Nuclear Energy R&D Infrastructure Report for The Blue Ribbon Commission on America's Nuclear Future

Dr. Andrew C. Klein

Oregon State University

Executive Summary

Over the past few years a number of important studies have been executed to identify and define the necessary nuclear energy research, development and demonstration (RD&D) infrastructure that must be sustained or developed.

This report is a compilation of work performed by numerous others to characterize the nuclear energy RD&D infrastructure in the United States. It collects and summarizes the key thoughts and understandings achieved in those previous works about the nature, status and needs of the nation's facilities and capabilities to perform the RD&D necessary to sustain the current fleet of operating nuclear power plants, to cultivate advanced nuclear reactor concepts for future deployment in the electrical energy, process heat, and potentially other economic sectors, to better understand the character of the nuclear fuel cycle, and to protect the nation from the proliferation of nuclear weapons and materials. This infrastructure resides primarily in the U.S. Department of Energy (DOE) national laboratory system, but many important aspects of the RD&D infrastructure are contained within the nation's universities and colleges who educate students in the areas of nuclear engineering and radiation science as well as in the corporations who develop, design, manufacture and build nuclear power plants and other nuclear facilities.

The nation's nuclear energy RD&D infrastructure is defined in this report to include the many and diverse facilities, equipment, capabilities, and assets needed to further understand and advance the state-of-the-art related to the development, demonstration and deployment of nuclear science and energy applications for the benefit of humankind and the appropriate nuclear science and engineering educated and trained workforce necessary to accomplish these applications.

The first section of the report introduces the nuclear energy infrastructure in the US and identifies the sources of material for this report. The second section of this report discusses the various infrastructure requirements to enable the nation's scientific and engineering communities to perform the varied RD&D activities necessary. This is followed by the third section which covers the status of the nation's nuclear energy RD&D infrastructure and a high-level summary of existing facilities that are currently used to approach meeting these requirements. The fourth section discusses the gaps in the current infrastructure and the final section of the report covers some of the options available for filling these gaps including the construction of new facilities in the US, the use facilities in other countries, the development of multi-national facilities both in the US and in other countries, and other possible opportunities.

The referenced series of reports identify several general and unique nuclear energy RD&D capabilities and/or facilities required for successful nuclear energy RD&D over the next 20 to 50 years. These capabilities and/or facilities are:

1. **Nuclear Education Facilities**
2. **Thermal Neutron Irradiation Capability**
3. **Fast Neutron Irradiation Capability**
4. **Radiochemistry Laboratories**
5. **Hot Cells for Separations and Post-Irradiation Examination**
6. **Facilities for Thermal Transport and Safety Analysis**
7. **Fuel Development Laboratories**
8. **Prototype High-Temperature Reactor for Licensing and Demonstration**
9. **Prototype Fast Reactor for Licensing and Demonstration**

The remainder of this report discusses in more detail the facilities needed in these areas, identifies the current status of the US, and in some cases the world infrastructure in these areas and elucidates the gaps between the needs and the currently available facilities to meet these needs. The report concludes with a discussion of potential options which can be approached to eliminate these gaps including building new facilities in the US, collaborations that build multi-national facilities in the US, collaborations that build multi-national facilities outside of the US, and collaborations that use facilities outside of the US. Different approaches may warrant consideration when addressing the various needs and gaps and the approaches chosen will probably include combinations of all four directions.

Section I. Introduction

This report is a compilation of work performed by numerous others to characterize the nuclear energy research and development (RD&D) infrastructure in the United States. It collects and summarizes the key thoughts and understandings achieved in those previous works about the nature, status and needs of the nation's facilities and capabilities to perform the RD&D necessary to sustain the current fleet of operating nuclear power plants, to cultivate advanced nuclear reactor concepts for future deployment in the electrical energy, process heat, and potentially other economic sectors, to better understand the character of the nuclear fuel cycle, and to protect the nation from the proliferation of nuclear weapons and materials. This infrastructure resides primarily in the U.S. Department of Energy (DOE) national laboratory system, but many important aspects of the RD&D infrastructure are contained within the nation's universities and colleges who educate students in the areas of nuclear engineering and radiation science as well as in the corporations who develop, design, manufacture and build nuclear power plants and other nuclear facilities.

The nation's nuclear energy RD&D infrastructure is defined in this report to include the many and diverse facilities, equipment, capabilities, and assets needed to further understand and advance the state-of-the-art related to the research, development, demonstration and deployment of nuclear science and energy applications for the benefit of humankind and the appropriate nuclear science and engineering educated and trained workforce necessary to accomplish these applications. It does not include for this report, the manufacturing, waste management, cleanup, or other infrastructures that must be in place to support the RD&D enterprises. These will obviously be important to the RD&D enterprise, but are not included in consideration nor discussed further in this report. It does also not include or discus the nation's nuclear weapons related RD&D infrastructure, based almost entirely at the national laboratories, some of which could be useful for advanced fuel cycle and proliferation RD&D.

Over the past few years a number of important studies have been executed to identify and define the necessary nuclear energy RD&D infrastructure that must be sustained or developed. Future improvement of these capabilities can be guided by the principal research objectives of the U.S. Department of Energy's Office of Nuclear Energy (DOE-NE) as described by their recent RD&D roadmap (**REFERENCE 1**):

- Develop technologies and other solutions that can improve reliability, sustain the safety, and extend the life of current reactors
- Develop improvements in the affordability of new reactors to enable nuclear energy to help meet the Administration's energy security and climate change goals
- Develop sustainable nuclear fuel cycles
- Understand and minimize the risks of nuclear proliferation and terrorism

These infrastructure studies build upon a number of studies over the years including a series of three reports on nuclear RD&D capabilities and facilities have helped to identify the needed nuclear infrastructure, including a summary report conducted by DOE-NE (**REFERENCE 2**) and two comprehensive studies commissioned by DOE-NE and conducted by the Battelle Memorial Institute. These two Battelle studies are particularly important because the first one used extensive nuclear industry input on their needs for nuclear energy RD&D from the US government (**REFERENCE 3**) and the second one that utilized the judgment of senior industry, academic and national laboratory leaders to identify the current and future RD&D capabilities required to enable nuclear energy to play a significant role in the future as the US strives to attain energy security and to reduce carbon emissions (**REFERENCE 4**). Another important study that was conducted by Idaho National Laboratory involved a bottom up collection/inventory of relevant research facilities across the US in the national laboratories, industry and academia (**REFERENCE 5**). This study also included listings of notable and relevant special facilities around the globe that will be important as the world moves ahead to implement various aspects of applying nuclear energy to solve some of the world's problems. Another document that was useful in developing this report was the Idaho National Laboratory's ten-year site plan (**REFERENCE 6**).

To emphasize the importance of infrastructure to future nuclear energy RD&D, recently the directors of ten national laboratories prepared their recommendations to DOE concerning the important role that nuclear energy will need to play in a sustainable, renewable energy future (**REFERENCE 7**). Their conclusions articulate the need for a long-term coherent strategy and strong U.S. leadership and makes a special call to sustain and modernize the nuclear energy science and technology infrastructure, including "irradiation systems for testing new fuels and structural materials; chemical separations and characterization capabilities; and physics facilities for radiation transport, thermo-hydraulics, cross-sections, and criticality science."

The second section of this report discusses the various infrastructure requirements to enable the nation's scientific and engineering communities to perform the varied RD&D activities necessary. This is followed by the third section which covers the status of the nation's nuclear energy RD&D infrastructure and a high-level summary of existing facilities that are currently used to approach meeting these requirements. The fourth section discusses the gaps in the current infrastructure and the final section of the report covers some of the options available for filling these gaps including the construction of new facilities in the US, the use facilities in other countries, the development of multi-national facilities both in the US and in other countries, and other possible opportunities.

Section II. Infrastructure Requirements

Early in 2008, DOE-NE commissioned Battelle Memorial Institute to engage the domestic nuclear energy industry, academic community, and national laboratories to analyze the capabilities required to support the successful deployment of nuclear energy opportunities by 2050 (**REFERENCE 4**). This series of reports was intended as a response to a 2008 report by the National Academy of Sciences on the nature of DOE-NE's RD&D programs (**REFERENCE 8**). DOE-NE's response included a series of three studies of the types of facilities that would be needed and the functionality required of those facilities to support nuclear energy research and development. DOE, Idaho National Laboratory and Battelle conducted a three-phase process to identify the highest priority capabilities and the facility needs to enable these capabilities.

In the first two phases, key studies were conducted to provide the basis for the development of recommendations by DOE. The first study, led by Battelle, (**REFERENCE 3**) included the participation of 34 organizations representing the nuclear energy industry, academia, and the national laboratories to articulate the industry's goals for the 2010 to 2050 timeframe and identify and prioritize the required capabilities to accomplish these goals. The second report, produced by Idaho National Laboratory (**REFERENCE 5**) assessed the availability and state of existing US facilities to provide the required capabilities. In the third phase (**REFERENCE 4**), a senior executive team, led by Battelle, but including members from industry, academia and the national laboratories, reviewed the results of both studies, the industry goals, current DOE program activities, and capability gaps and identified a set of key priorities and recommendations for the nation's nuclear energy RD&D programs. A summary of the process used to achieve these findings is included in Figure 1-1 from **REFERENCE 3.**

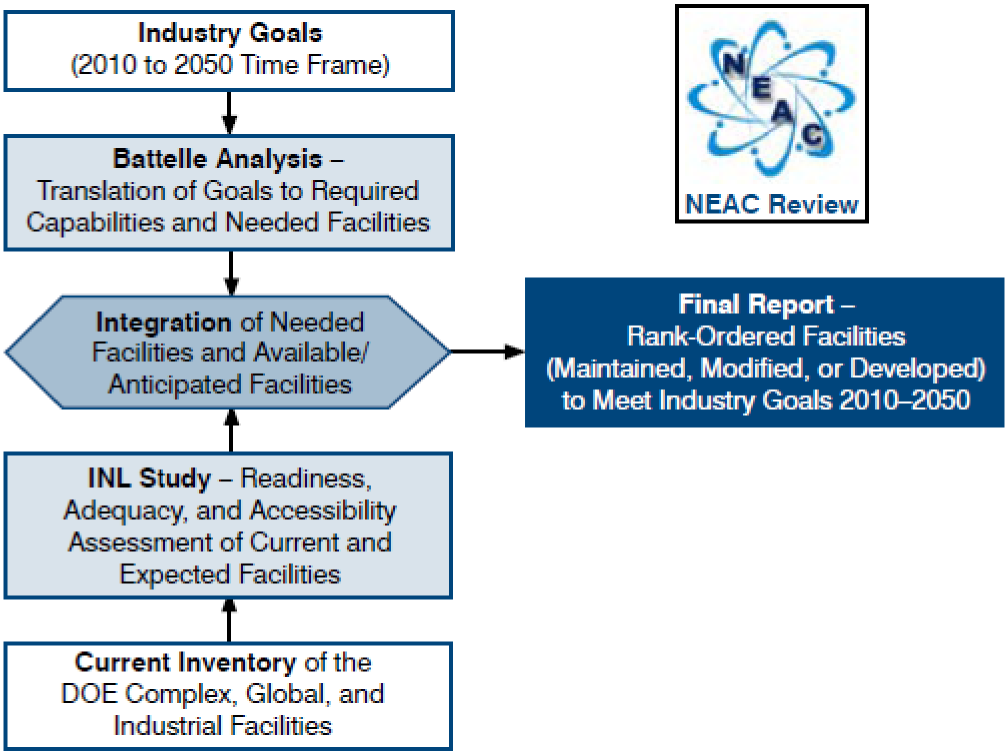

Figure 1-1. Top-Down/Bottom-Up Processes for Developing a Rank-Ordered Nuclear Energy Facilities Program (Nuclear Energy Advisory Committee [NEAC] review provided in the blue-colored steps)

The first Battelle study (**REFERENCE 3**) also identified nine general and unique essential RD&D capabilities and/or facilities required for successful nuclear energy RD&D over the next 20 to 50 years. These capabilities and/or facilities are:

1. **Nuclear Education Facilities**
2. **Thermal Neutron Irradiation Capability**
3. **Fast Neutron Irradiation Capability**
4. **Radiochemistry Laboratories**
5. **Hot Cells for Separations and Post-Irradiation Examination**
6. **Facilities for Thermal Transport and Safety Analysis**
7. **Fuel Development Laboratories**
8. **Prototype High-Temperature Reactor for Licensing and Demonstration**
9. **Prototype Fast Reactor for Licensing and Demonstration**

Table 5-1 from the first Battelle report (**REFERENCE 3**) summarizes the "unique-to-nuclear" RD&D facility needs and prioritizes them to meet the nuclear energy industry RD&D goals for the 2010 to 2050 time frame.

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

A more detailed description of these facility needs is included below.

1. Nuclear Education Facilities

A highly educated and trained workforce is essential to the safe and effective utilization of any nuclear facility (**REFERENCE 3 & REFERENCE 4**). The availability of hands-on nuclear educational capabilities is a vital aspect of the development of the nuclear workforce. There is no substitute for directly working with radioactive materials and radiation in the education of nuclear workers. Several types of research and education facilities are needed and each university, community college, or technical school must have the flexibility to decide which facilities best fit their research and teaching expertise and interest. Many of these facilities can be used for both research activities aimed at graduate student education and for teaching activities aimed at both undergraduate and graduate students. Specialized, large, expensive, and high risk capabilities located at national laboratories can also be made available to faculty and students as user facilities.

Relevant and useful on-campus educational facilities include:

- Nuclear reactors and accelerators for research and training
- Radiation measurement laboratories

- Computational facilities
- Instrumentation and control laboratories
- Heat transfer and fluid transport measurement laboratories
- Radiochemistry laboratories
- Hot cells and radioactive material handling capabilities
- Radiological environment training facilities
- Maintenance and repair training facilities

2. Thermal Neutron Irradiation Capability

The Battelle industry report (**REFERENCE 3**) identifies the necessity for thermal irradiation test facilities of sufficient size and availability to irradiate new fuel design pins and material test specimens to provide prototypical results. This capability can best be supplied by a thermal spectrum research and test reactor. Readily available hot cells should be closely associated with the test reactor to minimize radioactive materials transport issues and expenses.

3. Fast Neutron Irradiation Capability

To develop new fast reactors along with their fuel and structural materials, significant test irradiation capabilities need to be available to the research community (**REFERENCE 3**). These capabilities are needed to conduct tests on materials and fuel and to provide a source of fast neutrons to study materials aging issues and to develop models for aging phenomena in fast reactors. 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, nearby hot cells of sufficient size and capability to provide meaningful knowledge of the damage mechanisms and fuel performance are required.

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 neutron irradiation capabilities is needed to develop guidelines for construction materials for fast reactors, develop appropriate fuel types for fast reactors, and eventually provide data to support licensing and construction. Initially, small samples can be used to model the impact of irradiation damage. As the RD&D program progresses, 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.

4. Radiochemistry Laboratories

Radiochemistry laboratories are needed to support radiochemical, elemental, and isotopic analysis of nuclear fuels, both un-irradiated and irradiated, and the resultant fission products, as well as materials and waste products encountered in nuclear fuel processing and fuel development (**REFERENCE 3**). Detailed analyses of feed materials and resultant products are critical to characterize how separations processes perform during fuel recycle RD&D efforts. In addition to the separations needs, new fuels for irradiation tests must be analyzed to ensure that they meet requirements for irradiation and also that they can be analyzed post-irradiation. Finally, waste products need to be well characterized in order 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 RD&D facility will minimize radioactive/hazardous material transportation requirements and the time delays associated with those activities. Typically, these labs require 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.

5. Hot Cells for Separations and Post Irradiation Examinations

Development of separations processes requires the use of real used fuel, which requires the availability of heavily shielded hot cell facilities (**REFERENCE 3**). Implementation of new processes on a commercial scale will require testing first at a small scale, on the order of tens of kilograms, followed by extending the processes to larger scales, to provide engineering-scale demonstration of the most promising used fuel recycle technologies.

Hot cells for Post Irradiation Examination (PIE) 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. 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.

Ideally hot cells for both separations and PIE capabilities would be 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 should have the capability to fully examine and analyze test specimens on macroscopic and microscopic scales over a wide range of temperatures and environments.

6. Facilities for Thermal Transport and Safety Analysis

A thorough and detailed understanding of the movement of heat and fluids throughout a nuclear reactor system is absolutely required to ensure their safe design and operation. Research and development facilities in the form of scaled flow loops, separate effects tests, and other configurations are necessary for the development, validation and verification of computer codes used by designers and regulators to predict and verify the safe design and operation of nuclear power plants. Instrumentation and measurement of various heat transfer and fluid flow properties such as pressures, temperatures and flow rates form central components to understanding and predicting nuclear reactor system behavior under normal and accident conditions, thus forming a vital part of the regulation of nuclear power systems.

Thermal transport loops are required to test and reinforce the safety principles of currently operating power plants, projected next-generation water reactor plant concepts and advanced high temperature gas, liquid metal, and molten salt cooled reactor concepts (**REFERENCE 3**). These loops are also necessary to demonstrate the reliability of systems and components in harsh environments as well as to provide validation and verification (V&V) data for computer codes used in system safety analysis in regulatory proceedings. Thus, these loops create a critical demand for highly effective quality assurance and quality control programs and the capability to ensure the veracity of the data collected and used in licensing proceedings. An example of one particularly useful facility of this type would be a large-scale component flow loop or test facility for gas-cooled reactors. Such a facility would be very useful in testing various components, such as circulators, heat exchangers or instrumentation, in reactor-like conditions or as a base test facility for testing high-temperature process heat applications or hydrogen generation.

Additional testing capabilities are needed to investigate individual fluid flow and heat transfer phenomena. These separate effects testing facilities provide useful developmental data for better understanding of thermal and fluid phenomena important to reactor development and licensing, progress on new heat transfer and fluid flow correlations, and the advancement of new computer code development.

7. Fuel Development Laboratories

Fuel development facilities are needed for developing new fuel/clad types that will achieve high fuel burn up, converting products from the used fuel separations processes into appropriate fuel forms—either oxide, carbide, or metal—and developing new fuels for next-generation reactors (**REFERENCE 3**). For high-temperature gas cooled reactors using TRISO particle fuel technology, specialized coaters are required to apply 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. If recycled material is to be used in advanced reactors, unlike fresh light-water reactor fuel, recycled reactor fuel must be assembled remotely because of the hazardous conditions caused by this highly radioactive recycled fuel material.

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.

8. Prototype High-Temperature Reactor for Licensing and Demonstration

The further development of high–temperature gas-cooled reactor technology will likely require licensing high-performance test facilities, such as a prototype high-temperature reactor (**REFERENCE 3**). The Next Generation Nuclear Plant (NGNP) is a publicly/privately funded partnership aimed at designing, licensing, building and operating a high temperature nuclear demonstration plant that can generate both electricity and hydrogen using process heat to drive a thermo-chemical or high- temperature electrolysis water splitting process. The NGNP would be a large (300 to 400 MWth) demonstration of a combined electricity/process heat plant. Such a facility would be useful in addressing major technical issues such as fuel reliability and structural graphite and regulatory issues such as plant licensing. Engineering development and component test facilities are also needed to support demonstration of the NGNP.

9. Prototype Fast Reactor for Licensing and Demonstration

Fast reactors have been under development globally since the early 1950s. Most of these fast reactor systems 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 would seem to require the initial licensing of a demonstration fast reactor by the U.S. Nuclear Regulatory Commission (NRC) (**REFERENCE 3**). This need might also be met through a NRC licensing review of an international facility or by the NRC's direct involvement and application of US regulations to the licensing of a new international reactor facility that would be collaboratively designed and constructed. Such a detailed involvement by one country's regulatory agency in the development of another country's facility would represent a significant new development in international nuclear energy cooperation. Additionally, a demonstration fast reactor's role could also be extended to include its utilization as a research facility to test new fuel designs on a large scale, as well as new heat extraction, instrumentation, control and coolant circulation technologies.

Section III. US Infrastructure Status

The United States currently maintains a wide range of facilities to support its RD&D activities (**REFERENCE 1**). These include test reactors, large-scale hot cells, smaller-scale radiological facilities, specialty engineering facilities, and small non-radiological laboratories. The DOE employs a multi-level approach to ensuring that these capabilities are available when needed. Core capabilities rely almost entirely on DOE-owned irradiation, examination, chemical processing and waste form development facilities. These are supplemented by university and some industry capabilities ranging from research reactors to materials science and testing laboratories.

The physical infrastructure for nuclear energy RD&D tends to have significantly higher costs than the facilities needed for other industries. The extra costs of creating and maintaining nuclear energy RD&D infrastructure includes the necessary safety and security infrastructure. The current DOE approach to acquiring and maintaining nuclear energy RD&D infrastructure has concentrated on collecting several of the high-risk nuclear facilities at the Idaho National Laboratory (INL) while maintaining various unique capabilities at other sites. A series of annual INL Ten-Year Site Plans (TYSP) (**REFERENCE 6**) provides many useful, detailed points of reference for a significant fraction the US capabilities in nuclear energy RD&D. The most recent INL TYSP, produced in 2010, details DOE's strategy for implementing their nuclear energy RD&D infrastructure goals and also responds to recommendations of the National Academy of Sciences in 2008 for DOE to invest in research capabilities and to develop a process for prioritizing, evaluating, and obtaining these capabilities (**REFERENCE 8**). DOE also supports vital university infrastructure through its Nuclear Energy University Program (NEUP), negotiates equitable capability exchanges with trusted international partners, refurbishes and reequips essential facilities as required, and addresses maintenance backlogs, as needed, to ensure safe operation.

To support their nuclear energy RD&D mission, DOE has operated and developed core capabilities and facilities that are unique to nuclear energy RD&D. It often makes these facilities open to national laboratory, industry and to university researchers through direct participation in particular research projects and through user facilities. Available capabilities include core competencies in reactor technologies, fuel cycle development, and systems engineering as well as a remote location with the safeguards, security, and safety infrastructure to manage radiological and nuclear materials and testing under normal and abnormal conditions. Specific facilities include those for neutron irradiation, post-irradiation examination (PIE) and characterization, fuel development, separations and waste form development, and other specialized testing capabilities.

Much of the existing US nuclear infrastructure in the national laboratories, industry and universities is more than 30 years old. Even though the existing infrastructure is quite old, it can still serve many of its intended purposes as long as important modifications, upgrades, equipment additions, and sustained regular maintenance are completed **(REFERENCE 5)**. Maintaining and expanding the use of particular aspects of the current infrastructure, in addition to developing additional facilities to meet new and/or expanded opportunities – both domestically and internationally, appears to be the chosen approach by the DOE nuclear energy RD&D community.

Built in an era when environmental regulations were less demanding, many current US nuclear facilities face increasingly complex challenges if they are to be retrofitted and/or upgraded for new missions. Fortunately these older facilities retain all of their concrete and steel, which are currently often the most expensive components in the cost of new facilities. Adding complication to securing upgrades to these 50-year old facilities is the current demand for rigorous quality assurance pedigrees for all high-source-term nuclear activities. Extensive qualification and retrofitting will be required if these assets are to be extensively utilized in a modern nuclear energy RD&D program. The list of challenges includes tightened seismic requirements requiring extensive physical upgrades including enhanced bracing, new ventilation systems, new fire protection, and more; encroachment by other site activities and the surrounding community; availability of vital site infrastructure, including power, water, sewer, and office facilities; completion of National Environmental Policy Act documentation; and meeting modern DOE security requirements for protecting nuclear materials.

The status of the facilities and capabilities available to support the US nuclear energy RD&D mission at the national laboratories, universities, and to a limited extent industry, and their status is included below.

1. Nuclear Education Facilities

The nuclear engineering and science educational community maintains its teaching and research infrastructure and facilities to the extent that it can afford upgrades and expansion. Not every university has all of the capabilities and facilities listed above, but they do develop and maintain those that are most directly related to the RD&D and teaching interests of their faculty. The past two decades of US investments in nuclear engineering and science education programs and their facility and infrastructure needs has revealed inconsistent implementation of policy and Congressional intent (**REFERENCE 3 & REFERENCE 4**). Resources for nuclear educational infrastructure and facilities have risen and fallen over this period, sometimes in direct correlation to DOE nuclear energy RD&D budgets, but other times not. DOE has repeatedly restructured its university program leading to confusion and uncertainty throughout the government, industry and academia, often resulting in uncertainty with respect to the priorities for sustaining and developing required core competencies. The overall result was a general reduction of nuclear education laboratories including on-campus research reactors, and lagging development of teaching and research faculty. There remain approximately 27 research and training reactors on university campuses and most nuclear engineering programs have, at minimum, fundamental radiation detection and measurement laboratories. The recent introduction of the NEUP has enabled stronger and continuing investments in core competencies and infrastructure. During fiscal years 2009 and 2010 the NEUP provided more than $18M for infrastructure, instrumentation and facilities improvements on university campuses. The funding from NEUP has enabled some of the needed upgrades and expansion of the capabilities available on the nation's university campuses, but continuous support over a number of years is still needed after years of limited funding availability.

2. **Thermal Neutron Irradiation Capability**

Several thermal test reactor(s) of sufficient size and availability to irradiate new fuel design pins and material test specimens to provide prototypical results currently operate in the DOE complex (**REFERENCE 3**). These include the Advanced Test Reactor (ATR) at INL and the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL). The ATR has recently been designated by DOE as a National Scientific User Facility for use by industry and academia, as well as by the traditional Naval Reactors and DOE users.

3. **Fast Neutron Irradiation Capability**

There are currently no fast neutron irradiation testing facilities operating in the US. Limited, small-volume RD&D capabilities have been developed and exist at a few thermal research reactors by absorbing the thermal neutrons in the neutron energy spectrum (**REFERENCE 3**). Accelerators can also be used to test fairly small volumes of materials, but there are no large-scale domestic capabilities for fast spectrum materials and fuel development programs. Currently, the US uses irradiation capabilities in foreign countries to conduct limited tests on materials and fuel. Additional fast neutron 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. The development of fast neutron irradiation facilities would appear to be an especially attractive target for the US. Encouragement and activities that enable the development of internationally collaborative fast neutron irradiation capabilities would be a highly valuable US objective. Since the US has not operated any significant fast neutron irradiation capabilities for nearly two decades while other countries have continues to operate and provide such resources, the US could gain significant access to fast neutron irradiation capabilities at a fraction of the cost if it were to initiate and sustain international discussions on the development of these types of vital facilities. The specific location of these facilities would be the subject of significant international negotiations, as they have been in the development of the International Tokamak Experimental Reactor which will provide international collaboration in fusion reactor design and RD&D.

4. Radiochemistry Laboratories

Over the last 30 years, many fuel cycle research and development facilities have been shut down or re-directed for other uses due to lack of funds for sustained research and increased costs for maintenance and regulatory compliance (**REFERENCE 3**). A few facilities are still operating in the national laboratory system (mostly at INL and ORNL, but also at Pacific Northwest National Laboratory in Richland, WA, Los Alamos National Laboratory in Los Alamos, NM and Lawrence Livermore National Laboratory in Livermore, CA) which can continue to be used for RD&D efforts supporting a sustainable nuclear fuel cycle. As with the fast neutron irradiation capabilities discussed above, the US could gain access to significant sources of data and information if it took a lead role in the development of international collaborations resulting in sizable radiochemical RD&D laboratories, possibly in close association with the development of the international fast neutron irradiation capabilities.

5. Hot Cells for Separations and Post-Irradiation Examination

A number of DOE national laboratories maintain hot cell facilities that are currently used for separations research work, or could be configured to do so (**REFERENCE 3**). These facilities span a wide range of size and activity type to support fuel recycle. It is important to note that every hot cell is not necessarily suitable for all RD&D missions. The design of a hot cell takes into account the specific purpose for which it is intended. Some hot cells are most appropriate for wet work using aqueous solutions, some are more appropriate for dry or fuels RD&D activities and all hot cells have specific limits on the amounts and types of radioactive materials for which they can be used. Thus, specific care must be observed in the consideration of extending the application of current hot cells, or in the design of new hot cells to achieve specific RD&D applications and purposes. Specifically, facilities located at ORNL, INL, and the Savannah River Site (SRS) such as the hot cells at ORNL's Radiochemical Development Center, the Fuel Conditioning Facility at INL, and the H Canyon facility at SRS might possibly be considered use for in testing advanced separations technology, however the particular use must be fit into their original design and application envelope.

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, the Irradiated Fuels Examination Laboratory (IFEL), the Irradiated Materials Examination and Testing Laboratory (IMET) at ORNL and the Chemistry and Metallurgical Research Facility Wing 9 hot cells at LANL. The HFEF has recently been designated by DOE 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.

Additionally, international facilities could provide additional support for both separations and PIE RD&D by US researchers. As the efforts to close the fuel cycle and develop new nuclear fuels expand, new hot cell facilities will most likely be needed in the mid- to long-term to ensure that RD&D facilities can provide design data and ongoing support for new fuel cycle and fuel materials development. This would appear to be another area where international collaborations could provide a most fruitful avenue for development.

6. Facilities for Thermal Transport and Safety Analysis

Currently, there are no thermal loops operating in the DOE complex capable testing at the extreme temperatures required by the high-temperature gas-cooled reactor (HTGR) concepts being currently researched and developed (**REFERENCE 3**). There are a few industrial facilities of sufficient size and capability that are designed for use at much lower temperatures. A large-scale thermal test facility would need to be designed, developed and deployed to appropriately test materials and components required for these reactor concepts. A scaled HTGR integral testing facility is currently under development at Oregon State University and will be completed in the summer of 2011.

Limited thermal transport and safety analysis facilities currently exist for licensing and computer code verification and validation for the current generation of light water reactors (LWR) and for some advanced LWR concepts. These take the form of both integral systems test facilities, as exemplified by the APEX (advanced, large-scale pressurized water reactors) and MASLWR (small, modular pressurized water reactors) facilities at Oregon State University and the PUMA facility (advanced, large-scale boiling water reactors) at Purdue University, and separate effects testing facilities at INL and at Pennsylvania State University, University Wisconsin, University of California - Berkeley, Texas A&M University, North Carolina State University, Oregon State University, Purdue University and others.

There are only limited to no thermal transport and safety analysis flow loops available in the US today for either liquid metal or molten salt reactor simulation and testing or for computer model validation and verification for these systems or for safety analysis for use in licensing proceedings for these reactor technology types.

7. Fuel Development Laboratories

Fuel development typically proceeds through a number of phases prior to development of full-scale assemblies, including fabrication of pellets or particles; assembly of pellets into rods, or particles into pebbles or compacts; irradiation of rods, pebbles, or compacts; scale-up to full pins; irradiation of pins; scale up to full assemblies; and irradiation of lead test assemblies (**REFERENCE 3**). The phases of fuel development will require progressively 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 currently available at national laboratories and in industrial facilities that currently are used to develop the evolving fuel designs of the fuel vendors. Unlike new LWR fuel; however, recycled reactor fuel must be assembled remotely and will require heavily shielded and safeguarded facilities. The full range of facilities does not currently exist, but some of the national laboratory hot cells could be utilized, depending upon the size of the fuel components. International laboratories and fuel vendors, notably in France, Japan and Russia, might be utilized for a small number of fuel test development activities.

8. **Prototype High-Temperature Reactor for Licensing and Demonstration**

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 Pebble Bed Modular Reactor (PBMR) prototype, previously under construction in South Africa, is no longer under consideration (**REFERENCE 3**). The Next Generation Nuclear Plant (NGNP) would be the only large (300 to 400 MWth) demonstration of a combined electricity/process heat plant, if its design is ever completed and a public-private partnership can be assembled to deploy a prototype reactor.

9. **Prototype Fast Reactor for Licensing and Demonstration**

Most of the large-scale (greater the 200 MWth) fast reactors built globally have been shut down for a variety of reasons (**REFERENCE 3**). 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. There are no current plans in the US for a prototype fast reactor demonstration at the present time. Internationally, a few fast reactors still exist where limited US licensing and demonstration activities could be arranged. These include operating reactors in Japan, Russia, India, and China. Furthermore, there are fast spectrum reactors currently under design and construction in Russia and India where US researchers and regulators could obtain valuable experience through extensive collaboration in licensing and regulatory research and development, if enabled by the host countries.

Section IV. Infrastructure Gaps

A comparison of the two previous sections identifies some of the significant gaps that exist between the requirements and the current infrastructure.

In the area of **Nuclear Education Facilities** the primary gap that exists is the consistency of funding to provide regular upgrades and maintenance of university teaching and research facilities, including research reactor capabilities. The current NEUP program appears to appropriately address most of the issues related to supporting the teaching and research objectives for the university nuclear engineering and science community; however, it has only been fully functional for two years. Given the past wild fluctuations in DOE's support for nuclear energy human capital development, extended consistency in applying the NEUP will greatly affect this aspect of the nuclear infrastructure.

While it appears that the nation's **Thermal Neutron Irradiation Capabilities** are adequate to meet the expected RD&D needs of future light water reactors and the industries that support these reactors, the availability of high-volume, high-quality facilities for **Fast Neutron Irradiation Capabilities** are significantly deficient, especially if the nation chooses to utilize this technology for fissile material recycle or fission product destruction in the future. A large-scale fast spectrum test reactor would best meet all of the needs in this area. No other type of facility (neither thermal reactors nor accelerators) can provide prototypic condition in sufficient volumes to adequately test the materials and fuels required for fast spectrum reactors.

Modern and expanded **Radiochemistry Laboratories** and facilities are missing in sizes and capabilities needed to fully study various fuel cycle alternatives. It will also be important to maintain and re-furbish existing capabilities in order to meet the needed capabilities. Similarly, existing **Hot Cells for Separations and Post-Irradiation Examination** seem to currently meet the existing RD&D program demands; however, an expanding program to investigate fuel cycle options related to separations and/or fuels development would demand larger and more modern facilities and equipment. Both of these areas would significantly benefit from the development of an advanced fuel cycle facility that would include radiochemistry laboratories, hot cells, and fuel development laboratories.

Large-scale thermal loops for component and process testing, in addition to those flow facilities needed for licensing and safety analysis activities, form a significant gap in the area of **Facilities for Thermal Transport and Safety Analysis**. Facilities to test the thermal transport capabilities and effective in verifying and validating computer codes used for licensing procedures and safety analysis using to all coolant materials under consideration (pressurized and boiling water, high-temperature gas, liquid metals and molten salts) are missing, in addition to those flow loops and test facilities to investigate materials compatibility and various loop components (pumps, heat exchangers, instrumentation, etc.).

In the area of **Fuel Development Laboratories** the greatest gap exists in the facilities useful for manufacturing various fuel forms utilizing recycled nuclear materials. These facilities require significant shielding and remote operations to protect the health and safety of researchers and technicians. Significant volumes are needed to be able to handle and build full-length fuel elements that utilize recycled materials.

Large-scale prototypes form a significant gap in the facilities available for the continued development of both high-temperature gas-cooled reactors and fast spectrum reactors. Both a **Prototype High-Temperature Reactor for Licensing and Demonstration** and a **Prototype Fast Reactor for Licensing and Demonstration** would be needed to work out the idiosyncrasies and difficulties related to licensing these reactor concepts that are a significant departure from the well-known and understood light water reactor designs currently operating and being implemented in the next-generation of nuclear power plants currently under construction.

Section V. Options for Filling Gaps

The options that are available in each technology need area will determine the most effective manner in which to fill the particular gaps. Potential option paths include build new facilities in the US, collaborations that build multi-national facilities in the US, collaborations that build multi-national facilities outside of the US, and collaborations that use facilities outside of the US.

DOE has expressed its primary intention to "use its existing facilities to the extent possible, including those owned by the Office of Nuclear Energy and those available through other Departmental offices. In addition, the Department will pursue resources available at universities and internationally to supplement or provide new capabilities that do not exist in the DOE complex" (**REFERENCE 2**). Furthermore their analysis "supports the consolidation of federal nuclear facility capabilities at two sites: Idaho National Laboratory as the primary site and Oak Ridge National Laboratory as a secondary site. Access to facilities at other national laboratories, such as Pacific Northwest National Laboratory and Savannah River National Laboratory, as well as international facilities will be needed in the nearer term to support RD&D on used fuel reprocessing and recycle".

They also intend to focus on a "core set of materials test reactors, hot cells, and specialized facilities needed to support nuclear energy RD&D for 20 years and evaluate DOE's existing research facilities against needed capabilities, considering functionality, capacity and demand, operating status, adequacy of supporting infrastructure, and economy achieved through co-location with other needed facilities". Their plans also are to "use the same criteria to assess university, industry, and international facilities" and "consider facilities in standby when no suitable operating facilities exist".

It is likely that sponsoring RD&D programs will play a role in setting the priorities for building new facilities to satisfy capability requirements and those new facilities will only be considered if no other reasonable alternative exists in the US or internationally. Additional input into the decision making process for new nuclear energy facilities will most likely be provided by the international safeguards and security communities. Additionally, the DOE community appears to have concluded that facilities do not need to be co-located with those research experts who will benefit from the use of these facilities, provided that they can obtain access to them.

The mechanisms to provide funding for facility resources include public investment, public-private partnerships with federal and state government and nuclear energy industry investment, and U.S. government investment leveraged through international collaboration and investment (**REFERENCE 3**). Initiatives by DOE to work more closely with industry and expand international collaborations could make additional mechanisms possible and provide additional access to facility resources. The Nuclear Energy Advisory Committee has commented that DOE should consider evaluating the potential applicability of the Office of Science model for participating in major international experiments (**REFERENCE 5**). For advanced nuclear energy RD&D, there could be significant savings by sharing facility assets with international partners under existing agreements.

International collaboration and investment options particularly appear to warrant significant consideration for the development of fast neutron irradiation capabilities, for fast reactor licensing and regulatory activities and for fuel cycle research and development. Japan, Russia and France, all currently have major capabilities in these areas that are not available within the United States. In planning future US facilities, consideration should be given to complementing any international partners' existing facilities and plans rather than building a complete infrastructure in the United States. Strong participation and leadership by the United States in international nuclear RD&D, safety and nonproliferation programs is highly desirable (**REFERENCE 1**). The President's Council of Advisors on Science and Technology (PCAST) has also recently recognized the value of international cooperation and collaboration on the management of large-scale demonstration projects such as next generation nuclear power plants (**REFERENCE 9)**. PCAST also has called for an "aggressive program to demonstrate these technologies and point the way to cost reductions".

Portions of the future RD&D portfolio do not require a secure national laboratory infrastructure since they do not involve the use of nuclear materials which must be closely controlled. Examples include RD&D on digital, mechanical, and thermal systems. Significant aspects of this RD&D can readily be performed at universities at lower expense with the collateral benefit of developing the next-generation of the nuclear workforce.

On the other hand, for those facilities and capabilities that do require the national laboratory structure, INL has recently implemented a "User Facility Model" for the Advanced Test Reactor and associated hot cells and facilities that show great promise for involving university and industry researchers. INL seeks to offer its capabilities and related nuclear science and engineering infrastructure to these experts to advance DOE research goals (**REFERENCE 6**). Through the National Scientific User Facility (NSUF), the INL offers the ATR's irradiation and PIE capabilities to help researchers explore and understand the complex behavior of fuels and materials.

References

1. "Nuclear Energy Research and Development Roadmap Report to Congress", U.S. Department of Energy, Office of Nuclear Energy, Washington, DC, April 2010.
2. "Facilities for the Future of Nuclear Energy Research: A Twenty-year Outlook", U.S. Department of Energy, Office of Nuclear Energy, Washington, DC, February 2009.
3. "Nuclear Energy for the Future: Required Research and Development Capabilities – An Industry Perspective", Battelle Memorial Institute, Columbus, OH, 2008.
4. "Nuclear Energy for the Future: Executive Recommendations for R&D Capabilities", Battelle Memorial Institute, Columbus, OH, July 28, 2008.
5. "Required Assets for a Nuclear Energy Applied R&D Program", INL EXT-08-14092, Idaho National Laboratory, Idaho Falls, ID, September 2008.
6. "2012-2021 Idaho National Laboratory Ten-year Site Plan: DOE-NE's National Nuclear Capability – Developing and Maintaining the INL Infrastructure", DOE/ID-11427, U.S. Department of Energy Idaho Operations Office, Idaho Falls, ID, June 2010.
7. "A Sustainable Energy Future: The Essential Role of Nuclear Energy", Letter to the Secretary of Energy from Michael Anastasio, Los Alamos National Laboratory; Samuel Aronson, Brookhaven National Laboratory; Steven Chu, Lawrence Berkeley National Laboratory; John Grossenbacher, Idaho National Laboratory; Tom Hunter, Sandia National Laboratory; Thom Mason, Oak Ridge National Laboratory; George H. Miller, Lawrence Livermore National Laboratory; Robert Rosner Argonne National Laboratory; and Sam Bhattacharyyara, Savannah River National Laboratory; August 2008.
8. "Review of DOE's Nuclear Energy Research and Development Program," Committee on Review of DOE's Nuclear Energy Research and Development Program, Board on Energy and Environmental Systems, Division on Engineering and Physical Sciences, National Research Council of the National Academies, Washington, DC, 2008.
9. "Report to the President on Accelerating the Pace of Change in Energy Technologies Through an Integrated Federal Energy Policy", President's Council of Advisors on Science and Technology, Executive Office of the President, Washington, DC, November 2010.