Nuclear Energy University Programs Research Needs

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CONTENTS

FIGURES

TABLES

ACRONYMS

AFCI	Advanced Fuel Cycle Initiative
ASME	American Society of Mechanical Engineers
CFD	computational fluid dynamics
DOE	Department of Energy
DSA	deterministic safety analysis
HTE	high-temperature electrolysis
ILS	Integrated Laboratory Scale
HTGR	High-Temperature Gas-Cooled Reactor
I&C	Instrumentation and Control
IEEE	Institute of Electrical and Electronics Engineers
IHX	intermediate heat exchanger
LEU	low-enriched uranium (contains less than 20% of U-235)
LWR	Light-Water Reactor
LWRS	Light-Water Reactor Sustainability
MCNP	Monte Carlo N-Particle Transport Code
MOX	mixed (uranium and plutonium) oxide fuel **OR** mixed oxides (plutonium-natural uranium fuel)
NDE	nondestructive examination
NGNP	Next-Generation Nuclear Plant
NHI	Nuclear Hydrogen Initiative
PBR	pebble bed reactor
PIRT	Phenomena Identification and Ranking Table
PRA	probabilistic risk analysis
R&D	research and development
RISMC	Risk-Informed Safety Margin Characterization
TRISO	tri-isotropic, referring to multilayered fuel-particle coating consisting of pyrolytic carbon and silicon carbide
UCO	uranium oxycarbide
UNF	used nuclear fuel
VHTR	Very High Temperature Reactor

Nuclear Energy University Programs Research Needs

1. ADVANCED FUEL CYCLE INITIATIVE RESEARCH NEEDS

1.1 AFCI Program Objectives and System Architecture

The Advanced Fuel Cycle Initiative (AFCI) program develops the technologies required to make the nuclear fuel cycle sustainable in terms of resource utilization, waste management, and control of nuclear materials. A premise of the program is that in the foreseeable future the United States' nuclear infrastructure will consist of Light-Water Reactors (LWRs) operated in a once through mode (with the implementation of the AFCI technologies, they could be operated in a plutonium recycle mode). The resulting used nuclear fuel (UNF) contains a significant amount of isotopes that have value for producing energy (e.g., fissile and fertile isotopes), contribute to short- or long-term radiotoxicity (e.g., transuranic elements and certain fission products), produce short- or long-term heat load that needs to be managed (certain transuranic isotopes and certain fission products), and could be used if separated and diverted in the fabrication of nuclear weapons. The AFCI technologies are built around a systematic waste management approach that ultimately provides each of these isotopes a pathway to be either recycled and destroyed, decayed and destroyed, or provided a long-term stable waste form for ultimate disposal. This approach results in short- and long-term benefits: potential for more flexible waste management, better use of natural resources, potentially reduced long-term environmental impact, and better management of nuclear materials.

The key technical element of the AFCI approach is to create the opportunity for the transuranic elements of interest to be fissioned in a nuclear reactor, transforming them into mostly short-lived fission products. Earlier research on fission product transmutation, which had concentrated on I-129 and Tc-99, concluded that these transmutation schemes, while theoretically feasible, are not practical; thus these long lived fission products will be encased into stable long-term waste forms. Two types of reactors have been studied for use as transmuters: thermal reactors (such as LWRs) that are useful for transmuting fissile isotopes, in particular Pu-239, and fast reactors that can fission all transuranic elements.

A possible system architecture for the AFCI future deployment relies on an optimized combination of these two systems. Figure 1 illustrates that architecture where, as a first step, a comprehensive separation process is applied to the UNF and produces a series of manageable product streams. A majority of the products (fission products and actinide process losses) would be directed to a geological repository after being encased in adequate waste forms. The remaining material, including transuranics, plutonium and some uranium will be

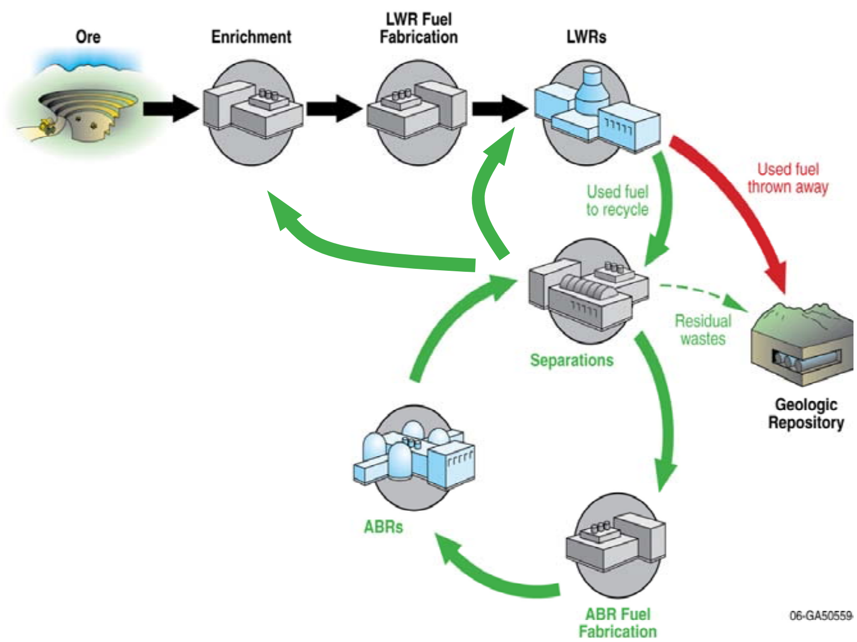


Figure 1. Illustration of a 2-tier closed fuel cycle.

recycled first in LWRs as mixed oxide (MOX) fuel. The resulting used MOX fuel is then separated, with the fission products sent to a repository. The transuranics, and possibly some uranium, may then be combined with the remainder of the transuranics from the LWR uranium oxide based (UOX) UNF, fabricated into advanced fuel forms, and sent to a fast reactor operated in a closed fuel cycle mode that destroys them by fission. This approach enables the destruction of most of the transuranic elements, except for a small fraction that is sent to the repository because of losses in the separations and fuel fabrication processes.

1.2 AFCI Development Needs

The technologies that form the basis of the AFCI approach have been demonstrated mostly at either laboratory or large scale, but key issues of scalability, economics, or performance still need to be demonstrated.

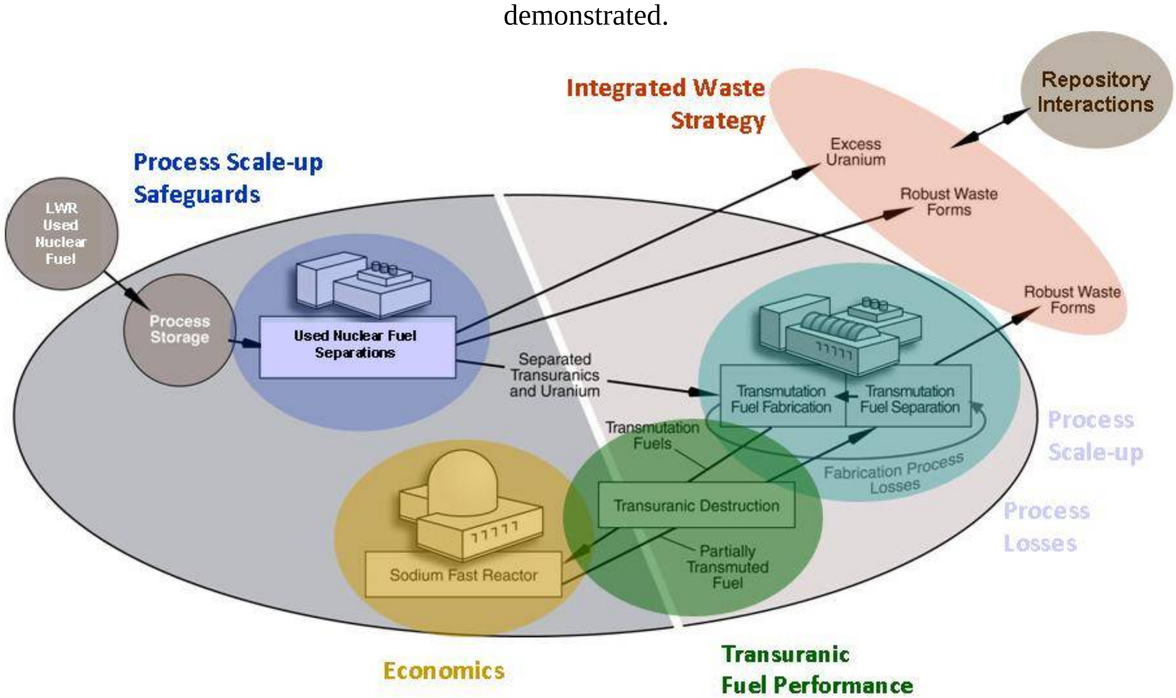


Figure 2 summarizes the key high-level challenges that need to be addressed:

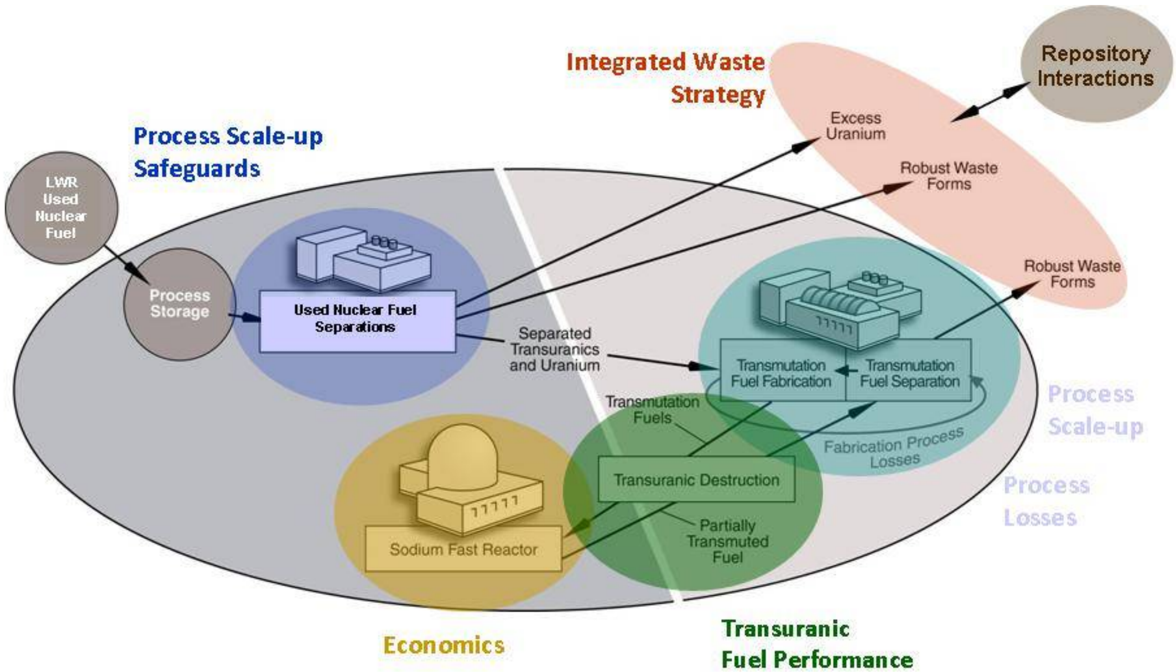


Figure 2. Key technical challenges.

- Front End Separations Process: This process ensures a fundamental waste management option, where the UNF is separated into manageable product streams (sent either to adequate waste forms for disposal, or to nuclear fuels for recycle). While several candidate processes have been demonstrated at the laboratory scale, issues remain for demonstrating their scalability to industrial sizes. Furthermore, the management and control of nuclear materials at this stage presents one of the greatest challenges to both domestic and international safeguards. Research and development to improve domestic safeguards technologies is needed.
- Transmutation Fuels: Plutonium and some uranium are first recycled into MOX fuel for LWRs; no research needs have been identified there. The resulting used MOX fuel is then separated using techniques similar to those used for UNF separations, and resulting transuranic elements (along with the remainder from the original UNF separations) are fabricated into transmutation fuel that is then irradiated in a fast reactor. Advanced fabrication techniques that are capable of remote and industrial scale operation with low losses and performance of the fuel during irradiation have been identified as key research needs.
- Fast Reactors: A significant number of fast reactors will be required to achieve complete transmutation of the transuranic elements. While sodium-cooled fast reactors have been built and operated, a perception of high capital costs and incomplete licensing requirements has inhibited commercialization. Thus, technology innovations for cost reduction and safety assurance are key research needs.
- Recycle of Transmutation Fuels: Because of the nature of these fuels (very high transuranic contents) the separation processes might be significantly different from those used for UNF, though they provide the same waste management options and present similar scalability and safeguard challenges.

1.3 Program Organization

In order to address the key challenges described above, the AFCI program is organized along five execution campaigns and two cross-cutting activities that are managed by a technical integrator:

- The separations and waste forms campaign develops and demonstrates industrially deployable and economically feasible technologies for the recycle of used nuclear fuel which provide improved safety, security, and optimized waste management. It also develops and demonstrates durable waste forms and processes to enable safe and cost-effective waste management as an integral part of a closed nuclear fuel cycle by establishing a fundamental understanding of behavior through closely coupled theory, experiment, and modeling.
- The transmutation fuels campaign develops and qualifies transmutation fuels for use in recycling reactors over the range of potential compositions, in order to enable closure of the fuel cycle while maintaining the commercial competitiveness of nuclear energy.
- The fast reactors campaign develops advanced recycling reactor technologies required for commercial deployment in a closed nuclear fuel cycle.
- The safeguards campaign develops advanced technologies and integrated techniques to ensure that future domestic facilities fully meet requirements under DOE and NRC regulations and assists with the International Atomic Energy Agency verification framework, thereby assuring the public that nuclear materials have not been diverted or misused.
- The systems analysis campaign conducts systems-wide analyses of nuclear energy developments and infrastructure deployment to enable a requirements-driven process for all technical activities and to inform strategic planning and key program decisions.
- The advanced modeling and simulation cross-cutting activity develops validated simulation tools that take advantage of the latest developments in high-performance computing and physical modeling.
- The safety and regulatory cross-cutting activity is guiding AFCI technology development efforts in order to support rigorous licensing requirements and allow the safe and successful operation of advanced fuel cycle facilities.

1.4 Specific R&D Needs and Priorities

Research needs suitable for university programs have been identified by each campaign and are described here and in more detail in Table 1. Advanced modeling and simulation research will be a major focus of AFCI university research, with funding up to 50% of the new funding available, and is described separately in Section 1.5 (Modeling and Simulation).

1.4.1 Separations and Waste Forms Research

Two key needs for university research have been identified for separations and waste forms:

- Development of new and innovative methods for the capture of tritium, iodine-129, krypton-85, and/or carbon-14 from spent fuel off-gas
- Development of alternative waste forms for fission products and gaseous products that provide enhanced performance.

1.4.2 Fast Reactors Research

Three key needs for university research have been identified for fast reactors:

- Development of improved nuclear theory models to enable the definition of higher precision nuclear data files
- Thermal aging and stability testing of AFCI candidate alloys
- Design, mechanical assessment, and testing of compact fuel handling equipment.

1.4.3 Systems Analyses Research

Three key needs for university research have been identified for systems analyses:

- Analysis of innovative heterogeneous recycle options in thermal reactors
- Analysis of innovative heterogeneous recycle options in fast reactors
- The economics of interim used fuel storage at reactors and/or away from reactors.

1.4.4 Transmutation Fuels Research

Three key needs for university research have been identified for transmutation fuels:

- Simplified fabrication processes adaptable for remote operations
- Fuel and target forms that can accommodate high actinide loading and achieve high burnup
- To support high burnup requirement, the cladding research will emphasize advanced alloys or composites that can sustain higher fluences.

1.4.5 Safeguards Research

Three key needs for university research have been identified for safeguards:

- Development of new sensor materials and techniques for nuclear material control and accountability (radiation and nonradiation based, including process monitoring)
- New methods for data validation and security, data integration and real time analysis
- Development of new active interrogation methods for accountancy measurements.

1.4.6 Safety and Regulatory Research

Three key needs for university research have been identified for safety and regulatory research:

- Assessment of regulatory databases and nuclear safety criteria
- Development of new data and phenomenological models and codes for safety analyses
- Development of new probabilistic risk analysis (PRA) methods and models for sodium fast reactors and recycling facilities.

Research project details for all AFCI areas are contained in Table 1.

1.5 Modeling and Simulation

1.5.1 Program Objectives, Development Needs, and Program Organization

The goals for multiyear research that will focus on advanced modeling and simulation for nuclear energy systems are described. This is especially important to the application of verified and validated numerical simulations to complex systems, particularly in cases where routine experimental tests are not feasible or too costly. These simulations require the integration of a diverse set of disciplines; each discipline in its own right is an important component of many applications. Success requires both software and algorithmic frameworks for integrating models and code from multiple disciplines into a single application and significant disciplinary strength and depth to make that integration effective.

The AFCI advanced modeling and simulation activities are intended to achieve the following:

1. Establish validated, large-scale, multidisciplinary, numerical simulation as a major academic and applied research program.
    a. Demonstrate its realization via both:
        (1) Simulation of large, complex problems
        (2) Discipline focused research in areas critical to nuclear energy
    b. Produce significant science/engineering results
    c. Establish new prediction, verification, validation and uncertainty quantification methodologies
    d. Improve the quantity & quality of tools, algorithms, and models
    e. Integrate science/engineering, computational mathematics, and computer science into a coordinated research effort.
2. Ensure the relevance of this program to the development of science-based approaches for the assessment of performance, reliability, and safety of existing and new nuclear energy systems.
    a. Experimentation and its interaction with simulation both for experimental design and for validation and verification and prediction
    b. Focus on discipline areas of critical interest to the nuclear energy
    c. Provide key research and development expertise in many of the disciplines critical to nuclear energy systems
    d. Discipline-specific modules, tools, and frameworks can contribute important technologies to the program.
3. Increase the visibility of the program in the academic community generally and across government and industry.

1.5.2 Specific R&D Needs and Priorities

Specific research needs suitable for university programs have been identified and are described in more detail in Table 1.

2. GENERATION IV RESEARCH NEEDS

2.1 Program Objectives, Development Needs, and Program Organization

The Very High Temperature Reactor/Next-Generation Nuclear Plant (VHTR/NGNP) Research Program is divided into four primary areas: VHTR/NGNP Methods, VHTR/NGNP Materials, VHTR/NGNP Heat Transport, and VHTR/NGNP Fuel Development and Qualification Program.

1. NGNP Methods

The goals of the Methods Program for VHTR are (a) to develop validation experiments and data to validate models and analytical tools for VHTR; (b) to resolve key safety, performance, and technical issues through confirmatory modeling and tool development when existing models and tools are judged to be inconclusive or inadequate; and (c) to modify, upgrade, or develop new analytical tools for future use that will reduce uncertainties and improve the capability of understanding the behavior, safety, and operating margins of a VHTR.

Current areas of focus in the NGNP Methods Program include:

- Developing improved differential cross-sections for plutonium and other transuranic isotopes to reduce uncertainties in the reactivity performance of high burnup low-enriched uranium High-Temperature Gas-Cooled Reactor (HTGR) cores
- Assessing and improving reactor physics and neutron kinetics methods for prismatic and pebble bed VHTRs
- Performing physics benchmark studies on past relevant experiments
- Evaluating important phenomena that influence thermal-fluid behavior in VHTRs and establishing relevant experiments for validation and verification
- Evaluating of air-ingress and water/moisture ingress phenomena in VHTRs and participating in relevant validation experiments
- Developing experiments to validate reactor cavity cooling system behavior
- Evaluating and establishing system level codes appropriate for VHTR safety analysis.

R&D is focused on those tools needed for: (a) operation of a VHTR with an outlet temperature of 750°C in the near-term and in the longer-term operation at 950°C, and (b) off-normal and anticipated accident conditions where the system temperature could rise to 1600°C and higher for sever accidents.

2. VHTR Materials

The NGNP Materials Program is focused on a Graphite Program and High Temperature Materials Program, each of which is described below.

The Graphite Program for NGNP develops the qualification dataset of thermomechanical and thermophysical properties for unirradiated and irradiated candidate grades of nuclear graphites. Where practical, other grades of graphite may be tested and characterized to provide a baseline for comparison or to help understand material property changes for the NGNP graphite grades.

The Graphite Program consists of statistical characterization of unirradiated graphite material properties to establish the lot-to-lot, billet-to-billet, and within billet variability of the material. Irradiations are planned at specified temperatures and doses within the design service condition envelope anticipated for VHTRs and in particular NGNP (600-1200°C and doses between 3 and 7 dpa). Extensive postirradiation examinations are planned to establish the change in relevant material properties as a function of temperature and neutron dose. Of particular interest is the irradiation induced creep of graphite, which is critical to determining the lifetime of the graphite under irradiation. From these datasets, constitutive relations will be established for use in a detailed predictive thermomechanical finite element model. These data will also support development of relevant American Society for Testing and Materials standards and American Society of Mechanical Engineers (ASME) design rules. In the long term, the program plans to evaluate processing route and raw material constituent influences on graphite behavior so that additional large qualification irradiation programs are not needed when new coke sources are used to make graphite for VHTRs. Carbon-carbon and SiC-SiC composites are also of interest in the longer term for VHTR applications for insulation, hangars, straps and potentially control rod guide tubes. Research and development (R&D) is focused on activities needed to support operation of a VHTR at 750°C outlet temperature in the near term and in the long-term operation at an outlet temperature 950°C.

The High Temperature Materials Program for NGNP establishes the relevant thermo-mechanical performance data to support the development of intermediate heat exchanger (IHX) and other high temperature components for an outlet temperature up to 950°C. Creep, creep-fatigue, aging, and environmental degradation testing is planned using the candidate high temperature material selected for NGNP. Thick and thin sections of base material, weldments and other joints (e.g., diffusion bonding) will be evaluated given the different design options under consideration for the IHX. (Current candidates are inconel 617 and Haynes 230.) Depending on the outlet temperature selected by the NGNP project, additional high temperature data may be needed to support relevant ASME code cases for the material. R&D that establishes requisite in-service inspection techniques will be developed at the same time as key components are being designed. Prototype testing of key components is envisioned in a high temperature flow loop to characterize overall behavior under prototypic flowing VHTR conditions and validate in-service inspection techniques.

3. Generation IV Heat Transport

The objective of the Generation (Gen) IV Energy Conversion program is to evaluate higher efficiency and lower cost electrical conversion technologies for advanced reactors. The focus is currently on the supercritical carbon dioxide (CO_2) cycle because of its long-term attractiveness for nuclear energy systems.

4. NGNP Fuel Development and Qualification Program

The overarching goal of the Advanced Gas Reactor Fuel Development and Qualification Program for a VHTR in general and NGNP in particular, is to qualify TRISO-coated particle fuel. TRISO-coated particles are currently being fabricated at pilot scale for use in the formal qualification testing. The testing program consists of irradiations, safety testing, and postirradiation examinations that will characterize the behavior of TRISO-coated fuel under both normal and off-normal conditions. The program also contains out-of-pile experiments, special irradiations, and safety and accident heatup testing to characterize the release and transport of fission products from the kernel, through the coatings, the fuel matrix, the graphite, and the primary system (i.e., source term). Formal validation testing is also planned to validate fuel performance and fission product models, required for core performance assessments and safety analysis.

The program is currently considering both UCO and UO_2. In the near term, the program is performing R&D to support moderate burnup (approximately 10 to 17%) for TRISO-coated particle fuel operating peak temperature of 1,250°C. In the longer-term AGR program activities related to higher burnup, higher temperature (>1,250°C) and alternative fuel types (e.g., ZrC, PuO_2, UO_2) to support transuranic missions with the VHTR are of interest.

2.2 Specific R&D Needs and Priorities

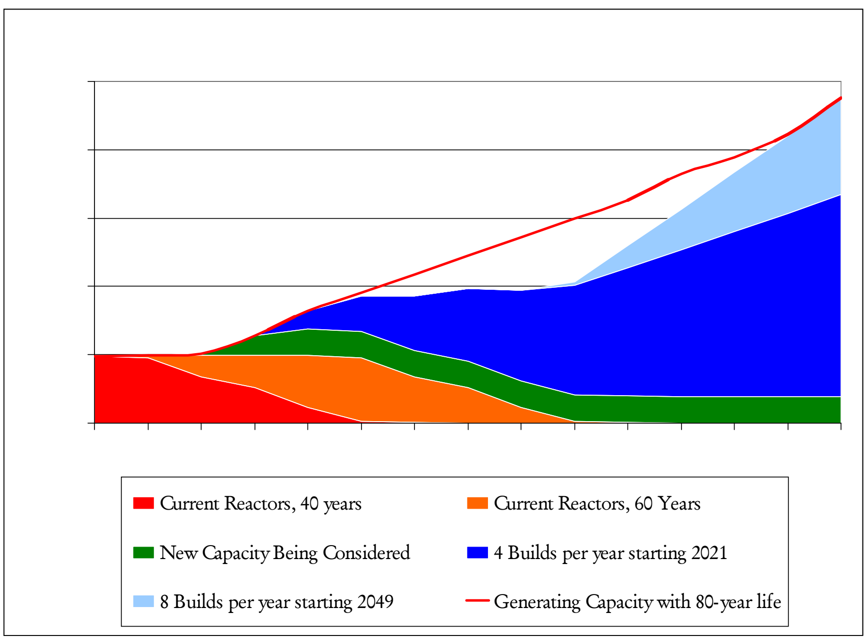
VHTR/NGNP research needs suitable for university programs have been identified and are described in more detail in Table 2.

3. LIGHT WATER REACTOR SUSTAINABILITY

3.1 Program Objectives, Development Needs, and Program Organization

The Light Water Reactor Sustainability (LWRS) Program is an R&D program sponsored by the Department of Energy (DOE), performed in close collaboration with industry and Nuclear Regulatory Commission (NRC) programs, to provide the technical engineering foundations for licensing and managing the long-term, safe and economical operation of current nuclear power plants. DOE’s program focus is directed towards longer-term and higher-risk/reward research that contributes to the national policy objectives of energy supply stability and environmental security.

There is growing consensus that large CO_2 reductions and energy security with stable supply and prices for electricity cannot be achieved without a major contribution from nuclear energy. Commercial nuclear power has reliably and economically contributed almost 20% of electrical generation in the U.S. over the past two decades. It remains the single largest contributor of non-CO_2-emitting electricity, ultimately providing more than 70% of the nonemitting energy generation capacity in the U.S. By 2030, domestic demand for electrical energy is expected to grow to levels at least 30% higher than today’s levels. At the same time, most currently operating nuclear power plants will begin reaching the end of their 60-year operating licenses. Figure 3 shows projected nuclear energy contribution to the domestic generating capacity. If currently operating plants do not operate beyond 60 years, the total fraction of generated electrical energy from nuclear power will begin to decline—even with the addition of new nuclear generating capacity.



The red line represents the total generating capacity of current and planned nuclear power plants, assuming extended operation to 80 years. The unshaded area below the line represents lost capacity if the current nuclear power plant fleet is decommissioned after 60 years.

Figure 3. Projected nuclear power generation.

The unique capabilities of nuclear power to meet national goals were recognized in the National Energy Policy which called for expansion in nuclear energy in the U.S. Subsequently, the National Energy Policy Act of 2005 authorized the Nuclear Energy Systems Support Program supporting R&D activities addressing reliability, availability, productivity, component aging, safety, and security of existing nuclear power plants. The LWRS Program implements this Congressional directive with initial focus on providing the technical basis for sustaining the current nuclear generating capacity for the long-term. Using the public-private partnerships created while developing the *Strategic Plan for Light Water Reactor Research and Development*, DOE uniquely possesses the tools and relationships to help integrate and coordinate critical research initiatives to help solve the nation's energy and environmental challenges.

The LWRS Program Vision is captured in the following statements:

> Existing nuclear power plants will continue to safely provide clean and economic electricity well beyond their first license extension period, significantly contributing to national energy security and protecting the environment.
>
> There is a comprehensive technical basis for licensing and managing the long-term safe, economical operation of nuclear power plants.

Three strategic program goals support the achievement of this vision:

1. Develop the fundamental scientific basis to understand, predict, and measure changes in materials, systems, structures, and components as they age in environments associated with continued long-term operation of existing LWRs
2. Apply this fundamental knowledge in collaborative public-private, and international partnerships, developing and demonstrating methods and technologies supporting safe and economical long-term operation of existing LWRs
3. Identify and verify the efficacy of new technology to address obsolescence while enhancing plant performance and safety.

Four principal R&D pathways addressing the Strategic Program Goals have been identified to better understand the challenges posed by nuclear power plant aging. These R&D pathways focus on improving the fundamental aging and degradation knowledge basis in reactor material sciences, creating improved inspection and monitoring technologies, fostering development of advanced fuels, and incorporating risk-informed, performance-based techniques in safety margin characterization and life extension decision-making. Following is a list of these R&D pathways as well as a description of each area's specific R&D objective:

1. <u>Nuclear Materials Aging and Degradation</u>. Research to develop the scientific basis for understanding and predicting long-term environmental degradation behavior of materials in nuclear power plants. Provide data and methods to assess performance of systems, structures, and components essential to safe and sustained nuclear power plant operation.
2. <u>Advanced LWR Nuclear Fuel Development</u>. Improve the scientific knowledge basis for understanding and predicting fundamental nuclear fuel and cladding performance in nuclear power plants. Apply this information to development of high-performance, high burn-up fuels with improved safety, cladding, integrity, and improved nuclear fuel cycle economics.
3. <u>Advanced Instrumentation, Control, and Information Systems Technologies</u>. Through use of scientific knowledge basis and advanced phenomenological modeling, establish advanced condition monitoring and prognostics technologies for use in understanding the aging of systems, structures, and components of nuclear power plants. Develop and demonstrate information system technology enhancements for knowledge migration and regulatory compliance.

4. Risk-Informed Safety Margin Characterization. Bring together risk-informed, performance-based methodologies with fundamental scientific understanding of critical phenomenological conditions and deterministic predictions of nuclear plant performance, leading to an integrated characterization of public safety margins in an optimization of nuclear safety, plant performance, and long-term asset management.

Each of these R&D pathways supports the needs of both industry and government in sustaining the existing nuclear power plant fleet as a viable option. The four R&D pathways overlap but the chosen pathways organize the LWRS Program on technical issues that will extend the life of the existing fleet of nuclear power plants beyond the first license extension period.

With the present 60-year licenses beginning to expire in 2029, utilities are likely to initiate planning base load replacement power by 2014 or earlier. If the option to extend current plant lifetimes is not available, the strategic planning and investment required to maintain the current LWR fleet may not happen in a sustainable manner. The research window to address fundamental aging questions must start now and is likely to extend through the following 11-year period, 2009 to 2020. The LWRS Program represents the beginning of the timely collaborative research needed to retain the existing U.S. nuclear power infrastructure.

3.2 Specific R&D Needs and Priorities

LWRS research needs suitable for university programs have been identified and are described in more detail in Table 3.

4. NUCLEAR HYDROGEN INITIATIVE RESEARCH NEEDS

4.1 Program Objectives, Development Needs, and Program Organization

The Nuclear Hydrogen Initiative (NHI) is developing electrochemical and thermochemical hydrogen production methods for use with the Very High Temperature Reactor (VHTR). The NHI focus is on high temperature electrolysis and the sulfur-based thermochemical cycles.

Following the completion of the High Temperature Electrolysis (HTE) Integrated Laboratory Scale (ILS) experiment, the primary HTE focus will be on a series of smaller experiments to determine the causes and remedies for the degradation of cell performance we have seen in long-duration tests.

In the area of thermochemical cycles, operations are being completed on an ILS for the sulfur-iodine cycle, while efforts in the hybrid sulfur cycle are focused on improving the long-term performance of the SO_2 electrolyzer component.

The Work Scope Identification Number for this program element is NHI-1.

4.2 Specific R&D Needs and Priorities

Two specific projects suggested within the NHI Program are:

1. Enhancing performance of high-temperature steam electrolysis cells.
   a. Investigation of mechanisms causing degraded cell performance during long-term operation
   b. Interfacial modeling, changes in morphology, transport of chromium, strontium and silicon at 800 to 900°C
   c. Corrosion of HTE materials in hot, high oxygen environments, protective coatings, valves and instrumentation.
2. Investigation of advanced catalysts and catalyst stability for sulfuric acid decomposition, a step common to both the sulfur-iodine and hybrid sulfur cycles.
   a. Mechanisms to increase platinum and platinum group metal catalyst stability
   b. Develop advanced catalyst options for H_2SO_4 decomposition (such as metal oxides).

Collaboration with ongoing NHI projects to identify materials and conditions of interest is possible. This collaboration could include university/student use of national laboratory facilities for testing.

4.3 Project Deliverables

Deliverables for these projects include technical reports, summarizing evaluation of mechanisms and results of analyses and experiments.

4.4 Estimated Project Cost

The estimated individual project cost for this element is $100K to $150K.

4.5 Estimated Project Duration

The estimated individual project duration is 1 to 2 years.

5. PLUTONIUM-238 DEVELOPMENT RESEARCH NEEDS

5.1 Program Objectives, Development Needs, and Program Organization

Pu-238 is an enabling isotope for National Aeronautics and Space Administration deep space missions. The United States DOE is seeking to re-establish the capability to produce Pu-238 using existing DOE reactors. This program optimizes irradiation of Np-237 to produce Pu-238 and to evaluate alternative pathways for Pu-238 production (e.g., irradiation of Am-241).

The Work Scope Identification Number for this program element is PUD-1.

5.2 Specific R&D Needs and Priorities

The work scope involves modeling reactor irradiation of Np-237 or other appropriate isotopes and evaluation of methods to optimize production. The DOE reactors to be evaluated are the Advanced Test Reactor at the Idaho National Laboratory and the High Flux Isotope Reactor at the Oak Ridge National Laboratory. The goal should be production of 5 kg/yr of Pu-238 while minimizing effects on other reactor users. This can be evaluated by use of sensitivity analyses. The research program should develop concepts for target design and for irradiation schedule. The conceptual target design should include an evaluation of the heat transfer characteristics of the targets since the reactor safety requirements will set maximum values for heat flux. The efficiency of production should be analyzed (e.g., the quantity of Pu-238 produced per unit of feed) as well as the amount of Pu-236 contaminant in the Pu-238.

5.3 Project Deliverables

A report detailing the type of nuclear materials modeled; the conceptual target design; Pu-238 production rate, results of MCNP/ORIGEN calculations detailing the effects on flux within the reactor, reaction products, and fission products; and the anticipated heat flux from the target.

5.4 Estimated Project Cost

The estimated project cost for this element is $100K to $150K.

5.5 Estimated Project Duration

The estimated project duration is 1 to 2 years.

6. INVESTIGATOR INITIATED RESEARCH

6.1 Program Objectives

Investigator initiated R&D is solicited in order to extend the understanding of nuclear energy related processes, materials, and systems. Approximately five percent of the total funding is targeted for investigator initiated research. This includes research that supports NE's mission even though the proposed research may not fully align with the initiatives and programs identified elsewhere in this solicitation. Examples of topics of interest are new reactor designs and technologies, advanced nuclear fuels, processes and materials, instrumentation and control/human factors, radiochemistry, nuclear waste management, and fundamental nuclear science.

The Work Scope Identification Number for this program element is IIR-1.

6.2 R&D Needs and Priorities

No specific work scope is designated under this category. Pre-applications will be accepted and evaluated in all areas related to the general areas of nuclear energy R&D.

6.3 Project Deliverables

At a minimum annual, and possibly quarterly, reports detailing the R&D conducted under this category will be expected from the principal investigator.

6.4 Estimated Project Cost

The estimated project costs for this element is $100K to $500K.

6.5 Estimated Project Duration

The estimated project duration for projects in this area is for up to 3 years.

Table 1. AFCI Program: Specific R&D Needs and Priorities.

Program of Interest	Work Scope Id. No.	R&D Project Work Scope	Research Expectations and Deliverables	Estimated Total Project Funding Range	Estimated Duration
AFCI Separations & Waste Forms	**AFW-X**				
	AFW-1	Develop new and innovative methods for the capture of iodine, krypton, and carbon-14 from spent nuclear fuel off-gas (during shearing and dissolution).	New adsorbents or separation technology for isolating and concentrating captured volatile off-gas species. Report describing technical results and efficacy of new technology.	\$200K - \$500K	2 - 3 years
	AFW-2	Develop alternative waste forms for fission products and gaseous products that provide enhanced performance. Develop science-based approach to develop waste forms and predict performance.	Alternative waste forms that could be used for immobilizing radionuclides. Technical reports describing tests and results of waste form development.	\$200K - \$500K	2 - 3 years
	AFW-3	Investigate Fundamental interfacial electrochemistry of actinides and fission product elements important in the fuel treatment process; for example, determination of thermodynamic properties in process relevant molten salts (e.g., LiCl, LiCl-KCl) or characterization of kinetics and mass transport properties of important species in process relevant molten salts	Fundamental data to support better data and understanding of electrochemical separation methods.	\$200K - \$500K	2 - 3 years
AFCI Reactors	**AFR-X**				
	AFR-1	Nuclear Theory and Modeling—Investments in nuclear experiments will only be fully realized when performed in conjunction with a more comprehensive theoretical treatment. This research topic will develop the capability to cultivate more than conventional cross-section data from modern high-precision measurements. Improved nuclear models will be developed and validated in collaboration with the AFCI Nuclear Data team. In addition, these models will be employed to construct and evaluate new data sets for key isotopes.	The University team will perform a systematic evaluation of how recent measurement techniques can be used for improved nuclear theory, resulting in a strategic plan at the end of the first year. The following years will focus on nuclear model development with periodic reporting on validation and cross-section evaluation studies.	\$200K - \$500K	2 - 3 years

Table 1. (continued).

Program of Interest	Work Scope Id. No.	R&D Project Work Scope	Research Expectations and Deliverables	Estimated Total Project Funding Range	Estimated Duration
	AFR-2	Aging and Stability Testing—The microstructural stability of advanced structural materials must be validated at elevated temperature and extended lifetimes. This requires specific testing of the candidate alloys being pursued in the AFCI Reactor Campaign under the anticipated fast reactor operating characteristics. Existing facilities should be able to perform this testing protocol.	The University team will perform thermal aging and stability tests. These tests will assess the AFCI candidate alloys and be closely coordinated with the advanced alloy development. Test results will be documented and provided to the program in a timely manner.	\$200K - \$500K	2 - 3 years
	AFR-3	Compact Fuel Handling—A key feature of modern sodium-cooled fast reactor SFR design is the application of a vastly improved fuel handling machine; in previous applications, fuel handling features had excessive space requirements and complicated reactor refueling operations. This compact fuel handling system is a key feature for cost reduction. The University work will first focus on a mechanical assessment of alternative fuel handling system designs to evaluate commodity, space, and reliability performance. Based on this assessment, a testing facility will be designed and constructed to test the key features of the fuel handling machine. Conduct of initial testing could be included in the proposal if appropriate facility requirements are available.	The University team will perform an assessment and develop mechanical engineering design for a compact fuel handling system for operation in a SFR environment. The demonstration and testing of key features will be pursued through design and operation of proper facilities.	\$200K - \$500K	2 - 3 years
AFCI Systems Analysis	**AFY-X**				
	AFY-1	Analysis of innovative heterogeneous recycle options in thermal reactors. This activity would include consideration of targets and heterogeneous fuels to recycle plutonium and minor actinides to achieve their destruction in a thermal spectrum system with limited recycle passes. Develop new concepts or core configurations and assess the transmutation performance. Assess system factors including material flow rates, and material handling parameters. Assess maturity of technologies needed to support approach.	Quarterly technical reports and a report that documents the following results with associated isotopic data in electronic form. Description of a range of fuel and target options focusing on one or more of the following: • Transmutation performance • Safety parameter assessment • Multicycle performance, if achievable	\$150K - \$300K	1 - 2 years

Table 1. (continued).

Program of Interest	Work Scope Id. No.	R&D Project Work Scope	Research Expectations and Deliverables	Estimated Total Project Funding Range	Estimated Duration
			• Characteristics of unirradiated and irradiated fuels/targets, including decay heat and estimation of shielding requirements and including isotopic information meeting VISION code requirements (~70 longer lived HM and FP isotopes) • Annual material flow rates per GWe-yr of reactor • Assessment of technical maturity of fuel/target concept, as well as technologies to achieve necessary separations, fabrication, and cladding.		
	AFY-2	Analysis of innovative heterogeneous recycle options in fast reactors. This activity would include consideration of targets, blankets, and heterogeneous fuels to recycle plutonium and minor actinides to achieve their destruction in a fast spectrum system with continuous recycle. Develop new concepts or core configurations and assess the transmutation performance. Assess system factors including material flow rates and material handling parameters. Assess maturity of technologies needed to support approach.	Quarterly technical reports and a report that documents the following results with associated isotopic data in electronic form. Description of a range of fuel and target options focusing on one or more of the following: • Core description • Transmutation performance and system sustainability • Safety parameter assessment • Single and multiple cycle performance for targets	$150K - $300K	1 - 2 years

Table 1. (continued).

Program of Interest	Work Scope Id. No.	R&D Project Work Scope	Research Expectations and Deliverables	Estimated Total Project Funding Range	Estimated Duration
			• Characteristics of unirradiated and irradiated fuels/targets/blankets, and including decay heat and estimation of shielding requirements and including isotopic information meeting VISION code requirements (~70 longer lived HM and FP isotopes) • Annual material flow rates per GWe-yr of reactor • Assessment of technical maturity of fuel/target concept, as well as technologies to achieve necessary separations, fabrication, and cladding.		
AFCI Regulatory & Safety	**AF-G**				
	AFG-1	In conjunction with the laboratories and industry, evaluate the existing regulatory databases (both domestic and international) and conduct gap analyses to identify areas requiring augmentation in data needs and model development. Support the development of consensus codes and standards (American Nuclear Society, ASME, Institute of Electrical and Electronics Engineers) associated with nuclear safety criteria for the design, construction, and licensing of sodium fast reactors.	Subject matter expert input and technical studies and analyses to support the sodium fast reactor Phenonmena Identification and Ranking Table (PIRT) process and codes and standards development activities.	$150K - $200K	2 - 3 years
	AFG-2	Conduct research to develop new phenomenological models, codes and data to address fast reactor safety and used fuel recycling safety and security. Work should address safety topics including neutronics, thermal-hydraulics, chemical interactions, material interactions, and fission product source term.	Development of new models, codes and data that would augment the existing safety technology base for evaluating and demonstrating safety for the licensing of sodium fast reactors used fuel recycling facilities.	$150K - $300K	2 - 3 years

Table 1. (continued).

Program of Interest	Work Scope Id. No.	R&D Project Work Scope	Research Expectations and Deliverables	Estimated Total Project Funding Range	Estimated Duration
	AFG-3	Develop advanced PRA methods and models for use in addressing fast reactor and used fuel recycling safety studies. This work should focus on the unique aspects of fast reactors, such as passive safety and sodium control, and on the safety significant aspects of recycling facilities.	Development of new PRA methods and models that would augment and enhance existing risk assessment technology specific to the safety of fast reactors and used fuel recycling facilities.	$150K - $300K	2 - 3 years
AFCI Modeling and Simulation	AFM-X				
	AFM-1 AFM-2	**Reactors** **Neutronics** **Deterministic methods**, fundamentally new solution algorithms will be required to achieve acceptable parallel performance at the petascale level for discussion of scalable algorithms. Furthermore, the need for predictability will require adaptation in all seven dimensions. Current adaptive methods generally relate only to spatial adaptivity. Extension of such capability to angle is required. Improved energy discretization techniques are critical to achieving predictability and estimating uncertainty. Tens of thousands of energy grid points are required to fully resolve the energy dependence of neutron interaction cross sections. Even at the petascale, a brute force resolution of this dependence is not practical. Current energy discretization methods are based on gross homogenization and are not compatible with a posteriori error estimation. Thus, novel subgrid models for treating the energy dependence must be developed. **Monte Carlo methods**, more sophisticated tally analysis is needed to ensure numerical stability and true convergence when coupling to fluids and heat transfer algorithms, CAD geometries, and deterministic codes on nonorthogonal grids. Another challenge is that there is currently no continuous energy adjoint capability for algorithm acceleration. The adjoint capability is also	The University team will develop and test computational models that address one or more of the issues described in the R&D Project Work Scope Section.	$200K - $500K	3 years

Table 1. (continued).

Program of Interest	Work Scope Id. No.	R&D Project Work Scope	Research Expectations and Deliverables	Estimated Total Project Funding Range	Estimated Duration
		needed for the calculation of sensitivities and uncertainties for reactivity parameters and for cross-section sensitivity analysis. Other challenges include the possibility of generating cross sections for deterministic calculations with Monte Carlo methods, “real-time” Monte Carlo analysis, and direct modeling of fission product transport and material damage. As for Monte Carlo needs, the first priority is the efficient accumulation of high precision fluxes (everywhere) throughout a reactor geometry on a nonorthogonal grid of cells to support multi-physics coupling, to more accurately calculate parameters such as reactivity coefficients, and perhaps to generate multi-group cross sections. New methods are needed to accelerate global convergence, to estimate the propagation of cross-section and statistical uncertainties throughout the reactor depletion process, and to enhance burn-up depletion capabilities. For reactor core modeling and simulation, deterministic methods will be used principally in the short term (3 to 5 years) with Monte Carlo as a benchmarking tool. In the intermediate term (5–10 years) Monte Carlo methods could be used as a hybrid tool with multiphysics coupling to deterministic neutronics and thermal hydraulics codes. In the long term (>10 years), multiphysics codes using nonorthogonal grids will provide complete, high accuracy design tools, fully integrated into reactor core design and operation.			
	AFM-3	**Fluids and Heat Transfer** The focus should be on multiscale and multiphysics coupling and on complex geometries. For the physical modeling of multiphase, multifluid flows, the main development is needed in multifield models, interfacial area transport, and transition between flow regimes. For numerical methods, the main development is needed in unstructured grids with adaptive mesh refinement, porous media modeling with provision for nonisometric permeability, all for a range of boundary conditions.			

Table 1. (continued).

Program of Interest	Work Scope Id. No.	R&D Project Work Scope	Research Expectations and Deliverables	Estimated Total Project Funding Range	Estimated Duration
	  AFM-4	Moreover, development is needed in uncertainties (input data plus propagation) and validation and verification. **Multiphysics Coupling** Two areas for multiphysics coupling algorithms research clearly are critical: (a) development of second order in time coupling methods and (b) development of coupling approaches that support sensitivity analysis, data assimilation, and partial differential equation constrained optimization. Possible starting points include Strang splitting, predictor-corrector methods, implicit-explicit methods, and Jacobian-free Newton-Krylov methods. There also exists a need to develop software architecture for efficiently treating the coupled problems. An example is the ability to define and plug in new and different combinations of physics module implementations to study different phenomena, define and combine different numerical techniques, configure the code easily to run on new platforms, and develop new physics components without expert knowledge of the entire system.			
	AFM-5	**Sensitivity Analysis** Sensitivity and uncertainty analysis methods need to be considered an integral part in the development of multiphysics methods. Sensitivity and uncertainty adjoint-based methods are required, as well as algorithms that are noninvasive (e.g., forward perturbation, random sampling, subspace). Of particular importance are innovative methods that address nonlinearity, can predict responses' probability distributions, treat discrete events, and handle simultaneously large input data and response fields in a computationally efficient manner.			
	AFM-6	**Materials and Fuels** **Radiation-induced microstructural evolution.** The nature of radiation-induced microstructural evolution and the associated property changes require a multiscale approach to their understanding and mitigation. Primary damage formation occurs on a time scale of	The University team will develop and test computational models that address one or more of the issues described in the R&D Project Work Scope Section.	$200K - $500K	3 years

Table 1. (continued).

Program of Interest	Work Scope Id. No.	R&D Project Work Scope	Research Expectations and Deliverables	Estimated Total Project Funding Range	Estimated Duration
		femtoseconds to picoseconds in a volume of a few cubic nanometers. This involves very high local energy transfer events (both electronic and elastic), creating both point defect and fission product formation. These defects and newly created impurities diffuse and aggregate over much longer time scales (ks to Gs) and length scales (mm to mm), leading to phenomena such as fuel restructuring, fuel cracking, fission gas release, fuel cladding mechanical interactions, and fuel and cladding creep and swelling. Over this same time solid fission product formation drives a complex evolution of fuel chemistry. Currently, there exist models or methods that can be applied at each of the relevant scales, although the quality or fidelity of these models varies. Fundamental material and defect properties for most materials (with the exception of actinides, as described below) can be provided by electronic structure methods, which support atomistic simulations employing molecular dynamics or Monte Carlo methods. The mesoscale microstructural evolution can be simulated by using models based on reaction rate theory, phase field, Monte Carlo, and discrete dislocation dynamics. At the largest scale, continuum elasticity and finite element models can be used. The primary deficiencies in this multiscale modeling scheme are well-defined methods for directly linking the models that operate at different scales and a strategy for determining when tight linking is appropriate (as opposed to simple information passing).			
	AFM-7	**Electronic structure methods for actinides.** A major scientific challenge is the need to develop robust electronic structure methods for actinides in which the behavior of 5f-electrons is strongly correlated and requires the consideration of relativistic effects. The now standard density functional theory employing the local density approximation or generalized gradient approximation, which has been successfully applied to many other materials, fails to describe the behavior of the			

Table 1. (continued).

Program of Interest	Work Scope Id. No.	R&D Project Work Scope	Research Expectations and Deliverables	Estimated Total Project Funding Range	Estimated Duration
		actinides. A new underlying theory is needed in order to compute fundamental properties such as defect formation and migration energies in both the pure metals and compounds (oxides, nitrides, carbides) involving these metals.			
	AFM-8	**Thermodynamic quantities in UO_2, PuO_2, and MOX fuels.** A fundamental understanding of thermodynamic quantities in UO_2, PuO_2, and MOX fuels is needed. This problem is strongly related to the electronic structure issue described above. The presence of the actinides makes the chemistry of nuclear reactor fuel initially complex, and continuous loss of uranium and plutonium and formation of a broad range of new species due to fission introduce a challenging time-dependence to this chemistry. The fuel ultimately contains multiple f-electron elements: uranium, plutonium, americium, neptunium, and curium as well as many lighter elements. This situation leads to the potential formation of many phases that can influence critical physical properties such as thermal conductivity. The integration of new ab initio results with available thermodynamic databases is necessary to enable the prediction of phase equilibria and oxidation states in fuel that contains fission products that may have been generated in situ or mixed into fresh fuel. An additional complicating factor is the influence of irradiation on phase equilibria due to the presence of persistent defect/solute fluxes and radiation enhanced diffusion. Scientists need to better understand the behavior of the fuel in service, in order to support the fabrication of new fuel forms that incorporate long-lived actinide waste and to predict the behavior of the waste forms ultimately sent to a repository for long-term storage.			

Table 1. (continued).

Program of Interest	Work Scope Id. No.	R&D Project Work Scope	Research Expectations and Deliverables	Estimated Total Project Funding Range	Estimated Duration
	AFM-9	**Mesoscale modeling**. Model development is required at the mesoscale for simulation of microstructural evolution of fuel and the effects on thermomechanical response of fuel. The challenges are both computational and conceptual. Defect generation information obtained from atomistic simulations indicates the need for simulating the interaction of irradiation-induced point defects with the microstructure (grain boundaries, dislocations, second-phase precipitates, gas bubbles, and voids) and its evolution. Such simulations must incorporate all relevant grain boundary and dislocation processes, gross deformation processes, such as crack nucleation and propagation, and transport phenomena to account for fission product migration and precipitation. The primary tools currently employed are (1): reaction rate theory, Monte Carlo, and phase field models, along with discrete dislocation dynamics. Approaches for combining methods, such as front tracking and phase field models into an integrated mesoscale model, may offer the opportunity to advance the state of the art.			
	AFM-10	**Modeling of fuel cladding and core structure**. The modeling and simulation needs for fuel cladding and core structural materials are generally similar to those of the fuel, without the complication of dealing with the actinides and fission products. Current ab initio theory is generally adequate, with the primary need being the ability to scale up from pure metals to complex, multicomponent alloys and to properly account for magnetism in ferritic alloys. The primary phenomena of interest are radiation induced hardening and embrittlement, thermal and irradiation creep, and void swelling. Mechanical contact between the fuel and cladding increases heat transport from the fuel but can also lead to cladding failure; chemical interactions with fission products can lead to thinning of the cladding by			

Table 1. (continued).

Program of Interest	Work Scope Id. No.	R&D Project Work Scope	Research Expectations and Deliverables	Estimated Total Project Funding Range	Estimated Duration
		corrosion. Greater understanding of the thermodynamic behavior and complex chemistry at the fuel-clad interface is, therefore, important.			
	AFM-11	**Separation Chemistry** **Plant-scale simulation.** There is a substantial need to improve individual and unit operations, such as distillation column, centrifugal contactors with entrainment and mixing, evaporators (including flow modeling and nucleation phenomena), recycle units for acid recovery (nitric plus nontraditional such as organics), water, organic solvents, and separations agents, unconventional acids, and off-gas recovery, both radioactive and nonradioactive. Similarly, there is a substantial need to develop models that involve full linking and integration of unit operations in a dynamic mode. Models also are needed that include all the mass transfer in the plant—particularly for scheduling of operations and for accounting for differences in the input fuel streams. Critical issues include the need to provide uncertainty information across the entire model of the plant to reduce the cost in construction due to lack of knowledge of the uncertainty; the ability to capture, manage, and mine the broad array of fuel stream input and sensor data, in order to achieve order-of-magnitude advances in monitoring transuranic for safety and nonproliferation issues; and the need to develop effective and computationally efficient optimization strategies beyond linear programming for complex systems varying in time, with a broad range of constraints. Moreover, the optimization and data management and archival strategies must be coupled, so that in the optimization effort one can investigate which changes can affect the optimal running of a process and can track the history of the design of the process. In addition, such information can be used to develop effective operator training and accident scenarios. The codes that can be used to predict	The University team will develop and test computational models that address one or more of the issues described in the R&D Project Work Scope Section.	$200K - $500K	3 years

Table 1. (continued).

Program of Interest	Work Scope Id. No.	R&D Project Work Scope	Research Expectations and Deliverables	Estimated Total Project Funding Range	Estimated Duration
		accidents or criticality are complex, and both probabilistic and deterministic elements are needed to predict accidents and determine how to deal with them.			
	AFM-12	**CFD.** There is a critical need to include CFD in the simulation portfolio for process optimization. Questions that need to be addressed include the following: How do we treat these types of flows from the atomic level up to the continuum and vice versa? Is it appropriate to use a mix of stochastic and deterministic mathematical approaches to treat the CFD in separation systems?			
	AFM-13	**Predictive methods.** Thermodynamic modeling tools are needed that accurately predict partition or distribution coefficients for vapor-liquid, liquid-liquid, and solid-liquid equilibria. Such prediction requires, for example, the ability to predict phase diagrams for a variety of solvents and solutes over wide concentration ranges including third phase formation. The prediction of reliable kinetics for separation processes must also include the dimension of time in order to predict the rate of change of a given species. Significant theoretical issues also must be addressed, and new theories incorporated in efficient algorithms. In addition, design tools must be developed to predict particle morphology based on chemical composition for optimal fuel structure and composition. All these predictions will need to include quantifiable error limits.			
	AFM-14	**Rational design of separation systems.** Accurate and computationally efficient methods are needed for relativistic quantum chemistry in order to make reliable predictions of the thermodynamic and kinetic properties of molecules and solutions containing actinides including dealing with the f-electron problem (multiplets, spinorbit, other relativistic effects), the lack of accurate density functional approaches for heavy			

Table 1. (continued).

Program of Interest	Work Scope Id. No.	R&D Project Work Scope	Research Expectations and Deliverables	Estimated Total Project Funding Range	Estimated Duration
		elements based on a firm theoretical foundation, and the lack of reliable experimental data for benchmarking and model building. In addition, advances are needed in the development of force fields to enable classical molecular dynamics simulations of solutions and new methods to enable molecular dynamics to reach long times (improved phase space sampling). New techniques also are needed for predicting the effects of radiolysis, which introduces trace species with cascading chemical effects leading to damage to surfaces and materials. Currently, it is difficult to predict reaction rates of radicals in solution, especially for fast reactions, much less the reactions of highly excited states formed from the interaction of radiation and molecules. Finally, new techniques for optimization and sampling large realms of parameter space need to be developed if we are to create new solvent systems (e.g., ionic liquids) that could help to minimize environmental concerns.			
	AFM-15	**Time and length scales.** New methods need to be developed to deal with uncertainty beyond current Monte Carlo approaches, which are computationally very time consuming and cannot adequately sample large domains of phase space. Uncertainty in the input data, the parameters, and the solvers is also of concern; especially needed are clearly defined goals of what the uncertainty is.			
	AFM-16	**Data management and visualization.** A critical need is the ability to extract key features from the data for different data users. Feature extraction must provide quantified measures of key characteristics and the ability to view the data from different technical perspectives. In addition, visualization must enable people to view data from different perspectives, including those from scientists and engineers, plant management, plant technicians and operators, regulators, and the public.			

Table 1. (continued).

Program of Interest	Work Scope Id. No.	R&D Project Work Scope	Research Expectations and Deliverables	Estimated Total Project Funding Range	Estimated Duration
	AFM-17	**Repository Modeling** **Waste form and material degradation.** Whereas current models for waste form degradation are based on conservative empirical correlations of well known waste forms, advanced modeling and simulation capabilities are required to predict thermodynamic, chemical, and radiation stability of advanced materials such as tailored ceramics, composite materials, and super-alloys. This advanced modeling, combined with focused experiments, will allow for development of optimal waste forms and disposal canisters and minimization of environmental impacts. The improvement of individual process models will be facilitated by tools for high performance computing capabilities, including dynamic domain decomposition, efficient parallel solution algorithms, and load balancing.	The University team will develop and test computational models that address one or more of the issues described in the R&D Project Work Scope Section.	\$200K - \$500K	3 years
	AFM-18	**High fidelity assessment of the chemical environment.** Modeling the local chemical environment that determines waste form behavior requires a tightly coupled multiscale simulation of the heat and mass transfer and chemical reactions in the waste package, emplacement drift (tunnel), and nearby host rock. High fidelity modeling is necessary to incorporate the effects of local variations in the environment due to heterogeneities in the thermal and chemical system and localized failure mechanisms of the engineered systems. Such modeling includes turbulent multiphase, multicomponent natural convection fluid dynamics with radiative, convective, and conductive heat transfer within the drift coupled to two-phase chemically reactive flow and heat transfer in the porous media of the host rock. These processes control the local environment that drives the degradation of all engineered components. This chemical environment also determines the mobility of radionuclides released from the waste form. Tight coupling of high fidelity solutions to disparate physical models requires the transfer of those solutions among			

Table 1. (continued).

Program of Interest	Work Scope Id. No.	R&D Project Work Scope	Research Expectations and Deliverables	Estimated Total Project Funding Range	Estimated Duration
		dissimilar meshes and multiple spatial and temporal scales. Advanced tools will help manage this process in a high performance computing paradigm.			
AFCI Fuels	**AFF-X**				
	AFF-1	Advanced Cladding: The fuels program is primarily focused on the development of ferritic-martensitic alloys for cladding and assembly materials. This activity includes efforts to qualify the primary core material for an advanced recycling reactor, HT-9 stainless steel, as well as the research and development of advanced alloys and composite clad structures. This includes cladding coatings and liners to mitigate fuel-cladding chemical interaction and investigation of advanced alloys such as steels strengthened by a dispersion of oxide particles. These activities are coordinated and integrated with materials development efforts in the Fast Reactor Campaign.	The university will be expected to provide monthly updates on the progress of their work, produce an end–of-year report on the accomplishments for the yearly effort, and participate in Fuels Campaign meetings as requested by the campaign director.	\$200K - \$500K	2 - 3 years
	AFF-2	Fuels Fabrication: Currently, the fuels program is focused on and principally interested in the development of oxide and metal alloy fuel systems. This includes the improvement of fundamental understanding of fuel behavior through characterization of microstructure, chemistry, and thermophysical properties of unirradiated fuel specimens, and the integration of these studies with theory and simulation. Of primary interest is the development of industrially viable, remote fabrication processes for oxide and metal alloy fuels, which have minimal losses of fuel material and generate a minimal amount of secondary waste.	The university will be expected to provide monthly updates on the progress of their work, produce an end-of-year report on the accomplishments for the yearly effort, and participate in Fuels Campaign meetings as requested by the campaign director.	\$200K - \$500K	2 - 3 years
	AFF-3	Modeling and Simulation: The principal activity in the Fuels modeling and simulation effort includes the development of a suite of lower length scale modeling and simulation capabilities to support fuels and materials development and qualification, including (1) thermomechanical code development; (2) fission gas retention and release modeling; (3) chemistry, species	The university will be expected to provide monthly updates on the progress of their work, produce an end-of-year report on the accomplishments for the yearly effort, and participate in Fuels Campaign meetings as	\$200K - \$500K	2 - 3 years

Table 1. (continued).

Program of Interest	Work Scope Id. No.	R&D Project Work Scope	Research Expectations and Deliverables	Estimated Total Project Funding Range	Estimated Duration
		distribution, and fuel restructuring models; (4) cladding performance models; and (5) verification and validation methodology and database development. These capabilities are necessary for fuels and materials qualification and will be valuable in the development of advanced fuels and alloys.	requested by the campaign director.		
AFCI Safeguards	**AFS-X**				
Safeguards	AFS-1	New sensors and techniques for nuclear materials control and accountability (including process monitoring)– increasing sensitivity, resolution, radiation hardness, cost to manufacture • Sensors based on radiation detection • Other (optical, thermal, etc.).	Development, design, and testing of new sensor materials and techniques. Universities will also be expected to provide monthly reports, participate in safeguards campaign working group meetings and activities, and provide an annual report.	\$200K - \$500K	2-3 Years
	AFS-2	New active interrogation methods, including basic nuclear data • Neutron and photo fission • Nuclear Resonance Fluorescence • Nonradiation based (stimulated Raman, laser-induced breakdown spectroscopy, fluorescence, etc.).	Development, design, and testing of new active interrogation methods; measurement of basic nuclear data (and other data as appropriate). Universities will also be expected to provide monthly reports, participate in safeguards campaign working group meetings and activities, and provide an annual report.	\$200K - \$500K	2-3 years

Table 1. (continued).

Program of Interest	Work Scope Id. No.	R&D Project Work Scope	Research Expectations and Deliverables	Estimated Total Project Funding Range	Estimated Duration
	AFS-3	New methods of data validation, authentication and security, data integration, and real time analysis • Information validation and security • Quantitative integration of disparate data • Real time analysis, review, and notification.	Development of new methods for data validation and security, data integration, and real time analysis with defense-in-depth and knowledge development of facility state in mind. Universities will also be expected to provide monthly reports, participate in safeguards campaign working group meetings and activities, and provide an annual report.	$200K - $500K	2-3 years

Table 2. VHTR Program: Specific R&D Needs and Priorities.

Program of Interest:	Work Scope Id. No.	R&D Project Work Scope:	Research Expectations and Deliverables:	Estimated Total Project Funding Range:	Estimated Duration:
Gen IV Methods (NGNP)	**G4M-X**				
	G4M-1	• Experimental and theoretical modeling of bypass flows in both prismatic and pebble bed reactors (PBR). • Methodologies, supported by appropriate closure models and applicable relationships, to enable coarse-grain computational fluid dynamics meshing in conjunction with fine-grain meshing of systems rather than just components. • Development of techniques to enable the use of laser and other optical diagnostics to produce validation data for CFD software at high temperatures and pressures. • Development of techniques to obtain high fidelity data for CFD validation for multiple species gas systems—in particular for countercurrent helium-air systems. • Acquisition and processing issues of scattering data for graphite-moderated reactors with potentially high burnup, low-to-moderately enriched fuels (effects for moderators and heavy nuclides). • Improve correlations, data, physics, methods, and codes for thermal-hydraulics feedback incorporation into reactor kinetics models of VHTRs (e.g., ultra-fast high fidelity T-h module for pebble bed and prismatic block cores). • Experimental and theoretical evaluation and modeling of friction coefficients for VHTR-grade graphite (pebbles on pebbles, pebbles on planar structures) and of graphite on structural materials.	Research results should be documented in a report or journal articles. Exact details are dependent on the nature of the work proposed. Universities are expected to integrate and collaborate with related laboratory or industry efforts. Quarterly progress reports are also requested.	$300K - $500K	2-3 years

Table 2. (continued).

Program of Interest:	Work Scope Id. No.	R&D Project Work Scope:	Research Expectations and Deliverables:	Estimated Total Project Funding Range:	Estimated Duration:
		• Experimental and theoretical evaluation and modeling of abrasion/wear coefficients for VHTR-grade graphite (pebbles on pebbles, pebbles on planar structures) and of graphite on structural materials in helium atmosphere within applicable range of pressure and temperature. • Develop and benchmark suitable VHTR/NGNP prismatic-block-design 3-D neutronic kinetic and steady-state methods with full core depletion and thermal feedback capability that can be coupled with thermal-hydraulic systems codes for analyzing accident and transients (e.g., reactivity initiated accidents, thermal-hydraulics induced events). • Identification and development of realistic static, depletion, kinetics, and dynamics benchmarks for VHTR/NGNP reactors (prismatic and PBR). • Advanced instrumentation to measure temperature and flux in VHTR core regions recognizing the constraints of these high temperature systems (moving fuel, harsh environment). • Custom neutronic modeling capabilities for salt-cooled pebble beds (e.g., AHTR). • Develop and benchmark models for handling air, moisture, and water intrusion (ingress) into the reactor vessel during accident conditions for both prismatic and pebble bed designs. Determine timing and extent of air, moisture, and water ingress during accident and severe accident conditions. Develop thermo-chemical models for the consumption of graphitic materials, corrosion and/or chemical reactions of air (oxygen) and water/moisture based on existing experimental results and/or propose new tests to evaluate air/moisture/water ingress phenomena.			

Table 2. (continued).

Program of Interest:	Work Scope Id. No.	R&D Project Work Scope:	Research Expectations and Deliverables:	Estimated Total Project Funding Range:	Estimated Duration:
Gen IV Materials (NGNP)	**G4A-X**				

	G4A-1	Graphite recycle issues
		• Methods to remove activated carbon-14 in carbon microstructure to enable recycling ceramic composite components
		• Development of thermal analysis testing techniques in light of anisotropic microstructure of composites especially after environmental degradation
		• Establishment of small sample testing techniques that address issues common to all material irradiation programs exacerbated by the large grain-structure presented in composite microstructures
		• An understanding of underlying creep mechanisms for graphite material is required to understand experimental data micromechanical-modeling results and predict whole core behavior. Specific areas include:
		  - Pinning/unpinning mechanism for irradiation creep considered the primary mechanism for irradiation creep in graphite
		  - Pore and crack interactions during irradiation believed to be associated with the onset of turnaround and beginning of tertiary creep regime
		• Understanding of thermal creep and irradiation creep mechanisms and ranges in which they are anticipated to occur
		• Assess potential for environmental embrittlement of alloys (e.g., by grain boundary oxidation or creep crack growth) in temperature range from 500 to 850°C
			Research results should be documented in a report or journal articles. Exact details are dependent on the nature of the work proposed.
			Universities are expected to integrate and collaborate with related laboratory or industry efforts. Quarterly progress reports are also requested.
				\$300K - \$500K	2-3 years

Table 2. (continued).

Program of Interest:	Work Scope Id. No.	R&D Project Work Scope:	Research Expectations and Deliverables:	Estimated Total Project Funding Range:	Estimated Duration:
		• Determination of hydrogen transport in candidate alloys and assessment of mitigation strategies, e.g., alumina formers or coatings • Characterization of creep and creep rupture properties of Grade 91 in suboptimal heat treatment that might be anticipated due to heavy sections and heavy section welds • Mechanistic understanding of stress and temperature conditions bounding negligible creep regime for Grade 91 steel in optimal and suboptimal heavy section and welded heat treatments.	Research results should be documented in a report or journal articles. Exact details are dependent on the nature of the work proposed. Universities are expected to integrate and collaborate with related laboratory or industry efforts. Quarterly progress reports are also requested.	\$300K - \$500K	2-3 years
Gen IV Heat Transport (NGNP)	**G4H-X**				
	G4H-1	• Corrosion chemistry and materials transport and determine performance limits in CO_2 • Determine limiting mechanisms and support selection of materials for 500 – 750°C (Stainless Steel, PH17-4, Inconel) • Turbomachinery performance and loss mechanisms in supercritical CO_2 • Develop models and/or test beds to predict seal performance (labyrinth, dry liftoff seal, brush, etc.) • Develop models for TM bearings (gas foil, magnetic, and hydrodynamic) and S- CO_2 windage loss.	Research results should be documented in a report or journal articles. Exact details are dependent on the nature of the work proposed. Universities are expected to integrate and collaborate with related laboratory or industry efforts. Quarterly progress reports are also requested.	\$300K - \$500K	2-3 years

Table 2. (continued).

Program of Interest:	Work Scope Id. No.	R&D Project Work Scope:	Research Expectations and Deliverables:	Estimated Total Project Funding Range:	Estimated Duration:
Gen IV Fuels (NGNP)	**G4F-X**				
	G4F-1	• Cesium interaction in SiC, ZrC focusing on understanding of the kinetics of the reaction over relevant temperatures (800-1800°C) and prototype partial pressures in a coated particle • CO interaction with SiC at very low particle pressure (1E-04 – 1E-01 atm) focused on understanding of kinetics of the reaction • Fission product sorptivity in graphite • Development of real time or near-real-time methods for measurement of adsorbed metallic species (e.g., cesium, strontium, europium, tellurium, iodine) on alloy or oxide surfaces, wherein the adsorbed species will be present at substantially less than monolayer quantities and are likely to have diffused partially into the intergranular boundaries at the substrate surfaces • Development of methods for the measurement and control of the elemental vapor of cesium, strontium, europium, tellurium, iodine at pressures much less than 1E-10 atm • Higher power, higher burnup particle fuel performance models for Advanced High-Temperature Reactor application • Assessment of ultra-high burnup, once through plutonium seeded fuel cycles for VHTR.	Research results should be documented in a report or journal articles. Exact details are dependent on the nature of the work proposed. Universities are expected to integrate and collaborate with related laboratory or industry efforts. Quarterly progress reports are also requested.	$300K - $500K	2-3 years

Table 3. LWR Sustainability Program: Specific R&D Needs and Priorities.

Program of Interest:	Work Scope Id. No	R&D Project Work Scope:	Research Expectations and Deliverables:	Estimated Total Project Funding Range:	Estimated Duration:
LWR Sustainability	**LWS-X**				
Nuclear Materials Aging and Degradation Pathway	LWS-1	**EVALUATION OF FLUX EFFECTS AND HIGH FLUENCE DEGRADATION OF REACTOR PRESSURE VESSEL STEELS.** Research is needed to evaluate high fluence effects (embrittlement and/or late blooming phases) as essential to ensuring reactor pressure vessel integrity for long term operation beyond 60 years. Evaluation of high fluence specimens from past industrial capsules or campaigns, and single variable experiments, may be required to evaluate the potential for embrittlement and to provide a better mechanistic understanding of this form of degradation. Testing may include impact and fracture toughness evaluations, hardness, and microstructural analysis. Modeling of microstructural changes and mechanical performance is also an important need. New methods to generate meaningful data from previously tested specimens are needed. Alternative methods for surveillance testing should also be evaluated.	Universities engaging in this effort will be expected to produce data, mechanistic modeling, or new testing methods to help reduce the uncertainty associated with the long-term aging of reactor pressure vessel steels. Universities are expected to integrate and collaborate with related national laboratory or industry efforts. Quarterly progress reports are also requested.	\$100K - \$500K	2 - 3 years
Nuclear Materials Aging and Degradation Pathway	LWS-2	**ANALYSIS OF CONCRETE PERFORMANCE IN LWR EXTENDED LIFETIME APPLICATIONS.** Research is needed assessing long term stability and performance of concrete structures exposed to unique nuclear power plant environments. Concrete performance under a nuclear aging environment is relatively unknown because there is little organized operational data or predictive modeling. The collection and analysis of samples from older or decommissioned plants or other nuclear facilities may be expected to provide valuable information on the long-term aging and degradation of	Universities engaging in this effort will be expected to produce data or mechanistic modeling to help reduce uncertainties associated with the long-term aging and degradation of concrete as associated with the nuclear environment.	\$100K - \$200K	1 - 2 years

Table 3. (continued).

Program of Interest:	Work Scope Id. No	R&D Project Work Scope:	Research Expectations and Deliverables:	Estimated Total Project Funding Range:	Estimated Duration:
		nuclear power plant concrete. The interface between concrete structures and metal components is also of high technical interest. This work will support the LWRS Program strategic goals by providing key data and an improved mechanistic understanding on concrete degradation phenomena. A more complete mechanistic understanding of this degradation mode will be critical to reducing uncertainty and providing reliable long-term predictions for this irreplaceable reactor component.	Universities are expected to integrate and collaborate with related national laboratory or industry efforts. Quarterly progress reports are requested.		
Nuclear Materials Aging and Degradation Pathway	LWS-3	**MECHANISTIC UNDERSTANDING OF EMBRITTLEMENT VIA MICROSTRUCTURAL INSTABILITY (PHASE TRANSFORMATIONS) IN HIGH FLUENCE AUSTENITIC STAINLESS STEEL COMPONENTS.** Research is needed developing predictive models providing insights into embrittlement caused by microstructural changes resultant from long term residence in an irradiation field. The relationship among microstructure, hardening, and embrittlement must also be explored. This work supports the LWRS Program strategic goals by providing key data and mechanistic understanding of irradiation-induced degradation effects, which are expected to become more severe with extended service. This work also provides data and a mechanistic understanding enhancing the current state of knowledge of irradiation-induced embrittlement.	Universities engaging in this effort will be expected to produce data or mechanistic modeling to help reduce the uncertainty associated with the long-term irradiation of nuclear reactor core-internals. Universities are expected to integrate and collaborate with related national laboratory or industry efforts. Quarterly progress reports are also requested.	$200K - $500K	2 - 3 years

Table 3. (continued).

Program of Interest:	Work Scope Id. No	R&D Project Work Scope:	Research Expectations and Deliverables:	Estimated Total Project Funding Range:	Estimated Duration:
Advanced LWR Nuclear Fuel Development Pathway	LWS-4	**ADVANCED ONLINE NUCLEAR FUEL MONITORING.** Research is needed focusing on potential nondestructive examination techniques to examine, or monitor in real time, those aging or degradation effects being studied in the Advanced Nuclear Fuels pathway, including fission gas release and transport, pellet-clad interaction, cladding oxidation, crud formation, corrosion, hydrogen embrittlement, and failure. This research may also develop inspection capabilities for on-line fuel monitoring. The ability to monitor ductility loss in spent fuel cladding while in storage is an example of this program element.	Universities performing this research will be expected to produce results that integrate multiple mechanistic processes and influences as related to nuclear fuel aging and degradation. The university will have to work closely with the LWRS Program Office. Quarterly progress reports are requested.	$200K - $500K	2 - 3 years
Advanced LWR Nuclear Fuel Development Pathway	LWS-5	**HYDROGEN-INDUCED EMBRITTLEMENT OF CLADDING.** Research is needed focusing on aging and degradation effects of hydrogen uptake and reorientation on nuclear fuel cladding, including hydride-induced, ductile-to-brittle transition for long term storage and transportation applications. Programs should investigate the susceptibility and behavior of spent fuel cladding mechanical properties to hydride reorientation affects. Development of a damage-based fuel rod performance model during long term storage may be an outcome of this research. Thermomechanical conditions representative of drying operations, storage, and transportation, should be considered. Results should be designed to enhance engineering safety analysis codes used in assessing cask accidents.	Universities performing this research will be expected to produce results that integrate multiple mechanistic processes and influences as related to nuclear fuel aging and degradation. The university will have to work closely with the LWRS Program Office. Quarterly progress reports are requested.	$200K - $500K	2 - 3 years

Table 3. (continued).

Program of Interest:	Work Scope Id. No	R&D Project Work Scope:	Research Expectations and Deliverables:	Estimated Total Project Funding Range:	Estimated Duration:
Advanced LWR Nuclear Fuel Development Pathway	LWS-6	**COUPLING OF ADVANCED NEUTRON TRANSPORT AND NUCLEAR FUEL PERFORMANCE CODES TO PROVIDE HIGH FIDELITY PREDICTIONS.** Research is needed focusing on methodology development coupling high fidelity three dimensional neutron transport codes to nuclear fuel performance codes. This research is intended to create advanced analytical capabilities sufficient to assess safety, fuel failure, and operability margins for reactivity insertion events applicable to existing and advanced LWR fuel. The work is to take advantage of high fidelity neutron transport solutions to improve fuel performance prediction accuracy, specifically in the areas of neutronic and mechanical conditions leading to fuel failure. High-fidelity analyses of fuel assemblies with explicit representation of individual fuel pins and coolant channels will be performed using transport code transient solution schemes and the mechanical response of fuel pins will be studied via fuel performance codes. Comparing conventional solutions with higher fidelity calculations, the same analysis will be performed by coupling a nodal diffusion code and a fuels performance code. The first research phase begins with computational methods improvements enabling three-dimensional neutron transport code coupling to a CFD code performing transient analysis. The second phase is an extension of the coupled codes to include a fuels performance code. Similar coupling of a three dimensional nodal diffusion code with a fuels performance code will be developed in parallel. The third research phase is to perform benchmark or standard problem comparisons between coupled	Universities engaging in this effort will be expected to produce advanced computational capabilities and demonstrations for analysis of nuclear fuel behavior. Universities are expected to integrate and collaborate with related national laboratory or industry efforts. Quarterly progress reports are also requested.	$200K - $500K	2 - 3 years

Table 3. (continued).

Program of Interest:	Work Scope Id. No	R&D Project Work Scope:	Research Expectations and Deliverables:	Estimated Total Project Funding Range:	Estimated Duration:
		transport/CFD/fuels performance calculations with more conventional analysis tools. The comparison results should establish the benefit of performing higher fidelity calculation..			
Risk-Informed Safety Margin Characterization Pathway	LWS-7	**RISK-INFORMED SAFETY MARGIN CHARACTERIZATION (RISMC).** Research is needed to address methodology and capability gaps in probabilistic risk analysis (PRA) and deterministic safety analysis to enable effective implementation of RISMC in contributing to a complete understanding of nuclear reactor extended operations. Areas of high priority include: (a) Comprehensive methodologies characterizing nuclear power plant safety margins within the risk-informed framework and determine how these margins are influenced over periods of plant extended operation (e.g., beyond 60 years); (b) Effective techniques for dynamic PRA and inclusion of reliability of passive systems and components; and c) advanced modeling and simulation methods to support the development, verification and validation of next-generation system safety codes that enable the nuclear power industry to perform analysis of a nuclear power plant's transients and accidents with a high degree of confidence.	Universities performing this research will be expected to produce results that integrate multiple mechanistic processes affecting the long term operability and reliability of nuclear reactors. The university will have to work closely with the LWRS Program Office. Quarterly progress reports are requested.	\$150K - \$500K	1 - 2 years

Table 3. (continued).

Program of Interest:	Work Scope Id. No	R&D Project Work Scope:	Research Expectations and Deliverables:	Estimated Total Project Funding Range:	Estimated Duration:
Advanced Instrumentation, Control, and Information Systems Technologies Pathway	LWS-8	**DIGITAL INSTRUMENTATION AND CONTROL TECHNOLOGIES FOR IMPROVED MONITORING AND RELIABILITY**. Research is needed to improve available methods for online monitoring of nuclear plant systems, including physical structures that are critical to safety, long term reliability, and systems aging and degradation, as well as control system reliability. Research should investigate use of advanced prognostic technologies for monitoring and predicting system health and performance, as well as methods needed to analyze the reliability of joint hardware-software technologies that comprise digital systems. High priority research areas include: (a) Prognostic methods to be deployed for monitoring aging and degradation of nuclear plant systems, structures, & components and that can be demonstrated in test bed environments representative of nuclear plant applications; (b) Methods for analyzing the dynamic reliability of digital systems, including hardware and software, based on formal processes that may be demonstrated on proposed systems for nuclear plant control and automation. This research is expected to provide developmental support of methods and technologies for digital instrumentation and control integration, as well as noting areas of reliability improvements requiring further research.	Universities performing this research will be expected to produce results that integrate multiple mechanistic processes affecting the long term operability and reliability of nuclear reactors. The university will have to work closely with the LWRS Program Office. Quarterly progress reports are requested.	$150K - $400K	1 - 2 years