 2010 to 2050 time frame across six key focus areas—the existing light water reactors (LWRs) and ALWRs, workforce development, the establishment of a sustainable fuel cycle, development of next-generation reactors, regulatory requirements, and safeguards and security. The second step identified and prioritized needed capabilities. The third step identified the gaps between available capabilities and the requirements to fill those gaps. The fourth step identified the types of facilities and resources needed to provide the necessary R&D capabilities.

This multistep process identified many capabilities that will be key to achieving nuclear energy goals, including ensuring the reliability of plant systems, structure, and component materials through the plant's extended lifetime; optimizing training through greater use of technical training centers, new methods, and improved skill and aptitude assessment tools; developing recycling technologies that are economically competitive, are more resistant to proliferation, and minimize waste disposal impact; and enhancing cybersecurity capabilities to ensure the safety and security of plant systems. Although many of the required capabilities exist or are under development in other industries, several capabilities are unique to the nuclear energy industry and require specialized facilities. Such facilities include radiochemistry laboratories, hot cells for post-irradiation examination and radionuclide separations, fuel development laboratories, specialized engineering development laboratories, and prototype reactors for licensing demonstrations.




Action is required to provide the R&D capabilities and facilities unique to nuclear energy in order to achieve the domestic industry's goals identified for the 2010 to 2050 time frame. This analysis identifies five priority R&D facilities including three new facilities. The new facilities are as follows: (1) the High-Temperature Reactor Licensing Demonstration, (2) the Fuel Cycle R&D facilities, and (3) the Fast Reactor Licensing Demonstration. In addition, a further evaluation of needed investment in Nuclear Education Facilities is required. Nuclear facilities require significant capital investment and substantial annual resources to operate and maintain. Facilities currently available in the U.S. DOE complex could satisfy many of the requirements, providing a bridge to the new facilities needed. However, the available facilities fall short of providing much of the critical capabilities required to achieve the nuclear energy industry's long-range goals. In addition, given the age and original purpose of the existing facilities, many of the U.S. DOE facilities require additional investment for improvements and needed modifications. To address these needs, it is recommended that the DOE NE establish the **Strategic Nuclear Energy Capability Initiative**, a multiyear, user-driven initiative to provide the required R&D capabilities and facilities. It is recognized that the cost of providing the required capabilities and facilities is significant. However, the benefits realized in terms of energy security and managing carbon emissions are enormous.

This analysis generated the following conclusions:

1. A robust workforce must be available for the domestic nuclear energy industry to continue with its proven record of delivering baseload electricity in a safe, reliable, and cost-effective manner.

2. The nuclear energy industry has established meaningful goals for the future. These goals include extending the service life of the currently operating reactors, deploying ALWRs, closing the fuel cycle, and developing next-generation reactors leading to new applications for nuclear energy.

3. Essential R&D capabilities and facilities are required to enable the industry to achieve these goals. Through the establishment of a multiyear, user-driven **Strategic Nuclear Energy Capability Initiative**, the DOE NE can provide the needed capabilities and facilities.

4. Successful establishment of the Initiative will also provide the DOE NE with the necessary foundation to build public-private partnerships and international collaboration to facilitate provision of the needed capabilities and facilities.

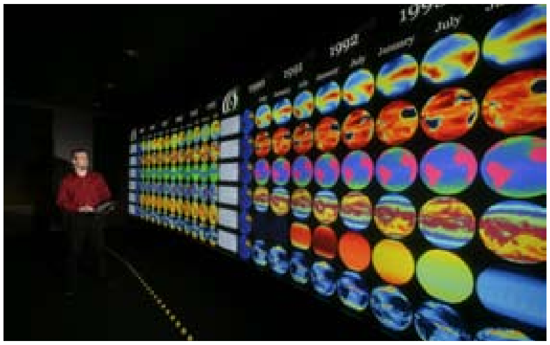
Section 1 – Perspective

We cannot rely on "silver bullets" to address either the national (or global) energy supply/demand situation or to manage global climate change in the next 50 years. The only pragmatic solution to either of these critical issues is a robust portfolio approach with a balance of energy sources. In all reasonable forecasts, nuclear energy must play an ever-increasing role in the generation of electricity, which accounts for roughly one-third of the global, man-made carbon dioxide (CO_2) emissions. However, to deal effectively with the combined threat of climate change and energy security, the role of nuclear energy must be expanded beyond generating electricity, to providing CO_2 emission-free process heat for chemical plants and refineries, and developing nonconventional, indigenous hydrocarbon sources. Eventually, nuclear energy will produce hydrogen from water to provide transportation fuels and enable the production of gases and liquids from our most abundant nonconventional hydrocarbon—coal—without the emission of large quantities of CO_2. A sidebar discussion on the following page provides an energy and environmental perspective for this report.

The U.S. Department of Energy (DOE), in particular, the Office of Nuclear Energy (DOE NE), must be a key driver in the continuing development of energy from fission. The nuclear energy industry's prioritized areas of focus, as articulated by the Nuclear Energy Institute (NEI), include the following:

- Safe and economic operation of the current fleet of 104 nuclear plants for as long as possible—to 80 years and beyond
- Introduction of new advanced light water reactors (ALWRs) through a manageable licensing process with reasonable financial risks
- Development and demonstration of a new generation of nuclear energy sources that will provide a useful range of emission-free process heat (250 degrees Celsius [°C] to 750°C) and higher temperatures (950°C) for efficient production of hydrogen and oxygen from water
- Closure of the nuclear fuel cycle to assure a reliable source of future nuclear fuel that has no undue proliferation risk and that minimizes the burden on deep geological disposal.

These focus areas require access to existing capabilities and development of new capabilities. Some existing capabilities that are common in other industries include automation, advanced instrumentation and control, knowledge management, high-capacity computing, and nano-materials. Existing capabilities that are needed by only a limited subset of other industries include automated welding and inspection techniques, training and simulation of operation, and heavy component construction. However,



a few capabilities are unique and vital to the further development and deployment of nuclear energy. These include high-capacity test reactors to irradiate materials and fuels, hot cells for examination, radiochemistry to develop alternate fuel cycles, new reactor demonstrations for higher-temperature systems, transmutation of undesirable fission products, utilization of certain fissionable materials as fuel, and the practical transformation of nonfissionable isotopes into fuel.

This report identifies the characteristics of capabilities required to achieve long-term goals of the nuclear energy industry and DOE NE. Most of this analysis highlights required research and development (R&D) facilities that are unique to nuclear energy (see Section 4). The remaining sections of this analysis include the following:

Section 2 – Articulates goals for the use of commercial nuclear energy using input from a broad range of participants (see Appendix A).

Section 3 – Translates the goals into capabilities required to achieve the goals, identifies gaps in existing and required capabilities, and proposes mechanisms to close identified gaps.

Section 4 – Identifies required R&D facilities that are unique to nuclear energy.

Energy and Environment – A Future View

Approaching the middle of the 21st century, the price (and availability) of natural gas has reached a level of $12 U.S. dollars (USD) (2008) per million British Thermal Units (MMBTU), making it too expensive to burn as an industrial fuel and limiting its uses to chemical feedstock and household heating. The price of carbon has reached a level of over $40 USD (2008) per metric ton. Even with strong measures to increase the efficient use of electricity, the demand in 2050 is expected to be double that in 2010. Carbon capture and sequestration is a viable, but expensive, approach to reducing CO_2 emissions from fossil-fired power plants. Electricity from "renewable" generation has reached a record 25 percent in 2045 with the advent of large wind machines and affordable solar panels using thin-film technologies. Geothermal developments are increasing each year. Technology makes it possible to extract almost 40 percent of the potential energy from each pound of uranium, and the volume of vitrified waste being placed into deep geological disposal is a fraction of what was thought possible in 2010. With the advent of new extremely low emission generation technologies, an atmospheric CO_2 concentration of 450 parts per million (ppm) is deemed to be practical within 30 years.

Oil has stayed at an inflation-corrected $130 USD per barrel for some time. Oil imports are down to a record low of 10 percent. The use of nuclear energy to provide reliable process heat and hydrogen is growing steadily. The earliest nuclear power plants are finally being decommissioned after 80 years of safe operation. Electricity and hydrogen now account for roughly one-half of automotive fuel. Bio-diesel and nonconventional hydrocarbon-derived diesel fuel all truck and rail transport.

Section 5 – Identifies recommended priorities and actions.

Section 6 – Provides analysis conclusions and a statement of expected benefits.

Appendices A, B, and C – Outline the process used for the 2010 to 2050 nuclear energy industry goal development, identification of required capabilities, and required capabilities transferred from or developed with other industries.

This analysis represents one phase of a three-phase process designed to develop a DOE Nuclear Energy Plan to ensure the highest priority facilities and staff are available through 2050 to meet the key objectives of the nuclear energy industry, as shown in Figure 1-1. Another phase is a parallel effort led by Idaho National Laboratory (INL) to assess the condition and readiness of current domestic and international facilities that could be used to provide the needed capabilities identified in Section 3 of this report. The final phase is to integrate the outputs of this "top-down" study and the "bottom-up" INL effort to develop a prioritized list of capabilities required to meet the long-term goals of the nuclear energy industry.

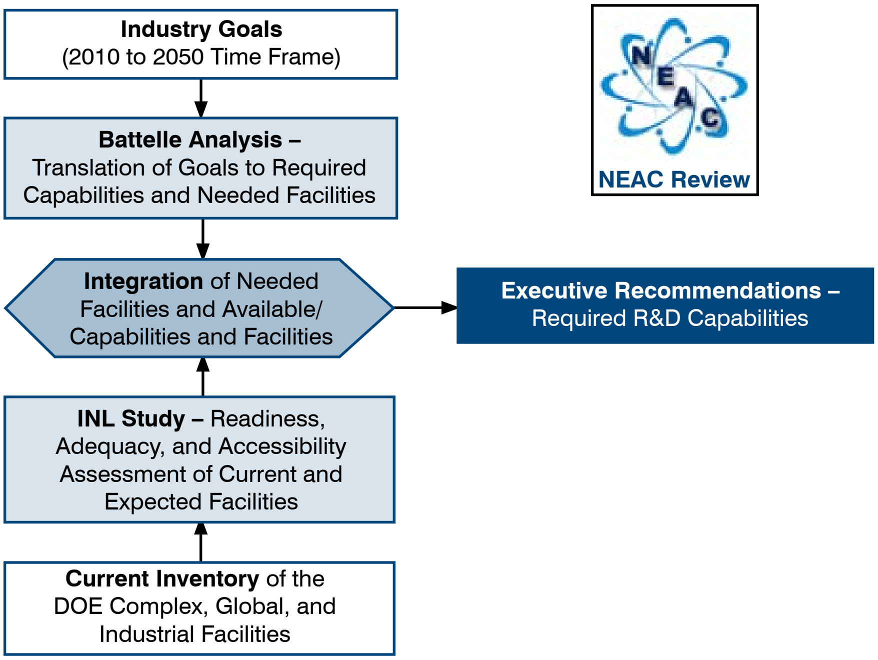


Figure 1-1. Top-Down/Bottom-Up Processes for Developing a Rank-Ordered Nuclear Energy Facilities Program (Nuclear Energy Advisory Committee [NEAC] review provided in the blue-colored steps)

Section 2 – Nuclear Energy Industry Goals 2010 to 2050

Systematic data gathering from industry, academia, and national laboratory participants was used to identify long-term nuclear energy industry goals, which in turn defined the R&D capabilities needed to support the domestic nuclear energy industry. Details of the Battelle-led data-gathering process are described in Appendix A. Information about specific subjects was elicited in several areas based on the key focus areas described in Section 1, with some modification in response to comments regarding the cross-cutting issues of workforce development (How do we provide the workforce necessary for the future?), regulatory requirements (What should the regulatory environment look like in the future?), and safeguards and security (How do we adapt to changing security requirements?). Life extension of the existing light water reactor (LWR) fleet was combined with the ALWR focus area mentioned in Section 1, because these topics are more near-term and have similar R&D capability requirements. Thus, the list of focus areas follows: (1) existing LWRs and ALWRs, (2) workforce development, (3) sustainable fuel cycle, (4) next-generation reactors, (5) regulatory requirements, and (6) safeguards and security. The balance of this section describes the goals for the 2010 to 2050 time frame for each of the focus areas identified as a result of the data Battelle gathered from study participants (see Appendix B).

2.1 Existing LWRs and ALWRs

FOCUS AREA 1

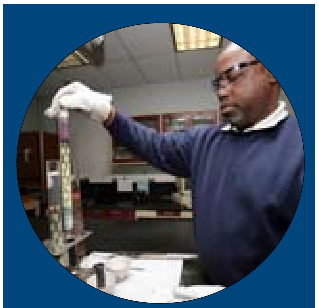
Existing LWRs and ALWRs

The current inventory in the United States includes 104 operating LWRs and several types of ALWRs in the Title 10, Code of Federal Regulations (CFR), Part 52 licensing process. Early in 2008, the first new nuclear power plant was ordered—the first in 30 years. Operation of existing reactors has been outstanding, producing 807 billion kilowatt hours (kWh) of electricity in 2007, with a capacity factor exceeding 90 percent. Continued operation of the current fleet will provide electricity in a safe, affordable, and carbon-neutral manner. However, ALWRs must be deployed to create new generating capacity to meet the forecasted increased electricity needs—offering the reliability of the existing fleet with improvements in safety and efficiency without increasing the U.S. carbon footprint. Industry goals for the existing LWRs and new fleet of ALWRs are as follows:

- Extend the lifetime of the current fleet to “life beyond 60” years while maintaining the current excellent safety record and high reliability (greater than 90 percent average fleet capacity factor).
- Build and deploy an additional 100 to 250 ALWRs. Using lessons learned from plant construction, evolve design and construction techniques to reduce schedules and costs. Design plants for reduced water consumption.

- Address material aging in existing reactors by implementing optimal aging management programs for:
  - Major pressure-retaining components and core internal structures
  - Key support systems, structures, and components (SSC), including cabling and concrete structures.
- Improve current fuel types to eliminate leaking fuel pins. Develop new fuel/clad combinations that increase burnup to 100 gigawatt days per metric ton of uranium (GWd/MTU).
- Replace existing analog instrumentation and control (I&C) systems with digital systems that can be upgraded as technology advances—with full regulatory acceptance where appropriate.
- Develop prognostic equipment that optimizes maintenance programs and also provides condition status reports to plant operators.

2.2 Workforce Development



FOCUS AREA 2

Workforce Development

In the 2010 to 2050 time frame, the nuclear energy industry will require a new workforce to operate both the existing fleet of reactors as well as new advanced reactors. Industry organizations (e.g., NEI, Electric Power Research Institute [EPRI]) currently are predicting significant shortfalls in trained operations staff, design engineers, construction workers, technicians, radiation protection personnel, and related technical staff. Aggressive near-term steps must be taken to ensure availability of a fully trained workforce. Goals identified by the nuclear energy industry are as follows:

- Establish a robust pipeline of new staff at all levels for all skill sets.
- Actively develop the next generation of engineers by promoting DOE, EPRI, and Nuclear Regulatory Commission (NRC) scholarship/fellowship programs that encourage students to enter nuclear energy fields at both the undergraduate and graduate levels to supply industry and government needs.
- Encourage a fresh, relevant advertising campaign, capitalizing on the current high level of awareness and interest in energy. Highlight the strategic importance of the nuclear energy industry and the career opportunities available to meet some of the nation’s biggest challenges.
- Encourage collaboration among universities, national laboratories, and industry to leverage infrastructure and enhance the skills of the entering workforce—including implementation of impactful rotational assignments to provide more effective education and training opportunities.
- Facilitate students entering technical fields of study through effective K-12 programs in collaboration with other industry and government initiatives (e.g., science, technology, engineering, and math education).
- Develop new technologies to capture exiting workforce knowledge and integrate this information into training programs, reference databases, and knowledge transfer tools. Retrain staff for new jobs where appropriate (including displaced staff from other industries)—improving staff retention rates.
- Deploy centralized, standardized, and cost-effective regional training centers for staff. Provide remote training tools for qualification, such as the Institute of Nuclear Power Operations’ (INPO’s) National Academy for Nuclear Training e-Learning (NANTeL) information system.

FOCUS AREA 3

Sustainable Fuel Cycle

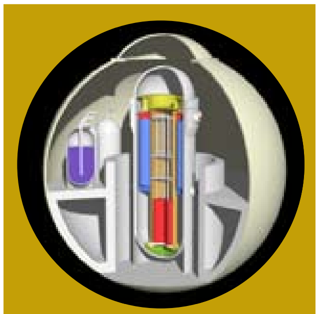
2.3 Sustainable Fuel Cycle

The current fuel cycle is open and uses only a few percent of the potential energy in uranium. Used nuclear fuel is discharged and cooled; eventually, it will be deposited into a deep geologic repository. The proposed repository at Yucca Mountain will reach its planned regulatory limit within three years, based on the current inventory and generation rate of used fuel. The fuel can be safely stored outside the repository for at least 100 years. Under the Nuclear Waste Policy Act, the DOE is obligated to take title of the used fuel and provide for its disposition. The nuclear energy industry is anxious for DOE to fulfill its responsibility.

Most of the "waste" in used fuel consists of cladding, hardware, and uranium. The troublesome elements—those that have long half-lives and must be managed for long times in the repository—contribute only about 3 to 4 percent of the total mass. By separating the various components of used nuclear fuel, it would be possible to concentrate the "difficult-to-deal-with" materials into much smaller volumes, effectively lengthening the operating life of the repository. A sustainable fuel cycle would use a significantly greater portion of the available energy. Adequate natural uranium resources are projected to be available to support the anticipated growth of nuclear energy in the United States through mid-century. The price of uranium will likely increase as the supply of easily recoverable uranium is reduced.

Industry desires the establishment of a sustainable fuel cycle, including the timely removal of used fuel from the reactor. The fuel can be recycled to ensure an affordable supply of uranium, and more compact waste forms can be developed. Industry needs a sustainable fuel cycle—one that provides reliable fuel at a competitive price. The goals identified for such a sustainable fuel cycle are as follows:

- Ensure that a secure, cost-effective, sustainable fuel supply exists.
- Close the fuel cycle through the recycling of used fuel in a cost-effective manner.
- Ensure that adequate deep geological disposal for high-level waste (HLW) and used fuel exists, with retrievability maintained for 100 years.
- Provide advanced safeguards to ensure control of the materials recovered from fuel recycling.



FOCUS AREA 4

Next-Generation Reactors

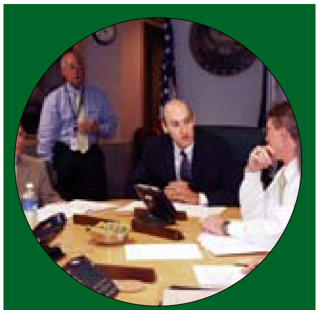
2.4 Next-Generation Reactors

The nuclear energy industry (including electric utilities and oil, gas, and chemical companies) has identified key roles in nontraditional areas for advanced reactor systems to significantly contribute to the nation's energy needs with increased security of supply. These areas include high-temperature reactors (HTRs) to supply process heat and hydrogen to oil refineries and chemical plants for the development of nonconventional hydrocarbon resources (i.e., oil sands and oil shale deposits). Additionally, HTRs, coupled with coal-to-liquids and coal-to-gas plants will allow the utilization of coal, our largest domestic hydrocarbon resource, to produce feedstock for refineries and chemical plants with essentially no CO_2 emissions. Smaller, grid-appropriate reactors could be deployed to areas of the country and the world that cannot support large ALWRs. Finally, fast reactors could be developed to transmute materials to reduce waste toxicity and enhance the use of uranium. The specific goals identified by industry are as follows:

- Use advanced reactors for process heat generation and/or hydrogen production.
- Develop and deploy grid-appropriate reactors.
- Develop and implement fast reactors to support fuel cycle sustainability.

- Ensure that new materials are commercially available for the advanced reactor fleet.
- Deploy advanced reactors rapidly into the marketplace.

2.5 Regulatory Requirements



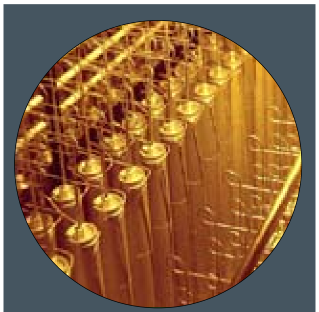
FOCUS AREA 5

Regulatory Requirements

Regulation of existing nuclear power plants as well as advanced nuclear reactors and fuel facilities must meet high expectations for public safety. The high level of confidence the public currently has in the ability of the NRC to protect general health and safety must be maintained. Regulatory agencies must begin addressing the challenges involved in developing a regulatory framework for new reactors and fuel recycling technologies. The study participants identified the following goals:

- Establish a significantly more efficient, consistent regulatory process.
- Establish a collaborative industry/regulatory agency relationship to address non-LWR technologies (i.e., advanced reactors and fuel facilities). Such a relationship will optimize the licensing and design function, while maintaining regulatory objectivity and independence.
- Develop a standardized, automated application process for all technologies.
- Ensure harmonization of safety standards to facilitate safe global deployment of new technologies.

2.6 Safeguards and Security



FOCUS AREA 6

Safeguards and Security

The need to maintain current high levels of safeguards and security (S&S) as well as develop new technologies for safeguards is a pervasive, core requirement for the nuclear energy industry. Currently, maintaining S&S involves labor-intensive and expensive approaches that rely on guns, guards, and gates. Implementation of S&S must ensure future cost competitiveness. The analysis participants identified several goals:

- Optimally use technology to ensure materials accountability and effectively assess and manage physical and cyber threats.
- Implement "safeguards-by-design" philosophies in the design of reactors and the fuel cycle.
- Develop and implement international S&S agreements to minimize proliferation.

These three general areas go hand-in-hand in forming an integrated and effective system that is optimized for both S&S effectiveness as well as incremental cost efficiency. As such, the following technologies will be required for materials accountability and physical and cyber threats:

- Online and at-line advanced detection instrumentation (radiation and non-radiation based),
- Advanced data integration and control systems, and
- Containment and surveillance, tags and seals, and intrusion detection and neutralization.

Formalized implementation of "safeguards-by-design" philosophies must take into consideration both domestic licensing requirements as well as international S&S agreements. In other words, the "safeguards-by-design" concept must go beyond an individual facility design and be applied in aggregate for the nuclear fuel cycle.

Section 3 – Identify and Close the Required Capability Gaps

To achieve the nuclear energy industry goals articulated in Section 2, certain capabilities must be available in the 2010 to 2050 time frame. This section identifies the required capabilities and defines any gaps that exist between currently available capabilities and those required in the future. Further, a mechanism for closing each identified gap is proposed.

As discussed in Section 2, diverse nuclear energy industry groups provided input into defining the goals for the 2010 to 2050 time frame in the form of workshops, focus group meetings, and interviews. Appendix A describes the process used to identify the necessary capabilities to achieve industry goals. In Appendix B, the identified capabilities are mapped to priority capabilities identified in workshops held in Columbus, Ohio, and Washington, D.C. Table 3-1 presents the required priority capabilities for each of the six focus areas. These capability requirements formed the basis for a follow-on gap analysis conducted by workshop participants to define necessary actions to meet nuclear energy industry goals for the 2010 to 2050 time frame.

3.1 Process to Identify and Close Capability Gaps

Figure 3-1 illustrates the multistep process to identify the capability gaps and proposes mechanisms to close the gaps. Each required capability was evaluated to determine the following key characteristics or properties:

1. Whether the capability is unavailable today and is required by a number of other industries. If so, the closure strategy is to transfer and adopt the technology to the needs of the nuclear energy industry. Examples include advanced instrumentation and control, high-performance computing, nano-materials, general-use digital sensors, and knowledge capture techniques.

2. Whether the capability is unavailable today and is of interest to other industries as well. If so, the closure strategy is to co-develop the capability with the other industries. Once developed, the capability must be validated and verified (V&V) for use in nuclear applications and deemed to be acceptable by the NRC, if it is safety-risk significant. Examples include heavy section welding, specialized sensors, non-destructive evaluation techniques, operational training, and advanced maintenance technologies for heavy process equipment.

3. Whether the required capability is unique to the nuclear industry and exists today only in the United States. If so, the closure strategy is to ensure that the capability

Table 3-1. Required Priority Capabilities for 2010 to 2050

Focus Area	Required Priority Capabilities
Existing LWRs and ALWRs	• **SSC Reliability.** Manage the reliability of the plant SSC materials through the plant's extended lifetime • **Fuel Performance.** Improve fuel performance • **Technology Innovations.** Adopt technology innovations to enhance plant performance and workforce productivity • **Manufacturing and Construction.** Enhance manufacturing and construction methods for plant life extension upgrades and construction of new plants
Workforce Development	• **Optimize Training.** Optimize training through adoption of proven approaches from other industries, greater use of technical training centers, new methods, and improved skill and aptitude assessment tools • **Knowledge Management.** Adopt knowledge management methods and techniques to enhance cross-generational knowledge retention, workforce development, and effective use of lessons learned • **Sustainable R&D.** Enhance nuclear education/training and research infrastructure to deliver a more effective multiyear, sustainable science and engineering R&D program to train the next generation of scientists and engineers • **Innovative Energy Educator.** Enhance innovative energy educator programs to effectively reach K-12 students—working with industry to build the pipeline
Sustainable Fuel Cycle	• **Geologic Repository.** Develop a geologic repository for the disposal of used nuclear fuel and HLW • **Interim Storage.** Develop an interim storage facility for receipt of used nuclear fuel • **Recycling Technologies.** Develop recycling technologies that are economically competitive, increasingly proliferation resistant, and minimize impact on waste disposal
Next-Generation Reactors*	• **Fuels Development.** Develop new fuels • **Heat Transport.** Understand heat transport for new applications • **Modeling and Simulation.** Enhance modeling and simulation capabilities • **Materials Development.** Develop improved materials
Regulatory Requirements	• **Licensing Efficiency.** Improve the NRC license application and review process • **Basis for NGR and SFC.** Establish risk-informed regulatory basis for next-generation reactors (NGRs) and sustainable fuel cycle (SFC) activities • **Staffing.** Ensure appropriate regulator staffing and effective staff training to meet job requirements including NGRs and SFC activities
Safeguards and Security	• **Optimized Technology.** Use technology to optimize the use of guns/guards/gates • **Cybersecurity.** Enhance cybersecurity capabilities to ensure systems security and plant safety • "**Safeguards-by-Design.**" Design advanced safeguards approaches and technology into ALWRs, NGRs, and fuel facilities

* Includes grid-appropriate reactors, reactors for the production of process heat, and reactors required for closure of the fuel cycle.

is maintained in an acceptable state of readiness and is accessible when needed. An example is the Advanced Test Reactor (ATR) at INL.

4. Whether the required capability is unique to the nuclear industry and is available globally. If so, the closure strategy is to ensure access and sustainability of the capability (through financial support, if necessary) and confirm the acceptability to the U.S. market (e.g., the NRC, owner operators, and the public). An example is the International Materials Aging Institute organized by Électricité de France.

5. Whether the nuclear-unique capability is unavailable globally. If so, then the U.S. nuclear energy industry, including the DOE, owner operators, designers, construction contractors, and related organizations (such as EPRI and INPO) must develop and maintain the capability as long as it is required to meet the goals of the industry. Examples include advanced radiochemistry laboratories, process demonstration facilities, and fast test reactors.

The nuclear-unique, gap-closure mechanisms are highlighted in dark blue in Figure 3-1.

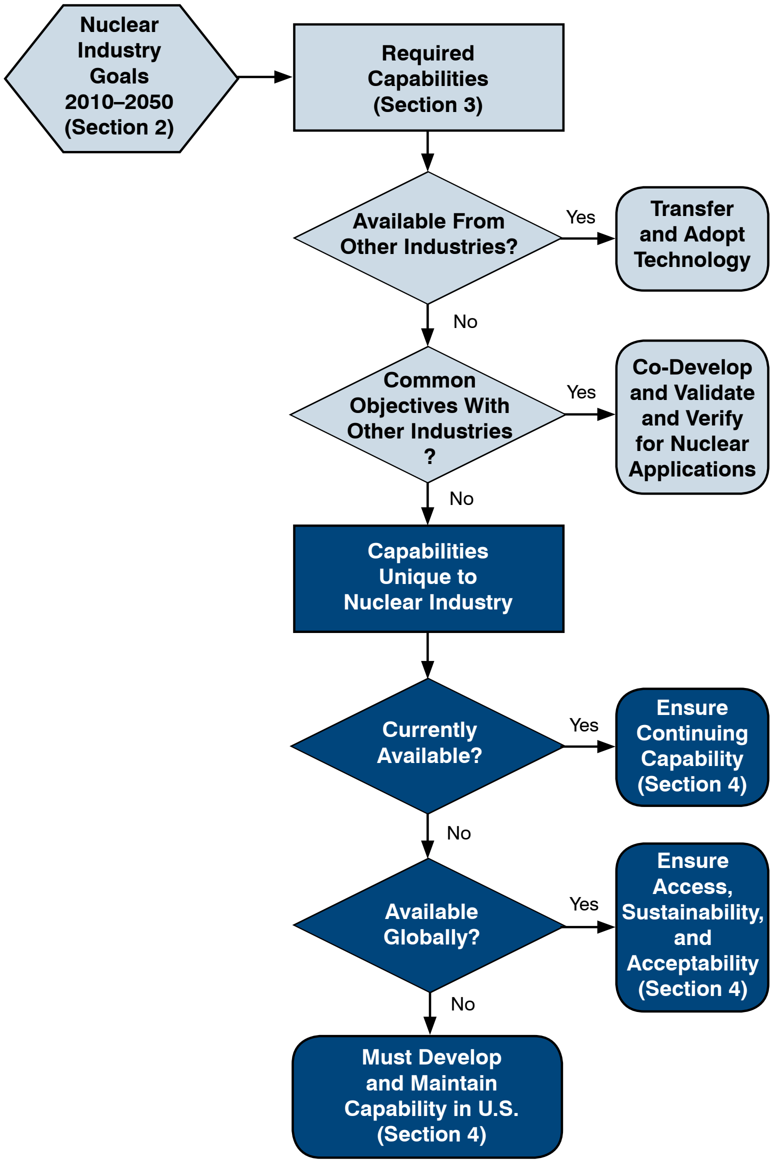


Figure 3-1. Capability Gap-Closure Flow Chart

3.2 Actions Needed to Close Required Capability Gaps

The difference between the capabilities available today and those required in the future represents gaps that need to be filled. The process described in this section and Figure 3-1 provides guidance on effectively and efficiently closing these gaps.

An expert panel reviewed each required capability and determined which portion of the capability could be transferred from other industries and which portion could be effectively co-developed with other industries. The residual gaps in the required capabilities must be closed within the nuclear energy sector. Each residual gap was further apportioned (through a subjective process) to the following three capability categories: domestically available, globally available, and needs to be developed.

The process and results were reviewed by an independent set of outside experts from industry, academia, and the national laboratories, and were deemed to be appropriate. Each required capability and its gap closure strategy is summarized in Table 3-2. The expert panel determined that to receive a check mark on Table 3-2, the identified source needed to provide at least 25 percent of the needed capability.

For example, consider the actions required to close the capability gaps for Next-Generation Reactors – Materials Development from Table 3-2. Some of the materials technology can be jointly developed with the fossil power industry, particularly for the ultra super critical power plants that experience temperatures in excess of 700°C. Portions of the materials development required for HTRs can be manufactured in existing U.S. facilities, such as thermal test reactors and hot cells. Some fast reactor materials development can be affected in global, nuclear-unique facilities, such as fast test reactors. Finally, some fast reactor materials demonstration can be conducted only in new facilities, such as a fast reactor demonstration project.

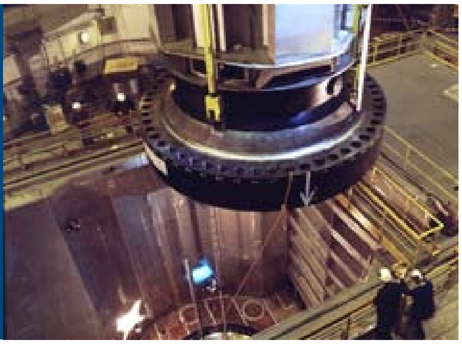
Table 3-2. Sources of Required Capabilities to Meet Nuclear Energy Industry Goals in the 2010 to 2050 Time Frame

Required Capability	Transfer From Other Industries	Co-Develop With Other Industries	Nuclear Unique — U.S. Available	Nuclear Unique — Globally Available	Nuclear Unique — Develop in U.S.
			Nuclear Unique (see Section 4)		
Existing LWRs and ALWRs					
SSC Reliability	√		√	√	
Fuel Performance			√	√	
Technology Innovations	√	√	√		
Manufacturing and Construction	√	√		√	
Workforce Development					
Optimize Training	√	√	√		
Knowledge Management	√		√		
Sustainable R&D	√		√		√
Innovative Energy Educator	√	√			
Sustainable Fuel Cycle					
Geologic Repository*					√
Interim Storage**					√
Recycling Technologies			√	√	√
Next-Generation Reactors					
Fuels Development			√	√	√
Heat Transport	√	√			√
Modeling and Simulation	√		√	√	√
Materials Development		√	√	√	√
Regulatory Requirements					
Licensing Efficiency	√		√	√	
Basis for NGR and SFC			√	√	√
Staffing	√		√		
Safeguards and Security					
Optimized Technology	√	√			
Cybersecurity	√	√			
“Safeguards-by-Design”			√	√	√

* Under the Nuclear Waste Policy Act of 1982, DOE’s Office of Civilian Radioactive Waste Management is responsible for the development of the geologic repository. This capability is outside the scope of DOE NE and is not addressed in this report.

**Interim storage of used fuel prior to transport to the repository is the responsibility of the nuclear energy industry. This capability is outside the scope of DOE NE and is not addressed in this report.

Section 4 – Required Nuclear Energy R&D Facilities



The analytis provided in this section is focused on identifying the general types of nuclear facilities required to realize the needed unique nuclear capabilities previously identified in Section 3. In turn, these capabilities will enable the nuclear energy industry to achieve the 2010 to 2050 goals described in Section 2. Facilities in the context of this section can span the range of plant simulators that provide classroom training for power plant operators, to heavily shielded, hot cell facilities for examination and testing of irradiated materials. Additional examples of the nuclear-unique capabilities requiring facilities include the ability to irradiate and test materials to evaluate the reliability of plant component materials, and to support development of recycling technologies that are economically viable, more resistant to proliferation, and improve waste disposal.

A fully coordinated complementary assessment entitled "Required Assets for a Nuclear Energy Applied Research and Development (R&D) Program" is being led by INL. This assessment will identify various facilities now available throughout the DOE complex, in the domestic energy or related industries, or internationally that could be called upon to implement the R&D capabilities described in this analysis. This analysis will provide input to that assessment. Outcomes and recommendations from that assessment are expected by the end of September 2008.

Finally, the facilities addressing these capabilities require significant capital investment and substantial annual resources to operate and maintain. Facilities currently available within the DOE complex, industry, and academic institutions will satisfy only a fraction of the requirements. In some cases, international collaboration could provide access to a portion of the needed facilities. However, currently available facilities fall short of providing several of the critical capabilities required to achieve the nuclear energy industry's long-range goals. In addition, given the age and original purpose of existing facilities, many DOE facilities require additional investment for improvements and needed modifications.

4.1 Identification of Facility Requirements

As mentioned previously, the nuclear-unique capabilities identified in Table 3-2 require facilities in order to conduct necessary research. The general facility types identified in this analysis include nuclear education facilities, thermal irradiation facilities, fast irradiation facilities, radiochemistry laboratories, hot cells for separations, hot cells for post-irradiation examination (PIE), thermal transport, fuel development laboratories, licensing demonstration for HTRs, licensing demonstration for fast reactors, and specialized engineering development laboratories (cold laboratories). Subject matter experts from academia, industry, and national laboratories identified these facility types during a round table discussion. Table 4-1 provides a summary mapping of capabilities into facilities. Specifically, the unique nuclear capabilities listed in Table 3-2 are mapped with the type of nuclear facility (or facilities) required. In the context of Table 4-1, facilities refer to all types of facilities—whether owned by industry, government, or available for use as a result of international collaborations.

As a specific example, the first entry in Table 3-2 is "SSC Reliability," which will require irradiation of materials followed by PIE of these test specimens to determine the effects of irradiation on the remaining useful life of the material. This capability maps into two types of facilities—thermal irradiation and hot cells for PIE and materials testing. The same logic was used to map the balance of the capabilities into the facilities as shown in Table 4-1.

Brief descriptions of the required nuclear facilities follow in Section 4.2.

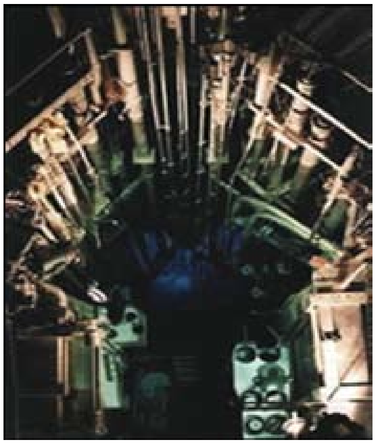
4.2 Description of Resources

The resources listed in Table 4-1 are briefly described below. INL staff are conducting a companion study to review existing domestic and international facilities for material condition, capability, readiness, and availability.

4.2.1 Nuclear Education

Nuclear education facilities provide hands-on education and training for the next generation of scientists and engineers. These facilities include teaching laboratories, research laboratories, training centers, research and training reactors, reactor and fuel recycle training simulators, hot cells for research activities, and computation centers.

Enhancement of nuclear education and training infrastructure enables creation of more effective multiyear R&D programs to train next-generation scientists and engineers. It also creates opportunities to leverage infrastructure investments through development of collaborative user facilities and research programs and helps provide additional internship and cooperative education opportunities for students as well as rotational assignments for nuclear energy industry workers. Increases in both undergraduate and graduate populations require commensurate growth in nuclear education facilities to ensure students are educated on modern and relevant techniques and instrumentation. Investment in nuclear education and training facilities encourages optimization of education and training programs through introduction of new methods, tools, and greater use of technical training centers. In addition, it provides an opportunity to more fully integrate knowledge management methods and techniques into education and training to enhance cross-generational knowledge retention, workforce development, and effective use of lessons learned.



Using the University of Missouri Research Reactor Center's resources, students participate in the National Science Foundation's (NSF's) Research Experience for Undergraduates Program (REU). The in-depth hands-on research opportunities offered through REU whet the appetites of college undergraduate students to pursue advanced degrees in nuclear science and engineering.

Table 4-1. Matrix of Necessary Nuclear-Unique Capabilities and Required Resources

Required Resource Required Capability	Nuclear Education Facilities	Thermal Irradiation Facilities	Fast Irradiation Facilities	Radio-Chemistry Laboratories	Hot Cells for Separations	Hot Cells for PIE
Existing LWRs and ALWRs						
SSC Reliability		X				X
Fuel Performance		X		X		X
Technology Innovations	X					
Manufacturing and Construction						
Workforce Development						
Optimize Training	X					
Knowledge Management	X					
Sustainable R&D	X					
Sustainable Fuel Cycle						
Recycling Technologies	X	X	X	X	X	X
Next-Generation Reactors						
Fuels Development	X	X	X	X		X
Heat Transport	X					
Modeling and Simulation	X	X	X			
Materials Development	X	X	X	X		X
Regulatory Requirements						
Licensing Efficiency	X					
Basis for NGR and SFC	X					
Staffing	X					
Safeguards and Security						
“Safeguards-by-Design”	X			X	X	

Increasing research opportunities will increase enrollment in graduate degree programs in universities across the United States. NEI and several operating nuclear utilities and nuclear vendors have initiated educational outreach activities to encourage interest in science and technology careers. The nuclear energy industry and government also have been proactive in undertaking several initiatives (such as EPRI’s in-service inspector training and qualification program) to improve training of workers and increase knowledge retention as the current workforce ages and retires.

Although several leading universities across the United States have nuclear education facilities, growth has not kept pace with the recent increase in demand or the number of students pursuing degrees in nuclear science and engineering. Further evaluation to define the specific nuclear education facilities is required. To augment available Federal funding sources (DOE, NRC, and NSF), the use of public-private partnerships could be investigated to provide funding for upgrading current facilities and constructing new facilities. Training of nuclear workers is generally tailored to individual plants and

Thermal Transport Facility	Fuel Development Laboratories	Licensing Demo-HTR	Licensing Demo-Fast Reactor	Specialized Engineering Development Laboratories
	X			
				X
				X
	X		X	X
	X	X	X	
X		X	X	X
X		X	X	
		X	X	
		X	X	X

conducted at the plant site. More recently, INPO has undertaken an initiative to provide standardized and centralized training. The feasibility of regional training centers and additional standardized training programs should also be evaluated.

4.2.2 Thermal Irradiation

To manage the aging of reactor vessel material and core internals and develop higher burnup LWR fuels, the nuclear energy industry must have access to test reactors that can irradiate materials and fuels in neutron spectra that match those of the operating LWRs and the soon-to-be-built ALWRs. Only with neutron flux levels that exceed those in service can realistic accelerated aging results be achieved. In addition to the irradiation capability, the PIE and testing of materials and fuels require hot cells of sufficient size and capability to provide meaningful knowledge of the aging mechanisms (see Section 4.2.6).

INL's ATR is capable of irradiating large fuel and materials experiments.

These capabilities are necessary to support the extended life (greater than 60 years) operation of the existing 104 U.S. reactors and to support the reliable and safe operation of the new fleet of ALWRs to be constructed in the next decade or so. The first commercial power orders in 30 years were placed in early 2008 by the Southern Company, NRG Energy, Inc., and South Carolina Electric and Gas Company. The results of the systematic irradiation and testing of new fuel designs will help reduce the time to develop reliable fuel designs that provide extended burnup of fuel (up to 100 GWd/MTU), resulting in improved economics and reduced waste volume and shipments. Similarly, the ability to irradiate and test core materials and reactor vessel materials of sufficient size to reflect actual component behavior facilitates an optimal aging management strategy. Such a strategy includes the appropriate level of in-service inspection and informed run/repair/replace decisions, while maintaining the requisite levels of safety for these key components.

The nuclear energy industry requires thermal test reactor(s) of sufficient size and availability to irradiate new fuel design pins and material test specimens to provide prototypical results. The hot cells should be closely associated with the test reactors to minimize the radioactive materials transport issues and expenses (see Section 4.2.6).

Several such facilities are operating in the DOE complex. These include the ATR at INL, shown here, and the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL). The ATR has recently been designated by DOE NE as a National Scientific User Facility for use by industry and academia, as well as by the traditional Naval Reactors and DOE users.

4.2.3 Fast Irradiation

To develop new fast reactors, significantly more test irradiation capabilities need to be provided for the research community. These capabilities are needed in the near-, mid-, and long-term. Currently, the United States uses irradiation capabilities in foreign countries to conduct limited tests on materials and fuel. Additional fast irradiation facilities are needed in the near-, mid-, and long-term to provide a source of fast neutrons to study materials aging issues and develop models for aging phenomena in fast reactors. For fast irradiation, these facilities should provide high fast flux levels to accelerate aging studies. Fast irradiation facilities are also needed to test fuels appropriate for use in a fast reactor. In addition to the irradiation capability, the PIE of fuels and testing of materials require hot cells of sufficient size and capability to provide meaningful knowledge of the damage mechanisms and fuel performance.

Fast reactors operate in harder neutron spectra than thermal reactors. The power density of fast reactors is generally higher than thermal reactors. Fast reactors generally use a heat transfer fluid other than water (e.g., liquid sodium), which must be compatible with reactor materials. Identification and assessment of stress, corrosion, and aging issues in this fast reactor environment are necessary for development of future fast reactors. Access to fast irradiation capabilities is needed to develop guidelines for construction materials for

The Monju reactor in Japan represents one of several international fast irradiation facilities.

fast reactors, develop appropriate fuel types for fast reactors, and eventually provide data to support licensing and construction.

Initially, small samples will be used to model the impact of irradiation damage. As the R&D program progresses, the fuel testing will need to progress to larger and larger sample sizes, eventually reaching the lead test assembly (LTA) size to provide proof-of-principle testing. In the near-, mid-, and long-term, both materials irradiation and test fuel irradiation can take place in a research reactor environment where the sample sizes can be small, but the neutron fluences must be high. As fuel development activities get closer to commercial applications, larger facilities will be required to provide irradiation of full-length fuel pins as well as LTAs at prototypical conditions.

4.2.4 Radiochemistry Laboratories

Radiochemistry laboratories are needed throughout the near-, mid-, and long-term to support radiochemical, elemental, and isotopic analysis of nuclear fuels (un-irradiated and irradiated) and the resultant fission products, as well as materials and waste products encountered in nuclear fuel processing and fuel development. Detailed baseline analyses of feed materials and resultant products are critical to characterize how well separations processes perform during fuel recycle R&D efforts. In addition to the separations needs, the new fuel for irradiation tests must be analyzed to ensure it meets requirements for irradiation and also analyzed post-irradiation to characterize the used fuel. Also, waste products will need to be well characterized to develop material balances and aging data needed for licensing.

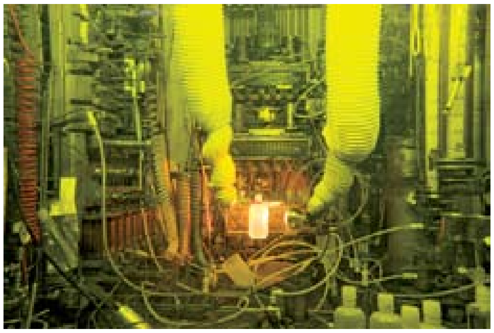
Ideally, these radiochemistry laboratories would be located close to the hot cell or glove box facility performing the work. Close proximity to the R&D facility will minimize radioactive/hazardous material transportation requirements and the time delays associated with those activities. Radiochemistry laboratories require licensing for an appropriate hazard categorization to adequately encompass the high levels of radioisotopes that will be present in the materials to be analyzed.

Radiochemistry laboratories provide chemical fume hoods and glove boxes for specialized analyses.

Radioactive specimens for analyses are generated prior to, during, and after R&D tasks, requiring a wide variety of analytical measurements. A majority of the analytical techniques requires dissolution of the specimens into an aqueous matrix prior to analysis. These dissolutions are performed on representative sample portions in a chemical fume hood, glove box, or hot cell depending on the specific radioisotopes present and their activity levels. Specimens of irradiated fuels are likely to require hot cell containment. Dilutions of the digested homogenized solutions are performed, which allow for handling of the analytical aliquots in chemical fume hoods in which most of the instrument or measurement techniques are conducted. Some techniques are performed on small solid aliquots of the samples and require more rigorous instrument containment such as a glove box or hot cell. Potential sample measurement techniques include (1) alpha/beta/gamma spectroscopy, (2) plasma and thermal ionization mass spectroscopy, (3) gas chromatography, (4) ion chromatography, and (5) various wet chemical techniques such as titrations and spectrophotometric measurements. In some cases, such as fuels development, the radiochemistry lab must also be capable of measuring particle morphology, pellet density, and oxygen to metal ratios with very high accuracy, employing high-end microscopy, X-ray diffraction, laser techniques, and high-temperature melts on the raw samples.

These labs will require the standard basic chemistry laboratory support systems such as bench tops, chemical fume hoods, deionized water sources, conditioned electrical power, and appropriate ventilation systems. Additional nuclear infrastructure requirements include radiological containment systems and protection support, liquid and solid radiological waste disposal systems, and staff trained to the rigorous standards needed to operate in a nuclear facility.

4.2.5 Hot Cells for Separations



Hot cells at ORNL's Radiochemical Development Center are among the DOE hot cell facilities that may be used to test fuel recycle separations.

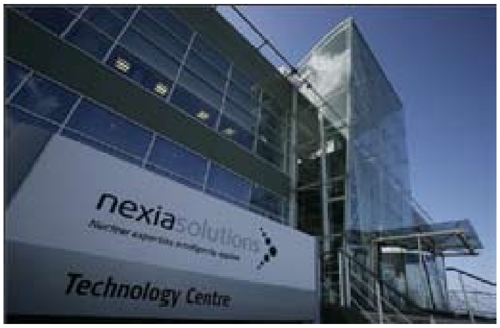
About 96 percent of used nuclear fuel pellets are made up of uranium. About 3 percent of the fuel is highly radioactive fission products along with small amounts (less than 1 percent) of plutonium. Chemical separations are needed for the recovery of the unused uranium and the plutonium along with isolation of the fission products into an appropriate waste form. In addition, the nuclear energy industry needs data to support licensing efforts for new fuel recycling facilities capable of processing thousands of kilograms per year. Development of these new separations processes requires the use of real used fuel, which requires the availability of heavily shielded hot cell facilities. Implementation of these new processes on a commercial scale will require testing first at a small scale (tens of kilograms) followed by scale-up. Small hot cells are needed in the near-, mid-, and long-term for small-scale separations R&D programs. Larger hot cell facilities are needed in the mid- to long-term to provide engineering-scale demonstration of the most promising used fuel recycle technologies so those technologies can be deployed in a full-scale plant.

The Fuel Conditioning Facility at INL is used for testing separations technology.

Industry and government agencies need to work collaboratively to improve the cost effectiveness of separations technologies that meet waste management and nonproliferation goals. Hot cell facilities are needed to conduct the research necessary to develop new separations processes to close the fuel cycle and provide data enabling scale-up of those processes. These facilities also generate important and unique experimental materials (e.g., recycle fuel and waste products) from used fuel, which are needed to ensure that composition, physical properties, and stability are well understood prior to committing resources for licensing and construction.

Hot cell facilities will provide a shielded environment for conducting experimental tasks in support of closing the fuel cycle. The facilities will need ventilation systems to ensure containment of the radioactivity and support systems to move heavy shielded casks containing spent fuel into the hot cells. Operations inside the hot cells will be conducted remotely using robotic technologies. An infrastructure of waste management services, trained staff, appropriate S&S controls, as well as current safety basis authorization will be necessary to support these hot cell facilities.

As mentioned in the introduction to Section 4, many DOE sites have hot cell facilities that could be used for separations research work. These facilities span a wide range of size and activity type to support fuel recycle. Additionally, international facilities could provide limited support. As the efforts to close the fuel cycle expand, new hot cell facilities will be needed in the mid- to long-term to ensure that R&D facilities can provide design data and ongoing support for the new fuel recycle plant.



The British Technology Centre may be available for international collaborations.

H Canyon at Savannah River Site is an example of a large-scale chemical separations facility.

4.2.6 Hot Cells for PIE

Hot cells for PIE and testing of fuels and irradiated materials are key facilities for understanding phenomena that limit fuel performance or useful life of reactor components. The cells must be of sufficient size to accommodate full-size fuel assemblies and have sufficient capability to provide meaningful examination and testing results. Ideally, they are situated close to the test reactor where the fuel/materials were irradiated or close to major transportation arteries to facilitate the shipment and handling of fuel/materials casks from operating reactors.

The hot cells for PIE will be required for extended life operation of the current fleet of LWRs and soon-to-be-built ALWRs for qualification of fuel for the next generation of reactors, new materials development for higher-temperature reactor components, qualification of fuels developed in the sustainable fuel cycle program, etc.

The hot cells should have the capability to fully examine and analyze test specimens on macroscopic and microscopic scales. Required irradiated material testing capabilities for a wide range of temperatures and environments include strength, toughness, hardness, stress corrosion crack growth rates, environment-assisted fatigue crack growth rates, and related parameters. For fuel examination, additional tests are required, including fission gas analysis, fuel pellet strain and cracking, cladding strain, corrosion product analysis, neutron radiography, and related parameters. In addition, the hot cells should be able to test and verify nondestructive examination technologies for future use in the field for fuel and material examinations.

Several large hot cell facilities in the DOE complex can be used to examine and test irradiated fuels and material. They include the Hot Fuel Examination Facility (HFEF) at INL and the Irradiated Fuels Examination Laboratory and Irradiated Materials Examination and Testing Laboratory (IMET) at ORNL. The HFEF has recently been designated by DOE NE as part of the ATR National Scientific User Facility for use by industry and academia, as well as by the traditional Naval Reactors and DOE users.

The Los Alamos Chemistry and Metallurgical Research Facility Wing 9 hot cells are used for irradiated fuel and materials examination, metallurgical examination, and neutron radiography.

4.2.7 Thermal Transport

Process industries such as oil refining and chemical manufacturing may be able to transfer many capabilities required for effective and efficient heat transfer and transport for nuclear energy heat sources. However, there are thermal transport considerations that are unique to the use of nuclear energy as a heat source. Most of these considerations relate to the reliability of the intermediate heat exchange (IHX) system that separates the nuclear system from the end user's systems. The effects of end-user facility (process heat users) upsets and transients on the safety and reliability of the high-temperature process heat reactor are also important.

Essentially, all applications of commercial nuclear energy have focused on the generation of electricity using the Rankin steam cycle. South Africa is developing a pebble bed HTR to produce electricity using the Brayton cycle with a gas turbine. Electrical grid disturbances and failures have been integrated in the design of existing LWRs. However, upsets and transients in refineries and chemical plants need to be considered in the design and operating procedures for process heat reactors. Large-scale loop tests will help the licensing of process heat reactors by providing credible benchmarks for system interactions analyses.

A thermal transport loop of sufficient size (about 60 megawatts thermal [MWth]) is required to demonstrate the reliability of the IHX design and materials for temperatures up to 950˚C. The results of the tests will be used to benchmark the thermal-hydraulics codes used in the design of process heat reactors for safety and reliability assessments. The same thermal loop may be used to evaluate the efficacy of large-scale water-splitting processes to make hydrogen and oxygen. Some bench-scale processes use either chemical assistance, high-temperature electrolysis, or a combination of the two to produce hydrogen from water. A fossil-fueled thermal loop would act as the heat source for the prototype testing. Eventually, the selected process would be evaluated with an HTR, either in the demonstration plant, Next-Generation Nuclear Plant (NGNP), or a follow-on facility. Such a facility may be used to test small high-temperature components for ultra super critical boilers in advanced, high-efficiency coal plant programs.

Currently, no such thermal loops operate in the DOE complex; industrial facilities of sufficient size are designed for lower temperatures. The thermal test facility would need to be a new facility designed and built for this purpose and operational by 2012.

4.2.8 Fuel Development

Research and testing programs are needed to increase the current LWR fuel burnup to the 100 GWd/MTU limit as envisioned by industry, requiring an increase in the current enrichment licensing limit. In addition, significant research and testing are needed to develop new fuel types for NGRs. Generally, these new reactors push the current envelope of acceptable burnup and irradiation damage to the extent that one-of-a-kind experiments with several different combinations of fuel, cladding, and irradiation conditions are needed to begin optimizing the fuel design. These new fuel types require extensive pre- and post-irradiation examination.

Fuel development facilities are needed over the near-, mid-, and long-term for developing new fuel/clad types that will achieve high burnups, converting products from the used fuel separations processes into appropriate fuel forms—either oxide, carbide, or metal—and developing new fuels for NGRs. For TRISO fuels, specialized coaters are required to apply the pyrolytic carbon and silicon carbide coatings. These facilities contain glove boxes with appropriate ventilation to contain radioactive materials as well as capability to provide inert atmosphere, if needed. In some cases, these facilities might require significant security resources depending on the amount and type of material being processed.

Fuel development facilities also require analytical equipment in proximity to characterize the feed materials prior to fabrication as well as characterization of the final fuel form. Analyses can include dimensional verifications, chemical and isotopic analysis, measurement of the oxide to metal ratios, characterization of the feed particle morphology, and other parameters.

Fuel development will proceed through a number of phases prior to development of full-scale assemblies, including fabrication of pellets or particles; assembly of pellets into rodlets, or particles into pebbles or compacts; irradiation of rodlets, pebbles, or compacts; scale-up to full pins; irradiation of pins; scaleup to full assemblies; and irradiation of LTAs. The phases of fuel development will require larger and larger facilities to handle the increase in mass and attendant increase in security requirements. Some of the required capabilities for the next-generation reactor fuels are available in strategic global facilities.

Unlike new LWR fuel, recycled reactor fuel must be assembled remotely.

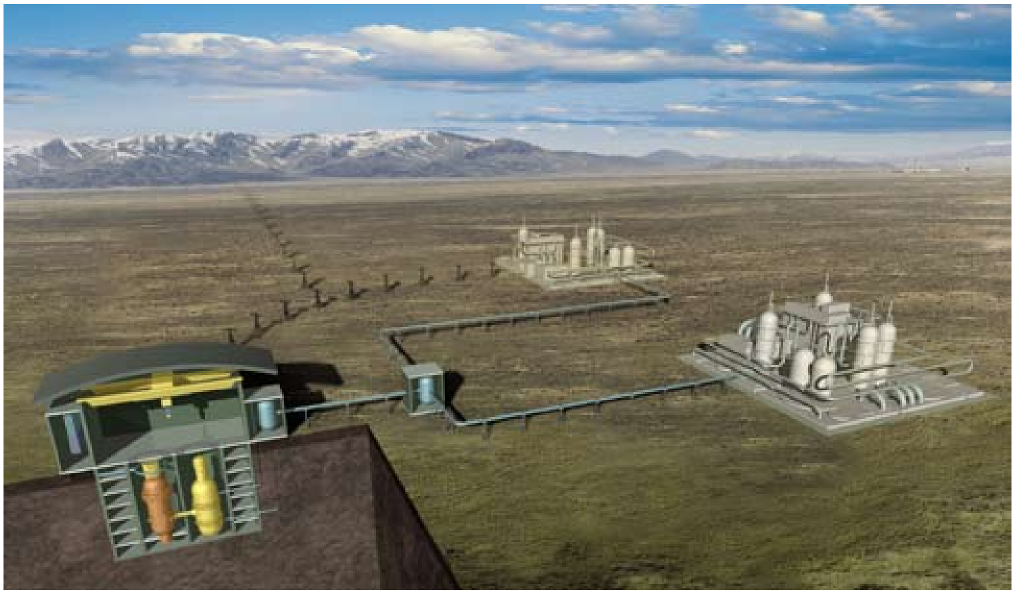
4.2.9 Licensing Demonstration for an HTR

ALWRs are excellent for generating electricity. However, if nuclear energy is to be used to provide other forms of energy, it will be necessary to develop and deploy higher-temperature reactor systems. The use of water as a coolant restricts ALWRs to about 300˚C. Process heat applications for refiners and chemical plants require 250˚C to 550˚C; oil shale and tar sands processing requires 300˚C to 600˚C; and electricity and steam cogeneration requires 350˚C to 800˚C. Reforming natural gas into hydrogen requires 500˚C to 900˚C, and thermo-chemical and high-temperature electrolysis of water into hydrogen and oxygen requires 800˚C to 1000˚C. To further reduce the U.S. industrial carbon footprint and our reliance on imported, conventional hydrocarbons, we must develop gas-cooled reactor systems.

High-temperature gas (helium) cooled reactors have been under development for more than 40 years, and a prototype system using pebble bed fuel technology will be started up in South Africa in 2015. However, to be deployable in the United States, the technology must be demonstrated in a plant licensed by the NRC of sufficient size to convince end users of its viability and potential competitiveness with other forms of energy—particularly natural gas.

NGNP is a publicly/privately funded partnership to design, license, build, and operate a high-temperature nuclear demonstration plant designed to generate electricity and hydrogen using process heat to drive a thermo-chemical or high-temperature electrolysis water-splitting process. The plant will use fuel particles coated with layers of pyrolytic graphite and silicon-carbide to provide fuel-level containment of radioactive materials, helium as a coolant, and graphite as the moderator.

Across the globe, there are only a few small gas-cooled test reactors, including the High-Temperature Test Reactor (HTTR) in Japan and the 100-MWth reactor in China. The only large-scale HTR prototype is the Pebble Bed Modular Reactor (PBMR) in South Africa, which begins construction in 2010, designed to use the Brayton cycle to generate electricity. The NGNP would be the only large (300 to 400 MWth) demonstration of a combined electricity/process heat plant. An artist's concept of the NGNP is shown below.



NGNP is a public-private partnership project to design, license, build, and operate an HTR for the production of electricity and process heat.

4.2.10 Licensing Demonstration for a Fast Reactor

Fast reactors are expected to play a central role in sustaining the nuclear fuel cycle in the 2030 to 2050 time frame. They will permit the transmutation of undesirable fission products into more "repository friendly" waste products with reduced toxicity. Fast reactors can also be designed to utilize certain fissionable materials as fuel, reducing high-level waste volumes and extending repository life. Finally, fast reactors can be designed to transform non-fissile isotopes of uranium into useful nuclear fuel, greatly increasing the energy derived from uranium ore.

Fast reactors have been under development globally since the early 1950s. Most of the fast reactors have been sodium cooled. The extreme incompatibility of sodium and water has proven to be problematic for most of the demonstration, prototype, and test reactors. The deployment of fast reactors to support a sustainable fuel cycle requires the licensing of a demonstration fast reactor by the NRC.

The funding of a fast reactor demonstration plant is the responsibility of the Federal government. The private sector may own and operate future fast reactors when the fuel costs become competitive with an open fuel cycle approach. The demonstration fast reactor will also be a research facility to test new fuel designs on a large scale, as well as new heat extraction, instrumentation, and control and coolant circulation technologies.

Most of the large-scale (greater the 200 MWth) fast reactors built globally have been shut down for a variety of reasons. The last large fast reactor shut down in the United States was the Fast Flux Test Facility (FFTF), which was built to test fast reactor fuel designs and primary circuit components.

FFTF was the last large operating U.S. fast reactor.

4.2.11 Specialized Engineering Development Laboratories

As the nuclear energy industry moves beyond the light water technology (300˚C), maximum hot leg temperatures, and an open fuel cycle, there will be a need for specialized engineering development facilities to provide engineering capabilities to support the goals of the industry in the 2010 to 2050 time frame. These facilities will deal with the nonradioactive testing and evaluation needs to ensure that the deployed power and process heat plants and fuel cycle facilities are safe and economically competitive.

These facilities must provide the special "unique to nuclear" capabilities that are not directly tied to fuel development and testing, fuel recycle chemistry, irradiated materials testing, and related areas. Historically, such capabilities have included seismic testing of major components, environmental qualification of equipment, flow loop testing, specialized sensor development, reactor simulator development, specialized welding process development and qualification, and specialized inspection and maintenance equipment development and qualification. Many facilities that currently provide these specialized capabilities are industrial, not DOE owned.

Many of the specialized engineering development facilities required for LWRs and ALWRs will still be required in the 2010 to 2050 time frame. Next-generation reactors and fuel recycling facilities will require additional capabilities, such as sodium flow loops for fast reactors, highly corrosive environment testing flow loops, instrumentation and equipment development qualification for sodium and high-temperature environments, in service inspection in sodium and high-temperature environments, and similar areas of interest. For some next-generation reactors, additional discussion with industry is warranted to define large component test requirements.

Section 5 –
Priorities and Actions

Action is required to provide the R&D capabilities to achieve the goals identified by the domestic nuclear energy industry for the 2010 to 2050 time frame. Although many of the required capabilities exist or are under development in other industries, several are unique to the nuclear energy industry and require specialized facility resources. These facility resources, identified in Section 4, require significant capital investment and substantial annual resources to operate and maintain. Facilities currently available in the DOE complex and internationally could satisfy many of the requirements. However, the available facilities fall short of providing many of the critical capabilities required to achieve the nuclear energy industry's long-range goals. In addition, given the age and original purpose of the existing facilities, many of the DOE facilities require additional investment to fund improvements and needed modifications.

Table 5-1 summarizes "unique-to-nuclear" R&D facility priorities resulting from the nuclear energy industry goals for the 2010 to 2050 time frame and the required capabilities identified by participants in the Columbus, Ohio, and Washington, D.C., workshop and focus group.

Table 5-1. Summary of Nuclear R&D Facility Priorities

Priority	Focus Area	Facility	Purpose	Notes
#1 (tie)	**Existing LWRs and ALWRs**	Thermal irradiation and PIE facilities	Maximize benefit from current reactor fleet	Existing facilities provide needed capabilities for materials aging and fuels improvement
#1 (tie)	**Workforce Development**	Nuclear Education facilities	Educate and train	Further evaluation of needs required
#2 (tie)	**Next-Generation Reactors**	HTR Licensing Demonstration	Develop and demonstrate new applications for nuclear energy	Engineering development and component test facility required
#2 (tie)	**Sustainable Fuel Cycle**	Fuel Cycle R&D facilities	Develop new, licensable fuel fabrication and separations technologies to improve fuel performance, enhance resource recovery, reduce proliferation risk, minimize waste, and improve economics	Available hot cell facilities with continued maintenance and upgrades should provide needed capabilities through laboratory-scale research
#3	**Next-Generation Reactors**	Fast Reactor Licensing Demonstration	Develop and demonstrate fast reactor technology to improve safety and help ensure sustainable fuel supply	Engineering development and component test facility required

Three of the facilities would be new—the HTR Licensing Demonstration, the Fuel Cycle R&D facilities, and the Fast Reactor Licensing Demonstration. Each requires support facilities to fulfill its mission. The mechanisms available to provide the needed facility resources are (1) public investment, (2) public-private partnerships with federal and state government and nuclear energy industry investment, and (3) U.S. government investment leveraged through international collaboration and investment. Recent initiatives underway in DOE NE to work more closely with industry and to expand international collaboration will provide vehicles for the development of and access to needed facility resources. Given the nature and purpose of the required facility resources, each mechanism requires government investment. Of the identified facility priorities, plans are already underway to establish a public-private partnership to provide the necessary funding for the NGNP—a licensing demonstration of an HTR.

The responsibility for the funding required for the facility priorities resides primarily with DOE NE. To achieve the required investment for the new facilities and the maintenance and enhancement of current facilities, it is recommended that the DOE NE establish the **Strategic Nuclear Energy Capability Initiative** to provide a significant increase in multiyear investments in capabilities that enable the domestic nuclear energy industry to achieve its 2010 to 2050 goals. Funds provided through the Initiative would be used to maintain and modify currently available facilities and provide new R&D facilities and associated equipment. This Initiative would also provide the financial foundation for DOE NE participation in public-private partnerships and international collaborations to leverage U.S. taxpayer investment in required capabilities and facilities.

Recommendations for the success of the **Strategic Nuclear Energy Capability Initiative** include the following:

- Use an integrated, time-phased, and user-driven approach. The initial focus would be on workforce development, procurement of needed research equipment, improvement in current R&D facilities, and development of user-driven concepts for new R&D facilities. Developing user-driven concepts provides the rationale for building the investment over time to enable construction of new user-driven R&D priority facilities.
- Provide multiyear investments in a manner that enables efficient development and commissioning of the needed facilities.
- Engage the nuclear energy industry, universities, and the national laboratories in the development and evaluation of user-driven concepts. Conduct integrated periodic reviews of the Initiative.

Input from industry, university, and national laboratory participants in this analysis provided the following additional recommendations for the DOE NE that are key to effective delivery of needed capabilities to the domestic nuclear energy industry:

- Increase the use of enterprise models that allow proper trade-off studies, integrating the economics of various future scenarios for development and deployment of different reactor types and fuel recycling technologies.
- Expand international collaborations to provide required capabilities and ready access to research facilities.
- Define a living process for facility consolidation, retirement of old facilities, and possible replacement with new, improved facilities when appropriate.
- Define a process to ensure maintenance of the “balance of plant”—roads, support buildings, etc., for critical facilities to ensure sustainability of capabilities.

Section 6 – Conclusions and Benefits

6.1 Conclusions

Four key conclusions can be derived from this analysis:

- A robust, fully trained workforce must be available for the domestic nuclear energy industry to continue with its proven record of delivering baseload electricity in a safe, reliable, and cost-effective manner.
- The industry has established meaningful goals that enhance the nation's energy security. These goals include extending the service life of the currently operating reactors, deploying ALWRs, developing a sustainable fuel cycle, and developing next-generation reactors leading to new applications for nuclear energy.
- Essential R&D capabilities and facilities are required to enable the industry to achieve these goals. Through the establishment of a multiyear, user-driven **Strategic Nuclear Energy Capability Initiative**, the DOE NE can provide the needed capabilities and facilities.
- Successful establishment of the Initiative can also provide the DOE NE with the necessary foundation to build public-private partnerships and international collaborations to help provide the needed capabilities and facilities.

6.2 Benefits

Provision of the required capabilities and facilities will enable the nuclear energy industry to deliver the following benefits:

- Meet the ever-increasing demand for energy.
- Reduce carbon intensity of U.S. electricity production.
- Reduce reliance on imported hydrocarbons.
- Create a sustainable nuclear fuel cycle and reduce risk of proliferation.
- Leverage DOE investment to maximize return to the U.S. taxpayer.

We cannot rely on "silver bullets" to address either the national (or global) energy supply/demand situation or to manage global climate change in the next 50 years. The only pragmatic solution to either of these critical issues is a robust portfolio approach with a balance of energy sources, including nuclear energy. This requires a long-term and prudent use of scarce resources.

Appendix A – Process to Identify Capability Requirements

A.1 Methods Used to Gather Input

To meet the request of DOE NE's Assistant Secretary to *"…seek…the insight of universities, customers, suppliers, and competitors…through workshops, interviews, and other appropriate means…,"* Battelle employed a disciplined process to gather input through a variety of methodologies. These methodologies, listed in the following subsections, involved a cross-section of 40 experienced nuclear energy professionals within industry, academia, national laboratory, and regulatory sectors over a two-month time frame. The following sections provide specifics of each forum and participant engagement.

A.1.1 Facilitated Workshop

Battelle hosted a two-day facilitated workshop in Columbus, Ohio, on April 30 and May 1, 2008, with participation by 13 representatives from industry, academia, regulatory organizations, and national laboratories.

A.1.2 Focus Group

A one-day focus group was held in Washington, D.C., on May 6, 2008. Nuclear energy industry participants included 13 utility executives, technology vendors, suppliers, architect engineers, and construction contractors. Two national laboratory representatives from Argonne and Pacific Northwest also participated in the focus group.

A.1.3 Individual Interviews

A total of five 1-hour interviews (with six participants) were conducted, including noted leaders from both industry and academia.

A.1.4 Web-Based Focus Group

Inputs from eight nuclear science universities from across the nation were provided via a web-based focus group that was introduced at a National University Consortium/Idaho University Consortium Symposium held in Idaho Falls, Idaho, on May 21, 2008. Given project background information and a demonstration of the website tool, participants were asked to provide their input online within one week.

A.2 Framework Used to Gather Input

Battelle's approach was to provide a structure that elicited broad input initially, then continually synthesized the data stream. This was accomplished by using data gathered early in the process as a baseline for subsequent data gathering, while simultaneously managing for bias.

A.2.1 Facilitated Workshop

Workshop participants identified the following six focus areas they considered to be critical to the future success of the nuclear energy industry: existing LWRs and ALWRs, workforce development, sustainable fuel cycle, next-generation reactors, regulatory requirements, and safeguards and security.

A.2.1.1 Current State/Future State/Gap Identification

For each of the six focus areas, participants outlined the current state and desired future state. Next, for each focus area, an R&D capability "gap analysis" was performed. Participants then identified the critical R&D gaps that hinder/prevent realization of the desired future state.

A.2.1.2 Prioritization Process

Participants then sorted the identified R&D capability gaps into near-term (2008–2015), mid-term (2016–2020), and long-term (2021–2030) time frame categories, based on the determined lead-time. They selected the top three R&D capability priorities for each time frame (near-, mid-, and long-term).

A.2.2 Focus Group

Participants used the same basic framework that was developed for the facilitated workshop (as discussed in Section A.2.1). However, in addition to employing a facilitator, Battelle used computer-assisted facilitation with GroupSystems Meeting Room software. Each participant had access to a computer, linked with other computers in the room. Information entered by the recorder or other participants appeared simultaneously on all participants' computers. Each of the six previously identified focus areas (identified by the Ohio workshop participants) was validated by the focus group participants.

A.2.2.1 Current State/Future State/Gap Identification

For each of the six focus areas, participants reviewed the current state descriptions identified in the facilitated workshop held in Ohio. The facilitator led participants through a verbal process of adding, merging, or removing current state descriptions. The participants followed this same process to refine the future state descriptions.

To refine the "gap analysis," conducted in the Ohio workshop while managing for bias, the R&D capability gaps were presented as an entire list (without being organized by time frame). Using the computers and a "round robin" process, participants added items to the capabilities list. Participants entered the most important idea they considered relevant to the subject. After all participants entered one idea, the facilitator reviewed the new list, clarified the entries, and merged similar ideas. The participants then entered another idea, not already on the list, and the facilitator repeated the process of clarifying and merging the newly entered ideas.

A.2.2.2 Prioritization Process

The participants sorted the list of capabilities into near-term (2008–2015), mid-term (2016–2020), and long-term (2021–2030) time frame categories. Once this was accomplished (via computer), the participants prioritized the capabilities in each time frame by placing them (electronically) in priority order. To effectively manage for bias, the prioritization ranking of capabilities resulting from the earlier Ohio workshop was not provided to the focus group participants. The focus group results of the electronic ranking process were provided to participants in "real-time" via the GroupSystems software.

A.2.3 Individual Interviews

Interviewees were asked a total of nine questions regarding current/future state of the nuclear industry, R&D capability gaps, and capability prioritization. As such, responses to the questions integrated seamlessly with the workshop and focus group input. The interview questions are shown in Attachment A-1.

A.2.4 Web-Based Focus Group

To provide the broadest opportunity for participation, Battelle organized and conducted a web-based focus group. It elicited more than 30 comments and recommendations from university participants across the nation. Each participant was provided with a link and password to the site. Participants were able to see others' comments and respond to them as well as add new input. The website included the six focus areas and the top-ranked R&D capability gap priorities for each focus area. Participants responded to each focus area R&D capability gap priority by answering the following question: *What role should universities play in the closure of the gap and what benefits will be realized by university participation?*

A.3 Outcomes

By using a sequential data refinement process involving a broad cross-section of industry, regulatory, and academic participants, recurring themes were clearly identified and three key outcomes achieved:

- Validation of the six focus areas originally identified by the Ohio workshop participants
- Substantiation and enhancement of identified R&D capability gaps
- Independent verification of capability prioritization.

As such, confidence in the results is high, providing DOE NE with a meaningful benchmark of capabilities required to support the domestic nuclear energy industry that has been defined with substantial industry and academic participation.

Appendix A – Attachment A-1

NUCLEAR ENERGY R&D CAPABILITIES OUTLOOK

INTERVIEW QUESTIONS

1) What terms/phrases come to mind as you consider the current state of the nuclear energy industry? What challenges/opportunities/threats exist (including "non-nuclear" barriers to adding nuclear capacity—for example, transmission capability)?
2) How do you envision the nuclear energy industry in the 2030–2050 time frame (future state)?
    a) What capabilities are in the early, mid, and mature stage?
    b) What key technology accomplishments have been achieved?
    c) How do you see market demand growing (including traditionally non-nuclear areas)?
    d) What other factors have key impact on shaping the industry in the future?

    At a minimum, please consider the following in your response:

    - Operating life extensions
    - Construction of new operating plants
    - Use of nuclear reactors for the production of process heat and hydrogen
    - Development of advanced reactors, and
    - Closing the fuel cycle
3) What technical challenges does the industry currently face in achieving the desired future state (2030–2050)? (Gap Analysis)
4) What regulatory challenges does the industry currently face in achieving the desired future state? (Gap Analysis)
5) What R&D capabilities and supporting disciplines/processes are needed to enable industry to address these technical and regulatory challenges and achieve the desired future state? (Gap Analysis)
    a) Near-Term (2008–2014)
    b) Mid-Term (2015–2021)
    c) Long-Term (2022–2028)

    Prioritize the top two capabilities for each phase (near-, mid-, and long-term).
6) What R&D facilities are needed to enable industry to address these challenges and achieve the desired future state? (Gap Analysis)
7) Are there "lessons learned" from other industries that we could take advantage of in the nuclear industry? If so, what?
8) Please make any other comments or suggestions you feel would assist in identifying the R&D capabilities needed by the U.S. nuclear energy industry over the next 20+ years.
9) Would you recommend that we speak with any other colleagues to gather perspectives for this project?

Appendix B – Workshop/Focus Group Summaries

Workshop Summary/Focus Group Prioritization

Tables B-1 through B-6 indicate the needed R&D capability priorities identified in each focus area, broken down by time frame (near-, mid-, and long-term) as determined by the Battelle-hosted Ohio workshop participants (April 30 and May 1, 2008) and the Washington, D.C., focus group participants (May 6, 2008).

From each focus area capability list, approximately three or four high-level, thematic priorities emerged (as shown at the top of each table). Each individual R&D capability has been "mapped" to the high-level capability priorities, as shown in the "Priority Mapping" column of each table.

Input gathered via individual interviews and the web-based focus group was consistent with the priority themes identified in Tables B-1 through B-6.

Appendix Table B-1. Light Water Reactors/Advanced Light Water Reactors Focus Area—Capability Priorities

1. Understand the reliability of the plant’s systems, structures, and component materials through the plant’s extended lifetime
2. Improve fuel performance
3. Adopt technology innovations to enhance plant performance and the productivity of the workforce
4. Enhance manufacturing and construction methods for plant life extension upgrades and construction of new plants

Capability Need	Priority Mapping			
	1	2	3	4
Near-Term (2008–2015)				
Extend life of irradiated material (or determine better ways to perform accelerated testing)	X			
Create supply chain: Real-time logistics model				X
Construction: Need modular build, shop build, zero re-work, innovative ways of demonstrating compliance, standardized (form-fit-function to use multiple suppliers), certified plant and component designs				X
Replace obsolete instrumentation and control (I&C) parts			X	
Conduct research on fuel failures		X		
Improve design, manufacturing, and construction methods				X
Enhance fuel fabrication capabilities (higher density fuels and fuel burnup, and reduce the number of leakers—“zero by 10”)		X		
Perform modeling with experimental verification for specific systems	X		X	
Enhance modeling/monitoring to understand risk	X		X	
Improve pool-side examination of fuel assemblies		X		
License and implement ALWRs		X	X	X
Develop advanced fuel forms with high Uranium-235 density		X		
Develop failure-free fuel for operating reactors		X		
Mid-Term (2016–2020)				
Conduct fuel testing in reactors and licensing		X		
Develop digital I&C design concepts so that systems can change as technology advances			X	
Develop a shared facility for development, deployment, and training			X	
Complete replacement of I&C during a single (economical) planning window			X	
Update safety evaluation criteria to account for digital I&C systems			X	
Develop advanced full core simulation models to improve fuel performance predictability		X		
Develop additional improved inspection technologies which include in-situ monitoring, in-situ microchemistry, stress, electrochemical noise			X	
Create accurate predictive modeling of materials behavior	X			
Develop the ability to inspect, repair, and replace at power			X	
Conduct process simplification and increase automation			X	
Employ remote NRC monitoring			X	
Develop high heat flux test facilities	X			
Implement modeling simulation/digital control systems which communicate with models			X	
Establish the regulatory basis for extending burnup limits		X		
Develop new disposition options for low and intermediate level waste			X	
Long-Term (2021–2030)				
Benchmark testing to validate models	X			
Design materials for end-use	X			
Develop transient test facility		X		
Create new methodologies to accelerate testing of materials and plant components	X			
Provide input into prognostic models			X	
Employ corrosion-free materials	X			
Improve hybrid, dry cooling sources, reduce manufacturing costs				X
Develop technologies to make use of rejected heat				X
Improve and/or implement new materials	X			
Utilize/adapt repair/refurbish technologies used by other industries such as military, aerospace, oil and gas, shipbuilding industries, etc.				X
Realize 100% reliable, real-time inspection			X	
Execute a digital control system which communicates with models			X	
Improve water chemistry (i.e., nano-fluids)	X			
Develop/commercialize technologies for ALWR fuels and cladding materials (e.g., silicon carbide cladding, fertile-free cores)		X		

Appendix Table B-2. Workforce Development Focus Area—Capability Priorities

1. Optimize training through adoption of proven approaches from other industries and greater use of technical training centers, new methods, and improved skill and aptitude assessment tools
2. Adopt knowledge management methods and techniques to enhance cross-generational knowledge retention, workforce development, and effective use of lessons learned
3. Enhance nuclear education/training and research infrastructure to deliver a more effective multiyear, sustainable science and engineering R&D program to train the next generation of scientists and engineers
4. Enhance innovative energy educator programs to reach K-12 students—working with industry to build the pipeline

Capability Need	Priority Mapping			
	1	2	3	4
Near-Term (2008–2015)				
Fund a multiyear, sustainable nuclear science and engineering R&D program to train the next generation of scientists and engineers (DOE)			X	
Develop a national certification program for skilled nuclear craft with attractive pay structure	X			
Implement a DOE/industry sponsored training program focused on personnel with high-school education (education of people displaced from offshoring)	X			
Establish/continue innovative energy educator programs to reach students early (K-12)—working with industry, etc., through a new Educator Forum to build the pipeline (DOE)				X
Enhance DOE/industry-sponsored research funding for universities to support advanced degree programs (researchers needed for national laboratories and Ph.D.'s for new NE faculty)			X	
Promote the message (to universities) that reactor plant design is multidiscipline—we need more than just nuclear engineers (Industry)			X	
Implement effective mentorship programs		X		
Set up programs/practices/technologies to retain knowledge		X		
Institute joint NRC/INPO/industry effort to optimize training toward competencies (performance-based)	X			
Accelerate industry/NRC acceptance of virtual simulator technology (control room or laptop)	X			
Benchmark with military, airlines, process industries (i.e., simulator training, distance education training)	X			
Consider skilled crafts in plant design—making their job easier and ultimately decreasing the number of staff required	X			
Mid-Term (2016–2020)				
Support development of a regional training reactor concept—operated jointly by a regional university consortium, national laboratories, and industry (DOE)	X		X	
Provide universities with needed major equipment to facilitate availability of radiation sources, such as access to accelerators or enhancement of research reactors			X	
Automate equipment (e.g., automated start-ups and shutdowns)			X	
Use virtual technology (e.g., avatars) to share knowledge	X	X		
Develop automated processes to optimize the human element			X	

Appendix Table B-3. Sustainable Fuel Cycle Focus Area—Capability Priorities

1. Develop a geologic repository for the disposal of used nuclear fuel and HLW
2. Develop an interim storage facility for receipt of used nuclear fuel
3. Develop recycling technologies that are economically competitive and more proliferation resistant and minimize impact to waste disposal

Capability Need	Priority Mapping 1	2	3
Near-Term (2008–2015)			
Develop fuel cycle closure research, development, and demonstration facility for advanced fuel cycle technologies and fuel qualification			X
Develop recycling technologies that are economically competitive and proliferation resistant and minimize impact to waste disposal			X
Develop and operate interim storage facility		X	
Begin building a sodium reactor			X
Develop cogent NE facility/program deployment strategy	X		
Create improved uranium resource assessment and mining capabilities			X
Build a pyro used nuclear fuel separations unit			X
Learn from INL/ANL processing of experimental Breeder Reactor-II fuel for direct application to LWR fuel			X
Identify alternate system approaches for the fuel cycle			X
Develop/maintain fast reactor expertise (vendors, DOE, NRC)	X		
Identify appropriate waste forms			X
Upgrade computer codes for modeling advanced design fuel behavior and benchmark to test results			X
Identify best facility for manufacturing and testing of the advanced recycling reactor lead test assemblies			X
Build a transient LWR test reactor to extend fuel burnup			X
Learn from others using MOX fuel (recycling staff and plant operators) from France, Japan, United Kingdom, and Russia)			X
Expand knowledge/expertise on the production and use of MOX			X
Study MOX Lead Fuel Assemblies from used nuclear fuel separated in another country in a few U.S. reactors			X
Reexamine the costs and benefits of implementing a process that separates pure plutonium. Are there any real reasons to believe we cannot safeguard it?			X
Mid-Term (2016–2020)			
Develop HLW repositories	X		
Develop appropriate HLW form (post-recycling) for long-term geologic disposition			X
Identify alternate recycling routes with appropriate safeguards, low waste generation, and fewer process steps			X
Develop recycling technologies for metal fuel use in a sodium fast reactor			X
Initiate process development work on high potential processes			X
Long-Term (2021–2030)			
Expand/continue MOX program and Global Nuclear Energy Partnership (GNEP) program			X
Develop extraction/recovery processes for all natural resources from recycling operations			X
Develop HLW retrieval capability to begin closing fuel cycle	X		
Mine GNEP transmutation fuels outcomes for transferable knowledge			X
Pilot and demonstrate work on high-potential processes			X
Implement thorium fuel development program			X

Appendix Table B-4. Next-Generation Reactors Focus Area—Capability Priorities

Develop next-generation reactors including grid-appropriate reactors, reactors for the production of process heat, and reactors required for closure of the fuel cycle

1. Develop new fuels
2. Understand heat transport for new applications
3. Enhance modeling and simulation capabilities
4. Develop improved materials

Capability Need	**Priority Mapping**			
	1	**2**	**3**	**4**
Near-Term (2008–2015)				
Initiate development and “proof of concept” for fast reactors	X		X	X
Identify possibilities for international collaboration using new or existing test facilities	X	X	X	X
Develop decision model to determine right reactor mix				
Continue progress to simplify design, operation, and maintenance of future reactors to ensure safe and efficient operation	X	X	X	X
Create component research and test facilities at universities and national laboratories	X	X	X	X
Build a PRISM prototype for fuel testing	X			
Develop concept of in-situ breeding/burning for high burnup fuel	X			
Define roadmaps to achieve commercial applications				
Continue NGNP program on current timeline	X	X	X	X
Develop fast reactor test capability (impacting factors: economics, sustainability/closing the fuel cycle)	X			
Develop an alternative secondary coolant for LMR		X		
Define materials characteristics				X
Develop an enterprise model to evaluate reactor use/grid systems/economics			X	
Co-develop modeling/simulation methods with regulators in the areas of neutronics, thermal-hydraulic, and thermal-mechanical materials			X	
Develop hydrogen production materials		X		X
Demonstrate pilot-scale hydrogen-production process		X		
Evaluate near-term applications for hydrogen generated from chemically assisted water splitting in support of current and future hydrogen economy		X		
Increase testing/verification of hydrogen-production processes		X		
Mid-Term (2016–2020)				
Develop HTGR fuel manufacturing processes/capability	X			
Develop high-temperature materials (code-qualified) for heat transfer systems				X
Develop instrumentation for a sodium-cooled fast reactor using actinide fuel	X		X	X
Develop applications at intermediate temperature (i.e., ~750°F) that displace premium fuels (i.e., natural gas, other fossil-based fuels) for industrial applications such as chemical plants and refineries)		X		
Scale up for commercial production of hydrogen		X		
Apply high-performance computing to development of new materials/fuel types				X
Long-Term (2021–2030)				
Implement “materials-by-design” for advanced reactor concepts				X
Use process heat for oil shale development/exploitation		X		
Use hydrogen and oxygen from nuclear heat to perform coal-to-liquids/coal-to-gas conversion		X		
Successfully start up reactor selected by the NGNP program	X	X		
Develop domestic graphite manufacturing capability				X
Develop supercritical CO_2 power cycle for LMR (and/or other high-temperature reactor) deployment				X
Develop Advanced Gen IV test reactor				
Enhance sensor development for use in new environments (high-fluence and high-temperature conditions)				X
Conduct uranium oxycarbide (UCO) fuel proof of viability	X			
Prepare to use commercially produced UCO and thorium-based fuels in high-temperature reactors	X			

Appendix Table B-5. Regulatory Requirements Focus Area—Capability Priorities

1. Improve the NRC license application and review process
2. Establish risk-informed regulatory basis for next-generation reactors and sustainable fuel cycle activities
3. Ensure appropriate regulator staffing and effective training of staff for job requirements, including next-generation reactors and sustainable fuel cycle activities

Capability Need	**Priority Mapping**		
	1	**2**	**3**
Near-Term (2008–2015)			
Continue DOE support for new generation and completion of the Part 52 licensing process		X	
Improve mechanism by which NRC manages organizational conflict of interest—making constrained resources available to NRC and industry			X
Implement training programs for new NRC employees and provide adequate management oversight to minimize variations in approach to regulatory requirements interpretation	X		X
Develop collaborative design/regulatory relationship (NRC, International Atomic Energy Agency [IAEA], Environmental Protection Agency [EPA], DOE, Army Corps of Engineers)	X		X
Develop framework for risk-based waste classification system		X	
Streamline licensing and accelerate lessons learned from international licensing experience	X		
Define regulatory requirements for licensing an integrated recycling reactor site		X	
Develop and deploy regulatory courses regarding general design criteria (with DOE funding) through collaboration between universities, industry, and NRC			X
Enhance NRC's capability to evaluate a sodium fast reactor license submittal			X
Process the Yucca Mountain license submittal in less than two years	X		
Increase R&D of analytical codes (advanced reactors), including thermal fluids, fuels, fission product formation and transport, high-temperature materials, graphite	X	X	
Employ a standardized, automated application process for ALWRs	X		
Develop new, innovative ways for NRC to manage conflict of interest (independent review of capability) to mirror industry-licensing capabilities in order to effectively validate			X
Mid-Term (2016–2020)			
Apply technology-neutral, risk-informed regulation	X		
Enhance and expand NRC capabilities to handle next-generation recycling facilities (i.e., HTGR and Liquid Metal)			X
Develop knowledge-based regulatory oversight system to assist in uniform application of regulations, inspections, and audits	X		
Enhance and expand NRC capabilities (HTGR and LMRs in process currently)			X
Develop regulatory baseline for co-location of power reactor and process heat unit through DOE/national laboratory		X	
Initiate an automated licensing process	X		

Appendix Table B-6. Safeguards and Security Focus Area—Capability Priorities

1. Optimize the use of technology to minimize guns/guards/gates
2. Enhance cybersecurity capabilities to ensure security of plant systems and safety
3. Design advanced safeguards approaches and technology into ALWRs, next-generation reactors, and fuel facilities

Capability Need	Priority Mapping		
	1	2	3
Near-Term (2008–2015)			
Implement risk-based, “safeguards-by-design” approach to fuel cycle facilities regulatory framework and design			X
Develop the capability to examine trade-offs between security based on the use of intrusion prevention/ protection and the use of more fault tolerant systems	X		X
Ensure that Design Basis Threat (DBT) is firmly established and that nuclear facilities have deployed appropriate measures			X
Develop new S&S technologies to meet new DBT and IAEA inspection requirements	X		
Develop a more frequent and effective personnel screening process	X		
Create S&S framework for an interim storage facility			X
Enhance cybersecurity development		X	
Strengthen international standards			X
Develop S&S framework for MOX transport and use			X
Install state-of-the-art video camera monitoring and surveillance	X		
Utilize detector development disciplines. Provide advanced security and material control and accountability (MC&A) detection systems	X		
R&D to support long-term core	X		
Mid-Term (2016–2020)			
Ensure fuel supply			X
Apply “safeguards-by-design” technologies in new construction			X
Implement advanced, real-time S&S data acquisition and advanced instrumentation technologies (MC&A) across the United States and worldwide	X		
Integrate S&S concerns into fuel design			X
Develop alternate aircraft defense technologies (other than mega-containment structures)			X
Optimize real-time life cycle tracking of special nuclear material fuel (i.e., embedded tracking chips)	X		
Deploy national laboratory-developed “state-of-the-art” S&S technologies to industry	X		
Encourage the use of weapons material (plutonium and uranium) for fast reactor start-up cores			X
Realize long-life core			X
Expand use of automation/robotics	X		

Appendix C – Required Capabilities Derived From Other Industries

Section 3 described a process for closing capability gaps to meet the goals of the nuclear energy industry in the 2010 to 2050 time frame. The gaps in capabilities that are unique to the nuclear energy industry are discussed in Section 4. The technologies transferred from or developed with other industries are discussed in this appendix. The discussions are organized in the five focus areas that rely on other industries (existing LWRs and ALWRs, workforce development, next-generation reactors, regulatory requirements, and safeguards and security). The capability description includes the applicability, the approximate percentage (to the nearest 25 percent) transferred or co-developed from other industries, and a brief description of the sources and capabilities. The sustainable fuel cycle focus area, which is unique to the nuclear energy industry, also is covered in Section 4.

C.1 Existing LWRs and ALWRs

To keep the existing 104 LWRs and the fleet of the new ALWRs running safely and reliably requires additional capabilities. Following is a summary of the capabilities that may be derived from other industries. The nuclear energy industry has the lead responsibility to transfer or co-develop these capabilities with limited DOE involvement.

- **Systems, Structures, and Components (SSC) Reliability** (LWRs and ALWRs, about 25 percent derived)—SSCs that are common to fossil power plants and other process industries include refineries and chemical plants. These capabilities include in-service inspection, aging management strategies (deterministic and probabilistic), weld-repair techniques, sealing and gaskets, bolting and fasteners, operation and maintenance techniques, and related items. Thermal aging management strategies of nonmetallic components, such as high-voltage and control cables, and concrete will be developed in concert with other process industries and the suppliers.
- **Technology Innovations** (LWRs and ALWRs, about 75 percent derived)—A large share of the capabilities required to improve nuclear energy technologies will be transferred from other industries. These include fully automated control systems, advanced sensors, robotics, prognostic maintenance technologies, and related items. Additional capabilities will be co-developed with other high-pressure, process industries, such as for chemical and petrochemical plants. Similarly, advanced crew training technologies can be co-developed with other process industries as well as the airline industry.
- **Manufacturing and Construction** (ALWRs and major upgrades of LWRs, about 75 percent derived)—Advanced manufacturing and construction techniques exist in most capital-intensive industries. With some modifications, these capabilities can be transferred to the nuclear energy industry. Some examples of these capabilities include construction logistics and management; modular construction techniques; on-site manufacturing of heavy components, including local stress relieving of

welds; heavy structure transport and lift; advanced concrete pours for reinforced, pre- and post-tensioned structures; automated welding (and inspection) of piping and structures; and related areas. Advanced heavy section welding and inspection techniques can be co-developed with other power and process industries.

C.2 Workforce Development

In maintaining a robust workforce for the 2010 to 2050 time frame, capabilities developed in or co-developed with other industries will prove invaluable to the nuclear energy industry. The issues faced in the nuclear energy industry are virtually identical to those of many other manufacturing and processing industries.

- **Optimize Training** (All areas, 75 percent derived)—Much of the work under way to optimize training in other industries (particularly the power, process, defense, and airline industries) will benefit the nuclear energy industry. Major efforts are under way to improve the effectiveness and efficiency of training for operators and maintenance personnel, designers and engineers, and welders and construction workers. These options include computer-based training, just-in-time and as-needed training, virtual reality-based training, and smart system-based training. In addition, major efforts exist to automate systems to eliminate the need for human supervision and control. Likewise, workplace assistive device developments will permit the more effective use of physically challenged individuals in work environments where obstructions previously existed—enlarging the workforce pipeline.
- **Knowledge Management** (All areas, 75 percent derived)—Of all knowledge, 85 percent is tacit, not formally documented in procedures and instructions. Most of the real insights into designing, manufacturing, operating and maintaining equipment and systems are locked in the memories of the experienced, but aging, workforce. All industries are faced with the "gray" (experienced) to "green" (new recruit) transition. Methods ranging from more traditional mentoring programs to sophisticated knowledge extraction techniques are under development to extract tacit knowledge, document it, and integrate it into training programs. The nuclear energy industry must transfer the more successful methods in the near-term to take advantage of the limited time remaining before the experienced workforce retires.
- **Sustainable R&D** (All areas, 25 percent derived)—Some of the R&D capability required in the nuclear energy industry is common to several other industries, drawing heavily from science and engineering disciplines (mechanical, electrical, control, chemical, industrial, engineering mechanics, computer science, and related areas). Therefore, the nuclear energy industry should take advantage of the efforts in DOE Office of Science, NSF, and other educational programs to provide the long-term R&D necessary to fulfill those technical capabilities that not unique to the nuclear industry.
- **Innovative Energy Educator** (All areas, 100 percent derived)—The nuclear energy industry should support and rely on the national endeavors to attract students (K-12) into math, science, and technology studies. While the efforts are not well coordinated, they are all a piece of addressing the workforce challenge. Numerous strong student outreach programs exist through technical societies, industrial organizations, federal and state governments, colleges and universities. Focused efforts are needed to attract women into science and technology.

C.3 Sustainable Fuel Cycle

The sustainable fuel cycle focus area is unique to the nuclear energy industry and is covered in Section 4.

C.4 Next-Generation Reactors

Heat Transport (Process heat reactors, 75 percent derived)—One of the key capabilities of the process heat reactors developed in the future is to transport heat efficiently and effectively with minimal concern for corrosion resulting from leakage, spillage, or intrusion into end-users' systems of the heat transfer medium. Most capabilities required for the nuclear energy industry in this vein derive from the process industries themselves. Heat is a required, but expensive, commodity in process industries and their commercial success is dependent upon effective transfer, transport, and use. Dry cooling condenser technologies developed in other industries should be adapted to the next-generation reactors to minimize water requirements. This will permit the incorporation of the expertise and experience gained in the process and power industries.

Modeling and Simulation (All areas, 25 percent derived)—With exception of capabilities that involve nuclear processes, modeling and simulation capabilities can be adapted from other areas of science and technology. High-performance computer and atomistic models are being developed by DOE Office of Science and others to promote basic understanding of physics, chemistry, and materials science. Complex system simulations are required to optimize design of process facilities such as refineries and chemical plants. The nuclear energy industry will take full advantage of the modeling and simulation capabilities for those processes and systems that are not unique to nuclear energy.

Materials Development (All areas, 25 percent derived)—The nuclear energy industry has many unique material aging issues, such as neutron irradiation-induced embrittlement, radiolysis of coolants in the core, and complex and corrosive environments in fuel recycling and separation systems. However, materials developed in other industries have equally challenging thermal and chemical conditions that can be adapted to nuclear applications after the proper V&V of the material's "fitness for duty." The chemical and advanced fossil power industries have appropriate capabilities that could be applied in nuclear environments. The new ultra super critical coal plants have a target main steam temperature of 700°C. Real opportunities exist to co-develop materials and manufacturing processes between the high-temperature reactor and ultra super critical industries.

C.5 Regulatory Requirements

Licensing Efficiency (All areas, 25 percent derived)—While most of the NRC licensing activities are unique to the nuclear energy industry, there are overlaps with other U.S. regulatory agencies, such as the EPA, Department of Transportation Pipeline Safety, and Food and Drug Administration. Additionally, every country in the world with a commercial nuclear program has a nuclear regulatory body. Examples of efficient and effective regulatory practices should be considered for NRC adoption, as long as it does not comprise NRC's principal mission to protect the health and safety of the public. Particular emphasis should be focused to reduce regulatory review cycle time and decision making and streamline the review process by eliminating low-value added steps.

Staffing (All areas, 25 percent derived)—The NRC and the nuclear energy industry are both faced with addressing similar aging workforce challenges. Of the skills required by NRC staff, many—but not all—are unique to the nuclear energy discipline. Capabilities gained in the industrial sector through optimized training, knowledge management, sustained R&D, and an increase in the number of students interested in science and technology will augment the NRC potential staff pipeline. In addition, the increased licensing efficiency discussed above will reduce the staffing requirements on a per-nuclear-facility basis.

C.6 Safeguards and Security

Optimized Technology (All areas, 70 percent derived)—Essentially all of the optimized security technology capabilities required for the nuclear energy industry in the 2010 to 2050 time frame will be developed for other industries. The military and national defense industries have large-scale programs to develop technologies to secure sensitive facilities and protect regions from physical intrusions and attacks. Replacement of the traditional "guns and guards" approach to securing nuclear energy industry facilities (particularly the current 104 commercial power plants) will transition to a technology-based approach requiring fewer humans while providing increased security. Such technologies include high-efficiency electronic surveillance with zero false calls, intruder detection, weapons and explosive detection, and aircraft and watercraft neutralization. The nuclear energy industry should select and deploy security technologies developed for other industries that optimize the securing of all facilities, including reactors and fuel and separation and radioactive material storage facilities.

A unique need of the nuclear energy industry (both commercial power and national defense) is the need to implement nuclear materials accounting systems. A key component of material accountability is advanced sensors, which will be highly specialized and integrated into the basic facility design (as part of "safeguards-by-design"). This instrumentation will use both radiation-based and non-radiation-based detection, will be online and at-line, and will be based on both passive and active modes of operation. Some fundamental technology development will occur in the nuclear physics R&D arena as well as the homeland security radiation detection arena. However, application in materials accountability requires the highest possible accuracy and reliability, necessitating additional development for use in the nuclear energy industry. Nuclear facilities built and operated within the DOE will create a synergistic effect that will benefit the needs of the nuclear energy industry in this area.

Data Integration and Control (All areas, 90 percent derived)—Advanced data integration and control systems needed as a critical component of the "safeguards-by-design" implementation will be primarily developed for other industries such as modern manufacturing and large relational database management organizations. The nuclear energy industry will also require near-real-time analysis and decision-making mechanisms, requiring specialization of these general approaches. For example, integration of disparate data will be developed as part of mining internet information, but the quantification of relations within such data with a high degree of accuracy and reliability is an aspect required by the nuclear energy industry to ensure a robust S&S system.

Cybersecurity (All areas, 100 percent derived)—Similar to optimized security technology, cybersecurity is the focus of major efforts in many industries, including the military. The nuclear energy industry should identify, adapt, and deploy the best cybersecurity approaches that meet NRC, owner/operator, and Department of Homeland Security requirements. Systems requiring protection from cyber threats are not unique to the nuclear energy industry, whether they are wired, optical, or wireless systems. In addition, all efforts should be made in the design process to ensure physical separation of the nuclear facility control systems from other systems that can be breached from the outside, such as the internet and other communication methods.

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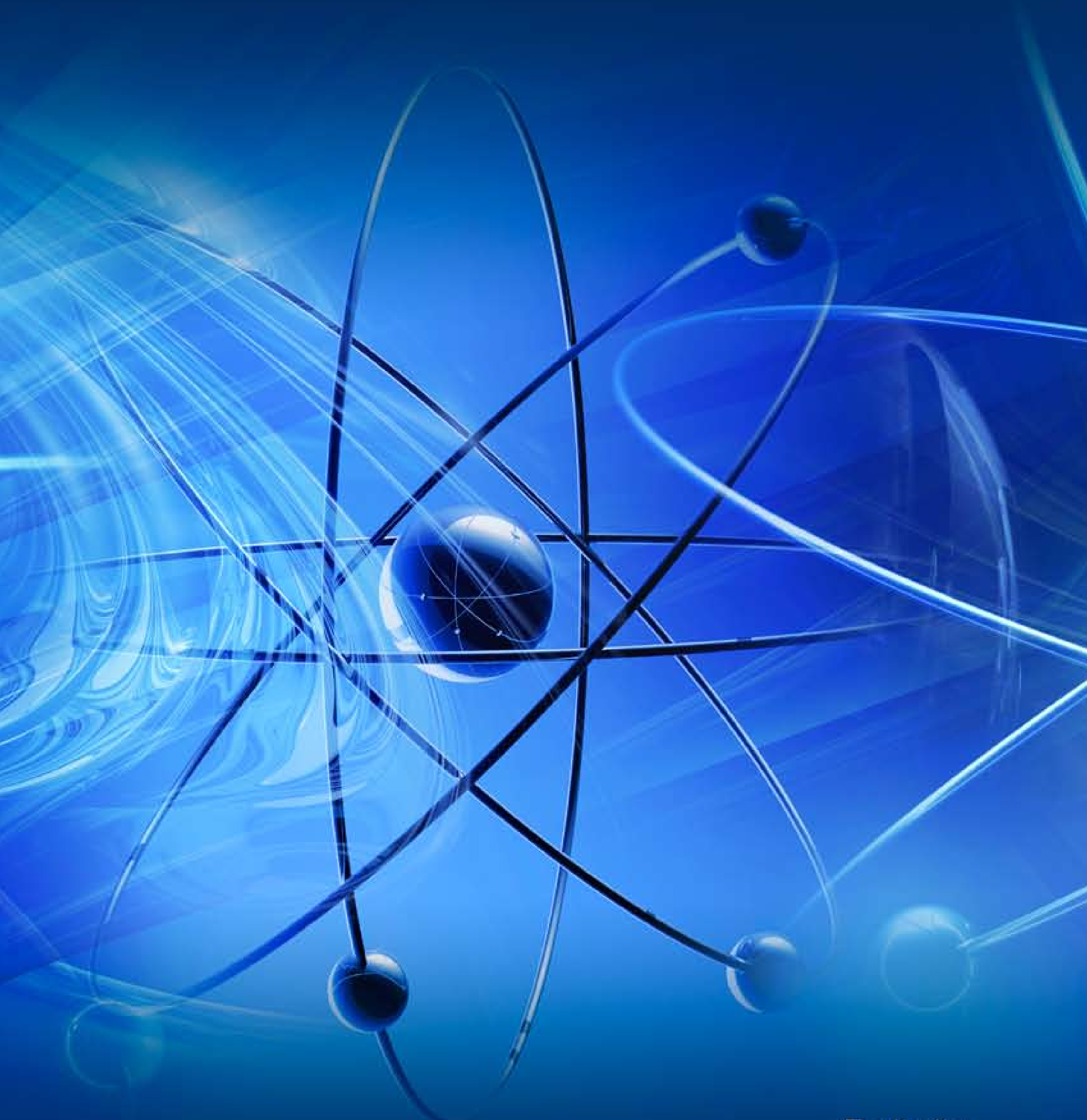

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