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Revision 0

Light Water Reactor Sustainability Program

Integrated Program Plan

January 2012

U.S. Department of Energy

Office of Nuclear Energy

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Prepared by the
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EXECUTIVE SUMMARY

Nuclear power has safely, reliably, and economically contributed almost 20% of electrical generation in the United States over the past two decades. It remains the single largest contributor (more than 70%) of non-greenhouse-gas-emitting electric power generation in the United States.

Domestic demand for electrical energy is expected to grow by more than 30% from 2009 to 2035. At the same time, most of the currently operating nuclear power plants will begin reaching the end of their initial 20-year extension to their original 40-year operating license, for a total of 60 years of operation. Figure E-1 shows projected nuclear energy contribution to the domestic generating capacity. If current operating nuclear power plants do not operate beyond 60 years (and new nuclear plants are not built quickly enough to replace them), the total fraction of generated electrical energy from nuclear power will begin to decline. The oldest commercial plants in the United States reached their 40th anniversary in 2009.

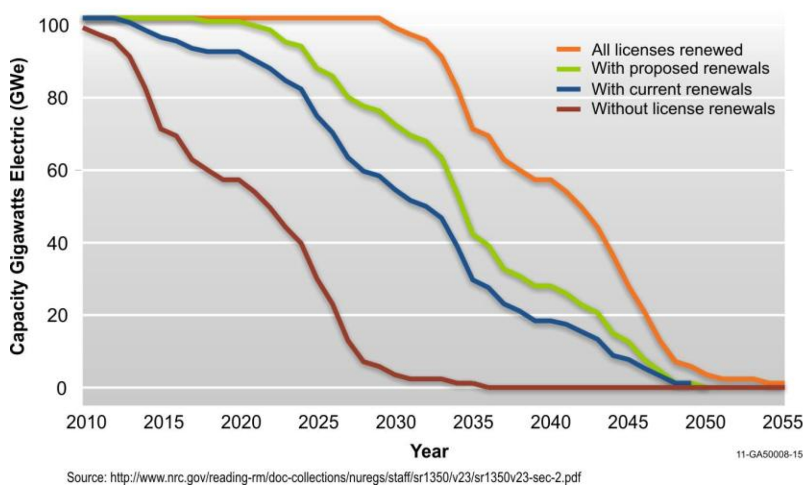

Figure E-1. Projected nuclear power generation.

The U.S. Department of Energy Office of Nuclear Energy's 2010 Research and Development Roadmap (2010 Nuclear Energy Roadmap) organizes its activities around four objectives that ensure nuclear energy remains a compelling and viable energy option for the United States. The four objectives are as follows:

1. Develop technologies and other solutions that can improve the reliability, sustain the safety, and extend the life of the current reactors.

2. Develop improvements in the affordability of new reactors to enable nuclear energy to help meet the Administration's energy security and climate change goals.

3. Develop sustainable nuclear fuel cycles.

4. Understand and minimize the risks of nuclear proliferation and terrorism.

The Light Water Reactor Sustainability (LWRS) Program is the primary programmatic activity that addresses Objective 1. This document summarizes the LWRS Program's plans. For the purpose of the LWRS Program, "sustainability" means the prudent use of resources – in this case, our nation's commercial nuclear power plants. Sustainability is defined as the ability to maintain safe and economic operation of the existing fleet of nuclear power plants for a longer-than-initially-licensed lifetime. It has two facets with respect to long-term operations: (1) manage the aging of plant systems, structures, and components so that nuclear power plant lifetimes can be extended and the plants can continue to operate safely, efficiently, and economically; and (2) provide science-based solutions to the industry to implement technology to exceed the performance of the current labor-intensive business model.

Extending the operating lifetimes of current plants beyond 60 years and, where practical, making further improvements in their productivity is essential to realizing the administration's goals of reducing greenhouse gas emissions to 80% below 1990 levels by the year 2050.

The Department of Energy's role in Objective 1 is to partner with industry and the Nuclear Regulatory Commission to support and conduct the long-term research needed to inform major component refurbishment and replacement strategies, performance enhancements, plant license extensions, and age-related regulatory oversight decisions. The Department of Energy research, development, and demonstration role focuses on aging phenomena and issues that require long-term research and/or unique Department of Energy laboratory expertise and facilities and are applicable to all operating reactors. When appropriate, demonstration activities will be cost shared with industry or the Nuclear Regulatory Commission. Pilot projects and collaborative activities are underway at commercial nuclear facilities and with industry organizations.

The following LWRS Program research and development pathways address Objective 1 of the 2010 Nuclear Energy Roadmap:

1. ***Materials Aging and Degradation*****.** 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, providing key input to both regulators and industry.

2. ***Advanced Light Water Reactor Nuclear Fuels.*** Improve 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. ***Advanced Instrumentation, Information, and Control Systems Technologies.*** Develop, demonstrate, and deploy new digital technologies for instrumentation and control architectures and provide monitoring capabilities to ensure the continued safe, reliable, and economic operation of the nation's operating nuclear power plants.

4. ***Risk-Informed Safety Margin Characterization.*** Develop and deploy approaches to support the management of uncertainty in safety margins quantification to improve decision making for NPPs. This pathway will (1) develop and demonstrate a risk-assessment method tied to safety margins quantification and (2) create advanced tools for safety assessment that enable more accurate representation of a nuclear power plant safety margin.

Measurable milestones have been developed for each of the pathways; these include both near-term (i.e., 1 to 5 years) and longer-term (i.e., beyond 5 years) milestones.

The following list provides the near-term major milestones to be completed by each LWRS Program pathway. Additional milestones to be accomplished by each pathway in the longer term are discussed more generally in the pathways sections of this report. The work planned in the near term, combined with feedback from stakeholders in the public and private sectors, will help to further define and prioritize the accomplishment of those milestones.

Materials Aging and Degradation

- (2012) Complete the Expanded Proactive Materials Degradation Analysis gap analysis of the materials degradation modes.
- (2013) Complete Containment Inspection Guidelines for extended-service conditions through partnership with Constellation Energy and the Electric Power Research Institute.
- Deliver mechanistic understanding for key materials and degradation modes, including the following:
  - (2014) Issue a final report on irradiation-assisted stress corrosion cracking (data and mechanistic understanding).
  - (2015) Deliver the final model to predict reactor pressure vessel embrittlement over a variety of conditions for extended service (e.g., time, temperature, composition, flux, and fluence) together with all supporting research data.
  - (2016) Issue a final report covering the controlling mechanisms for cable insulation, implications for extended service conditions, and supporting experimental data.
  - (2016) Issue final report on crack initiation in nickel-based alloys for piping (data and mechanistic understanding).
- (2015) Deliver model capability for key core internal issues, including the following:
  - Issue a final report on the experimental results and details of the predictive model of swelling of core internal components.

- Issue a final report on the experimental results and details of the predictive model for phase transformations of core internal components.

- (2016) Deliver a detailed database containing relevant and validated data for extended service, high-temperature effects, and irradiation effects on concrete performance.

- (2016) Deliver prototype detection and monitoring tools for key material components, including cabling, concrete, reactor pressure vessel, and piping.

- (2016) Issue a final report on the technology transfer of advanced weld repair techniques (mechanistic studies, model development, supporting data, and development).

Advanced Light Water Reactor Nuclear Fuels

- (2012) Issue a fuel development plan for silicon carbide (SiC) ceramic matrix composite (CMC) nuclear fuel systems, including technology challenges, development schedule, and approximate costs for implementation.

- (2012) Complete an SiC CMC material technology tradeoff study on advanced light water reactor fuels cladding material to guide program development.

- (2012) Complete the initial characterization of the SiC CMC clad fuel performance to allow design activities. Characterization will allow an understanding of what technology is needed to meet the performance requirements.

- (2013) Complete an analysis to support fueled SiC CMC matrix fuels in-pile testing to demonstrate practical operation. Demonstration of advanced cladding performance with simulated nuclear fuel heating.

- (2013) Fabricate a second generation of advanced SiC CMC cladding that incorporates high-performance features.

- (2013) Predict fuel interaction with cladding to demonstrate adequate performance for operating conditions using advanced fuel models of SiC CMC cladding.

- (2014) Conduct transient testing of SiC CMC cladding with simulated nuclear fuel heating to define an operating envelope in advance of in-pile testing.

- (2014) Fabricate extended-length fuel cladding that represents commercial nuclear fuel rods to demonstrate economic and technical practicality.

- (2014) Deliver a computational model of an advanced SiC CMC fuel system to predict performance during accident scenarios in advance of in-pile demonstration tests.

- (2014) Issue a report on licensing requirements and research program requirements to guide transfer to industrial development.

- (2015) Perform accident scenario and reactivity insertion tests with simulated nuclear fuel heating to assess performance and provide data for verification and validation.

- (2015) Perform in-pile testing of extended-length SiC CMC cladding to demonstrate in-reactor performance of extended-length rods.

- (2016) Perform in-pile testing of rods at higher exposure limits to demonstrate long-term performance of SiC CMC cladding.

- (2016) Begin an evaluation of vendor-specific nuclear fuel rod features to establish critical operating limits for advanced commercial fuel designs.

Advanced Instrumentation, Information, and Control Systems Technologies

- (2012) Publish a technical report for implementing digital technologies that facilitate communications, coordination, and collaboration in obtaining accurate outage activity status, managing the flow of information through the outage control center, and enabling the resolution of emergent problems in an efficient and effective manner, resulting in improved work efficiencies, production success, and nuclear safety margins.

- (2012) Publish a technical report for implementing integrated mobile technologies for nuclear power plant field workers that provide real-time connections to plant information and processes, thereby reducing human error, improving human performance and productivity, enabling distance collaboration, and maximizing the "collective situational awareness."

- (2012) Develop a digital, full-scale mockup in the Human Systems Simulation Laboratory of a conventional nuclear power plant control room.

- (2013) Publish guidelines for an optimized, human-factored control board layout for integrating digital operator interface screens with analog controls and indicators.

- (2013) Implement an upgrade of the Human Systems Simulation Laboratory, enabling research on function allocation, staffing, situational awareness, and workload in multiple-unit control rooms.

- (2013) Publish a technical report on measures, sensors, algorithms, and methods for monitoring active aging and degradation phenomena for Generation Step-Up transformers as an important passive component, including the diagnostic and prognostic analysis framework to support utility implementation of online monitoring for the component type.

- (2013) Publish guidelines for implementing integrated mobile technologies for nuclear power plant field workers to improve human performance and worker productivity.

- (2013) Publish guidelines for implementing digital technologies to improve outage communications, coordination, and collaboration.

- (2014) Publish a guideline standard for an advanced alarm management system in an nuclear power plant control room and a methodology for integrating diverse alarms and annunciators across all systems and digital platforms.

- (2014) Develop human factors evaluations and an implementation strategy for deploying automated field activity work packages built on mobile technologies, resulting in more efficient and accurate plant work processes, adherence to process requirements, and improved risk management.

- (2014) Develop human factors studies and publish implementation guidelines for an advanced outage control center that is specifically designed to maximize the usefulness of communication and collaboration technologies for outage coordination, problem resolution, and outage risk management.

- (2014) Publish a technical report on measures, sensors, algorithms, and methods for monitoring active aging and degradation phenomena for a large active component, including the diagnostic and prognostic analysis framework to support utility implementation of online monitoring for the component type.

- (2015) Publish implementation guidelines for computer-based procedures that enhance worker productivity, human performance, plant configuration control, risk management, regulatory compliance, and nuclear safety margin.

- (2015) Develop an advanced digital architecture integrating plant systems, plant work processes, and plant workers in a seamless digital environment, and publish guidelines to implement the architecture using industry open standards.

- (2015) Publish a technical report on measures, sensors, algorithms, and methods for monitoring active aging and degradation phenomena for a large passive plant component/structure, involving nondestructive examination-related online monitoring technology development and including the diagnostic and prognostic analysis framework to support utility implementation of online monitoring for the component type.

- (2016) Develop an end-state vision and strategy, based on human factors engineering principles, for the implementation of both a hybrid and a full highly integrated control room as new digital technologies and operator interface systems are introduced into traditional control rooms.

- (2016) Publish a technical report on measures, sensors, algorithms, and methods for monitoring active aging and degradation phenomena for a second large active plant component, including the diagnostic and prognostic analysis framework to support utility implementation of online monitoring for the component type.

Risk-Informed Safety Margin Characterization

- (2012) Deliver software development and quality assurance plans for RELAP-7.

- (2012) Demonstrate the Risk-Informed Safety Margin Characterization approach using a test case based on the Idaho National Laboratory Advanced Test Reactor.

- (2012) Assist Electric Power Research Institute in defining the station blackout conditions for a postulated event in a boiling water reactor with analysis focusing on the impact on safety margins associated with an extended power uprate.

- (2013) Develop a reactor loop capability in RELAP-7 for two-phase flow, including the representation of several simplified major physical components for a boiling water reactor's primary and safety systems.

- (2013) Demonstrate RELAP-7 capability to simulate boiling water reactor station blackout with the RAVEN system controller.

- (2013) Deliver the RELAP-7 verification and validation plan.

- (2013) Demonstrate RELAP-7 capability to simulate loss-of-coolant accident of both small and large break events.

- (2014) Complete software structure, allowing rapid and scalable development. At this time, RELAP-7 can be fully controlled by RAVEN for complete systems analysis. RELAP-7/RAVEN will have the capability to be coupled to other applications (e.g., aging and fuels modules) and perform as a balance-of-plant capability for the multidimensional core simulators under development in other Department of Energy programs.

- (2014) Demonstrate current margins analysis techniques on selected case studies using the completed software structure. The case studies will be selected in consultation with external stakeholders and will be chosen based on their potential to address an issue important to LWR sustainability and/or to achieve widespread stakeholder acceptance of the Risk-Informed Safety Margin Characterization approach.

- (2015) The margins analysis techniques will be sufficiently mature to enable industry to conduct margins quantification exercises for their own plants, including using RELAP-7/RAVEN/Grizzly (component aging module)/others (multiscale system analysis of plant performance such as coupling to localized fuel behavior for a boiling water reactor station blackout and other defined light water reactor scenarios).

- (2015) RELAP-7 will be validated against an accepted set of data.

- (2016) Complete full-scope analysis of a power uprate using RELAP-7/RAVEN (test case will be chosen in consultation with external stakeholders).

- (2016) Use margins analysis techniques, including use of RELAP-7/RAVEN/Grizzly (component aging module)/others, to analyze an industry-important issue (e.g., assessment of major component degradation in the context of life extension or assessment of the safety benefit of advanced fuel forms). Test case will be chosen in consultation with external stakeholders.

Sections 1 through 5 in this document provide a comprehensive overview of the LWRS Program and how it functions, including detailed descriptions of each of the four pathways and the near-term and longer-term milestones.

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ACRONYMS

BISON	Implicit simulation of nuclear fuel (fuel performance model)
CMC	ceramic matrix composite
DOE	Department of Energy
EPRI	Electric Power Research Institute
Grizzly	Component aging and damage evolution application
HSSL	Human Systems Simulation Laboratory
I&C	instrumentation and control
IASCC	irradiation-assisted stress corrosion cracking
II&C	instrumentation, information, and control
INL	Idaho National Laboratory
LWR	light water reactor
LWRS	Light Water Reactor Sustainability
MAaD	materials aging and degradation
NDE	nondestructive examination
NE	Office of Nuclear Energy
NEUP	Nuclear Energy University Program
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
R&D	research and development
RAVEN	Reactor Analysis and Virtual Control Environment (simulation controller for RISMC)
RISMC	Risk-Informed Safety Management Characterization
RPV	reactor pressure vessel
SiC	silicon carbide
SSC	systems, structures, and components
UWG	utility working group

Light Water Reactor Sustainability Program Integrated Program Plan

1. BACKGROUND

The U.S. electric energy sector is in a time of serious challenges and tremendous opportunities. Expanding energy demand and a growing awareness of the environmental impact caused by various forms of electricity generation prompts debate on how to best achieve sustainable, affordable, and environmentally sensitive solutions to the generation, transmission, distribution, and utilization of electricity. Nuclear power is central to meeting the electricity generation objective.

The Light Water Reactor Sustainability (LWRS) Program is a research and development (R&D) program sponsored by the U. S. Department of Energy (DOE), performed in close collaboration and cooperation with related industry R&D programs. The LWRS Program provides technical foundations for licensing and managing the long-term, safe, and economical operation of current nuclear power plants (NPPs), utilizing the unique capabilities of the national laboratory system.

Electric power is a vital component of the nation's economy and is essential to continuing improvements in the quality of life. Currently, almost 70% of domestic electricity generation relies on fossil fuels. Greenhouse gas emissions from burning fossil fuels are a mounting problem that threatens the future production of electricity from coal and natural gas. The President has set a goal of reducing greenhouse gas emissions to 80% below 1990 levels by the year 2050. In addition, shrinking domestic sources of liquid fuels increases the United States' reliance on imported sources of energy, which exposes the United States to even greater price and supply volatility. Meeting these aggressive emission reduction goals, while continuing to increase the overall energy supply to meet domestic demand, requires that all non-emitting technologies be used and improved. Further reduction of greenhouse gas emissions requires increased electrification of the transportation infrastructure, which places even greater challenges on the electric sector.

Nuclear power is the nation's largest contributor of non-greenhouse-gas-emitting electric power generation, comprising nearly three-quarters of the non-emitting sources (Figure 1). Energy efficiency, renewable energy, and carbon capture and storage technologies are expected to play increasing roles in providing clean and reliable energy. Nevertheless, our nation and others will depend on nuclear energy for large-scale supply of economical, dependable, and clean electricity.

The other forms of low carbon dioxide-emitting and renewable energy production methods (e.g., hydroelectric, wind, geothermal, and solar) have the potential to produce substantial energy; however, none of these other energy sources appear to be available in a sufficient scale to provide baseload power for the foreseeable future. Hydroelectric power is the most widely used renewable energy source in the United States; however, there is limited opportunity for expansion. While wind, geothermal, and solar power have demonstrated promise in meeting the nation's growing demand, these sources currently contribute only a small fraction of the nation's growing energy demands. In addition, wind and solar power are inherently dilute with low power density and are intermittent, resulting in low capacity factors. Geothermal is not intermittent, but is limited to locations or regions, such as the Geysers in California, where very hot water is easily accessible. Figure 2 provides a graph of the current capacity factors by energy source. The very high capacity factor for nuclear power makes it the only reliable and non-carbon dioxide-emitting source of baseload power available.

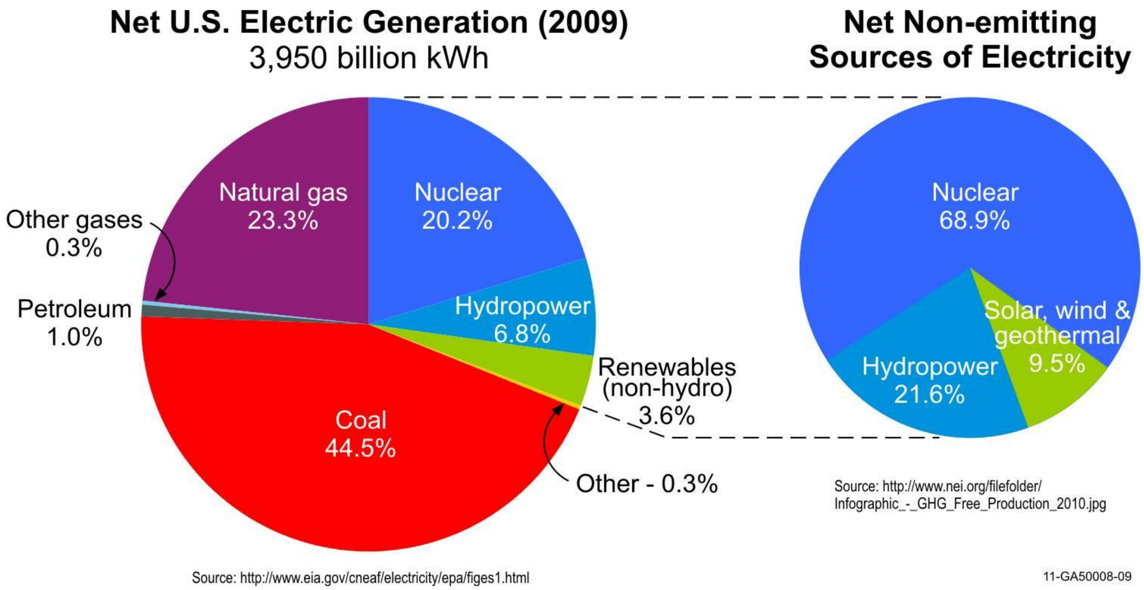

Figure 1. Current electric generating portfolio showing dominance of nuclear as a low carbon emission power source.

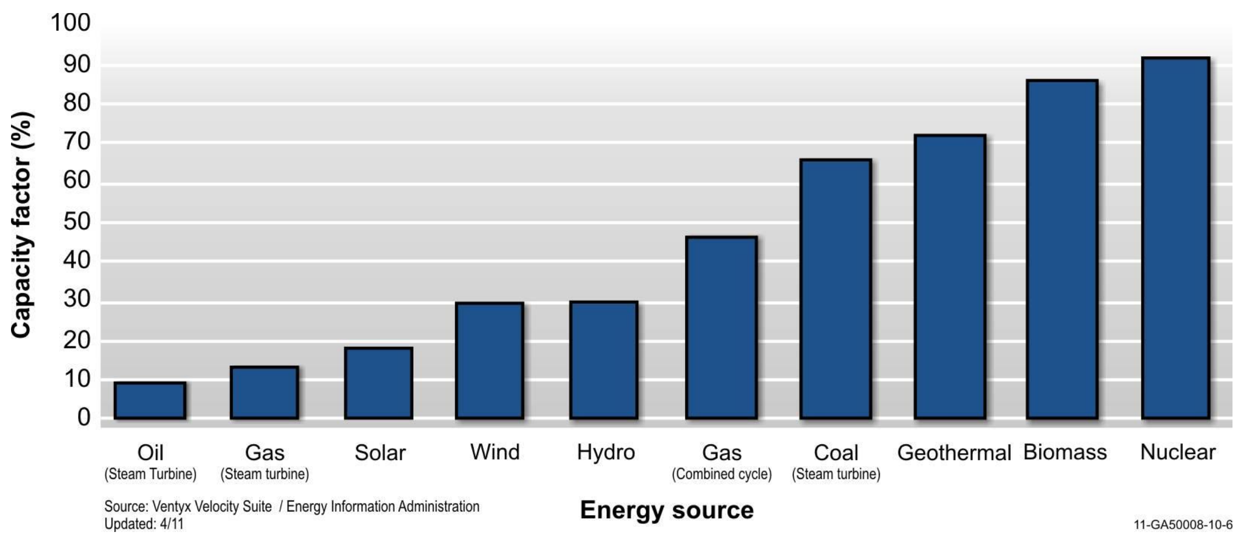

Figure 2. United States electrical generation capacity factors by energy source, showing high operating performance.

Construction of new NPPs is a clear option for new, emission-free, electrical generating capacity. However, bringing new NPPs online is facing substantial challenges and uncertainties, including high upfront capital cost, high financing cost, long construction time, and limitations in domestic fabrication capacity. A modest pace of new NPP construction is anticipated. For example, the U.S. Energy Information Administration's Annual Energy Outlook for 2011 predicts completion of a second unit at the Watts Bar site and an additional four new NPPs to be brought online by 2020.

Currently, 104 NPPs operate in 31 states (Figure 3). The existing, operating fleet of U.S. NPPs has consistently maintained outstanding levels of nuclear safety, reliability, and operational performance over the last two decades and operates with an average capacity factor above 90%. NPP capacity factors improved from around 50% in the early 1970s to 91.2% in 2010. Over the same period of time, the safety of the NPPs has improved substantially, as measured by predicted core damage frequency. The significant improvements in performance, reliability, and safety have made NPPs considerably more economical to operate. Major improvements were made in all areas of plant operation, including operations, training, equipment maintenance and reliability, technological improvements, and improved understanding of component degradation. More broadly, these improvements reflect effective management practices, advances in technology, and the sharing of safety and operational experience among utilities. Today, nuclear production costs are the lowest among the major U.S. power-generating options.

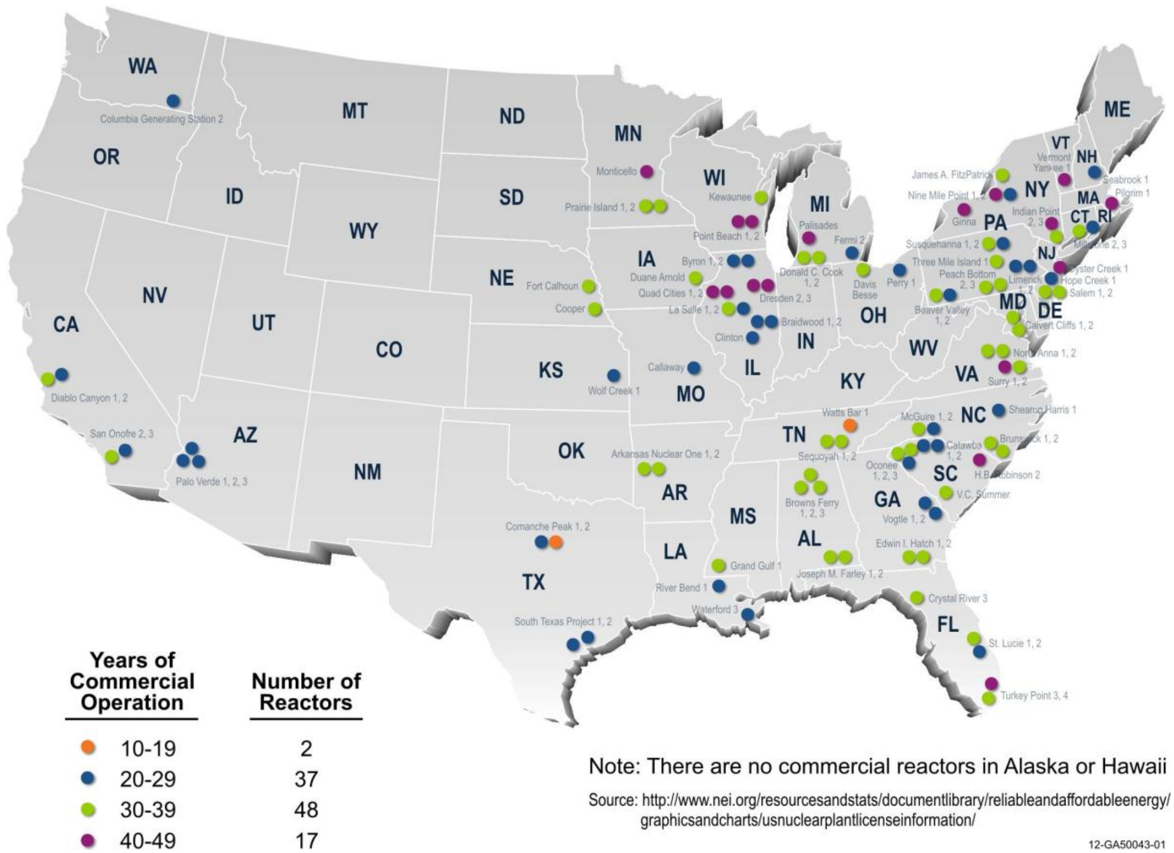

Figure 3. National distribution of operating nuclear power plants.

Figure 4 shows the following: (1) the oldest operating NPP started operation in 1969 and the newest plant started operation in 1996, (2) the first group of NPPs were brought online between 1969 and 1979 and the second group between 1980 and 1996, and (3) almost all operating NPPs have been issued, are applying for, or plan to apply for a 20-year license extension. This license extension will result in a licensed operating period of 60 years.

In about the year 2030, unless subsequent license renewals are granted, decommissioning of the current fleet of NPPs will begin. Over the next three decades beyond 2030, decommissioning of the existing fleet would result in a loss of nearly 100-GWe of emission-free electrical generating capacity, leaving a shortfall of required emission-free generating capacity. This gap might be filled with higher construction rates of new NPPs or with other technologies. However, the continued safe and economical operation of current reactors beyond the current license limit of 60 years is an option for filling this energy gap and maintaining the existing level of emission-free power generation capability at a fraction of the cost of building new plants.

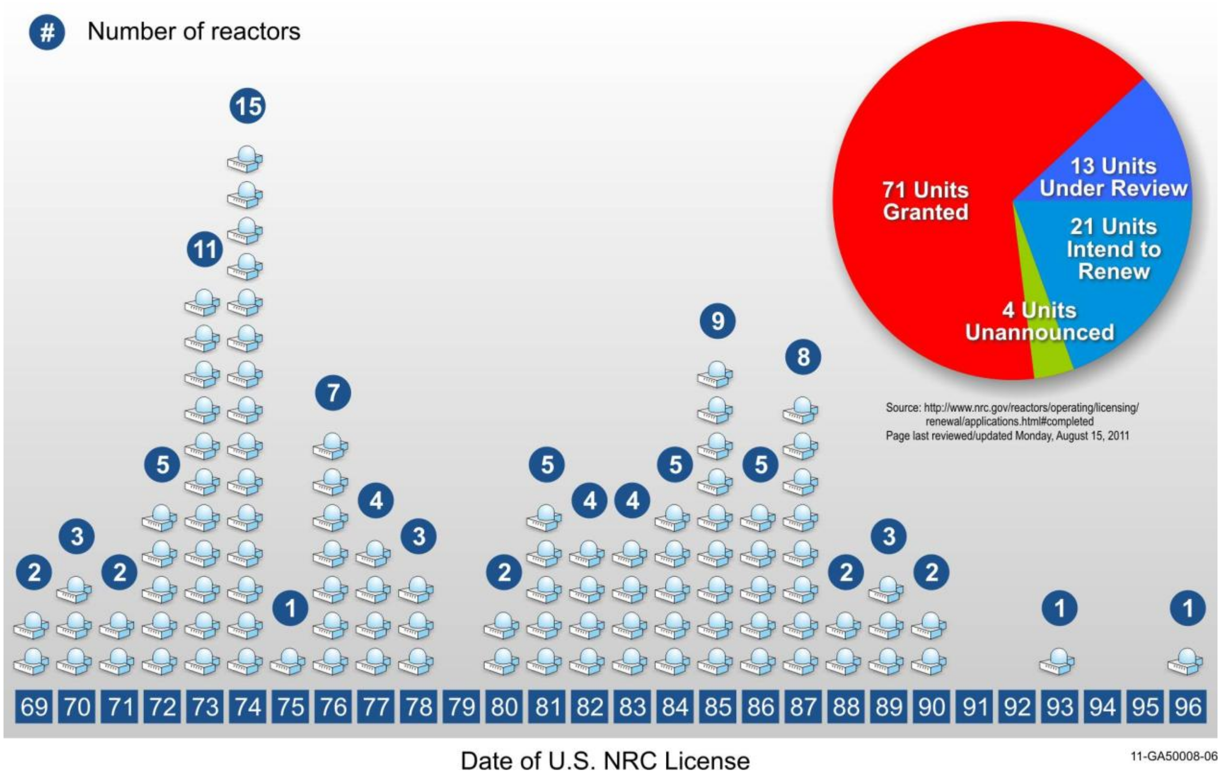

Figure 4. Nuclear power plant initial license date and license extension plans (as of October 2011).

To receive a 20-year license extension, an NPP operator must ensure the plant will operate safely for the duration of the license extension. The 40-year initial operating license period established in the Atomic Energy Act was based on antitrust and capital depreciation considerations, not technical limitations. The 20-year license extension periods are presently authorized under the governing regulation of 10 CFR Part 54, "Requirements for Renewal of Operating Licenses for Nuclear Power Plants."[a] This rule places no limit on the number of times a plant can be granted a 20-year license renewal as long as the licensing basis is maintained during the renewal term in the same manner and to the same extent as during the original licensing term (e.g., the licensee can demonstrate continued safe and secure operation during the extended period).

This regulatory process ensures continued safe operation of NPPs during future renewal periods. The license extension process requires a safety review and an environmental review, with multiple opportunities for public involvement. The license extension applicant must demonstrate how they are, or are planning to be, addressing aging-related safety issues through technical documentation and analysis, which the U.S. Nuclear Regulatory Commission (NRC) confirms before granting a license extension. A solid technical understanding of how systems, structures, and components (SSCs) age is necessary for NPPs licensees to demonstrate continued safety. A well-established knowledge base for the current period of licensed operation exists; however, additional research will be needed to obtain the same robust technical basis required for continued operational evaluations beyond 60 years.

In early 2007, DOE, with the Idaho National Laboratory (INL) engaging the Electric Power Research Institute (EPRI) and other industry stakeholders, initiated planning that led to the LWRS Program. The aim was to develop an R&D strategy that addresses nuclear energy issues within the

[a] 10 CFR 54, "Requirements for Renewal of Operating Licenses for Nuclear Power Plants," *Code of Federal Regulations*.

framework of the National Energy Policy and the National Energy Policy Act of 2005. Based on considerable analysis and information gathering, the "Strategic Plan for Light Water Reactor Research and Development,"[b] was developed and reviewed by an independent committee of experts. The plan, which recommended ten top priority areas for a government-industry, cost-shared R&D program, was issued in November 2007.

Building on the strategic plan and collaborative relationships that were developed while preparing it, DOE and INL immediately started developing the LWRS Program. In February 2008, DOE and NRC co-sponsored a workshop, which identified necessary R&D for long-term operation and licensing of NPPs.[c] Input from a large set of stakeholders provided important definition of needs and focused program objectives on long-term operation of existing NPPs. A follow-on workshop was held in February 2011 to review progress and discuss challenges with R&D for long-term operation.

In developing the strategic plan and the more specific program plans, it became apparent that a government/industry collaborative cost-sharing arrangement for R&D is needed for addressing the long-range, policy-driven goals of government and the acceptability and usefulness of derived solutions to industry. The national strategic interests in the long-term operation of existing NPPs include meeting climate change objectives, providing energy security, and minimizing cost impacts (due to plant replacements) to rate payers. The nuclear industry also has an incentive to ensure the continued safe and reliable operation of their operating NPPs. Therefore, at the nexus of these mutual interests, "cost-sharing" is being employed through cooperative R&D activities. DOE and industry are independently funding specific, related projects and sharing information to achieve goals of mutual interest. DOE-funded R&D addresses fundamental scientific questions, where private investment or capabilities are insufficient to make progress on broadly applicable technology issues for public benefit. The U.S. government (i.e., DOE and its national laboratories) holds large theoretical, computational, and experimental expertise in nuclear R&D that is not available within the industry. As such, the benefits will extend to the next generation of reactor technologies being deployed and those still in development. A federal program (i.e., the LWRS Program) creates an environment (by reducing uncertainty and risk) that provides incentives for industry to make the investments required for power operation periods beyond 60 years.

Further, the U.S. government's role in this area is merited in addressing the question, "How safe is 'safe enough'?" Even with continuous improvements in safety and performance, nuclear power is still perceived by the public as not safe enough. Nuclear power does involve high consequence events like those at Three Mile Island, Chernobyl, and Fukushima that are rare but can be catastrophic. When these events happen, the government invests substantial quantities of resources (financial and personnel) to deal with the consequences. Therefore, the government has an incentive to mitigate its risk by developing advanced materials, technologies, and analytical tools to better predict plant response and prevent/mitigate such accidents. DOE and its national laboratories can play a very important role as an honest broker in this debate.

While industry is likely to invest in applied research programs that are directed toward enhancing operations or in developing incremental improvements, industry is unlikely to invest significantly in research programs that focus on longer-term or higher-risk gains. Additionally, because research necessary for NPP life extension is of a broad nature that provides benefits to the entire industry, it is unlikely that a single company will make the necessary investment on its own.

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[b] INL/EXT-07-13543, *Strategic Plan for Light Water Reactor Research and Development*, INL, November 2007.

[c] "Life Beyond 60 Workshop Summary Report, NRC/DOE Workshop U.S. Nuclear Power Plant Life Extension Research and Development," NRC and DOE, prepared by Energetics Inc., February 19 through 21, 2008.

Government cost sharing and involvement is required to promote the necessary programs that are of crucial long-term, strategic importance. The LWRS Program, by incorporating long-term collaborative industry stakeholder inputs and shared costs, will support the strategic national interest of maintaining nuclear power as an available resource.

1.1 Program Overview

Sustainability in the context of light water reactors (LWRs) is defined as the ability to maintain safe and economic operation of the existing fleet of NPPs for a longer-than-initially-licensed lifetime. It has two facets with respect to long-term operations: (1) manage the aging of hardware so the NPP lifetime can be extended and the plant can continue to operate safely, efficiently, and economically; and (2) provide science-based solutions to the industry to implement technology to exceed the performance of the current labor-intensive business model.

In April 2010, DOE’s Office of Nuclear Energy (NE) issued the R&D Roadmap (2010 NE Roadmap). The NE Roadmap organized DOE-NE activities in accordance with four objectives that ensure nuclear energy remains a compelling and viable energy option for the United States. Objective 1 of the NE Roadmap focuses on developing the technologies and other solutions that can improve reliability, sustain safety, and extend the life of the current fleet of commercial NPPs. The LWRS Program is the primary programmatic activity that addresses Objective 1. The LWRS Program is focused on the following three goals:

1. Developing the fundamental scientific basis to understand, predict, and measure changes in materials and SSCs as they age in environments associated with continued long-term operations of the existing reactors

2. Applying this fundamental knowledge to develop and demonstrate methods and technologies that support safe and economical long-term operation of existing reactors

3. Researching new technologies to address enhanced plant performance, economics, and safety.

The LWRS Program consists of the following four primary technical areas of R&D:

1. ***Materials Aging and Degradation*** (MAaD) with R&D to develop the scientific basis for understanding and predicting long-term environmental degradation behavior of materials in NPPs. The work will provide data and methods to assess the performance of SSCs essential to safe and sustained NPP operations. The R&D products will be used to define operational limits and aging mitigation approaches for materials in NPP SSCs subject to long-term operating conditions.

2. ***Advanced LWR Nuclear Fuels*** with R&D to improve the scientific knowledge basis for understanding and predicting fundamental nuclear fuel and cladding performance in NPPs, and applying this information to development of high-performance, high burn-up fuels with improved safety, cladding integrity, and improved nuclear fuel cycle economics. The R&D products will be used to deploy new fuel/core designs for the existing NPP fleet with improved safety and economic operational capabilities.

3. ***Advanced Instrumentation, Information, and Control (II&C) Systems Technologies*** with R&D to address long-term aging and modernization of current instrumentation and control (I&C) technologies through development/testing of new I&C technologies and advanced condition monitoring technologies for more automated and reliable plant operation. The R&D products will be used to design and deploy new II&C technologies and systems in existing NPPs that provide an

enhanced understanding of plant operating conditions and available margins and improved response strategies and capabilities for operational events.

4. ***Risk-Informed Safety Margin Characterization (RISMC)*** with R&D to develop and deploy approaches to support the management of uncertainty in safety margins quantification to improve decision making for NPPs. This pathway will (1) develop and demonstrate a risk-assessment method tied to safety margins quantification and (2) create advanced tools for safety assessment that enable more accurate representation of a NPP safety margin. The R&D products will be used to produce state-of-the-art NPP safety analysis information that yields new insights on actual plant safety/operational margins.

The technical plans for each of the four pathways are discussed in Sections 2 through 5. Measurable milestones have been developed for each of the pathways, including both near-term (i.e., 1 to 5 years) and longer-term (i.e., beyond 5 years) milestones.

1.2 Program Management

The entire LWRS Program falls within DOE-NE. Program management and oversight, including programmatic direction, project execution controls, budgetary controls, and Technical Integration Office performance oversight, are provided by the DOE Office of LWR Technologies in conjunction with the DOE Idaho Operations Office. The functional organization, reporting relationships, and roles and responsibilities for the Technical Integration Office are explained in the following sections and Figure 5.

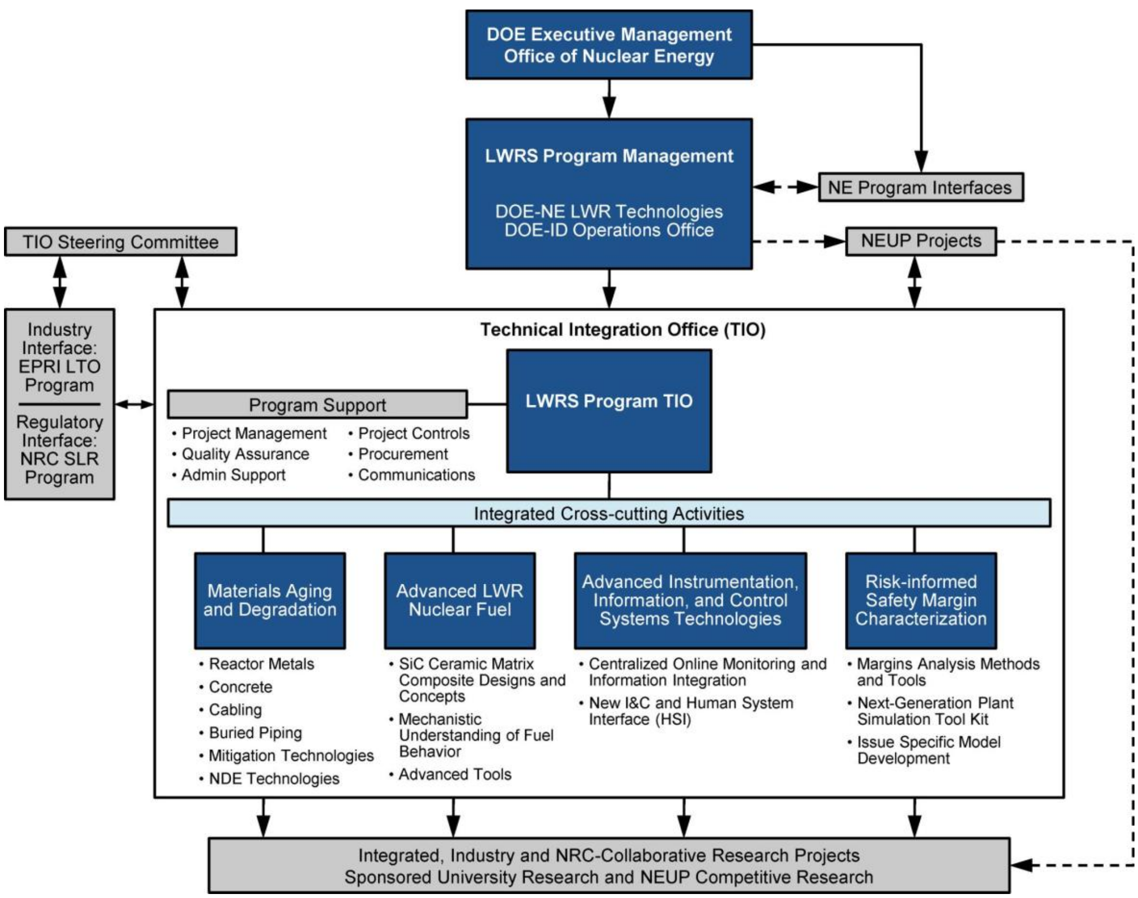

Figure 5. Light Water Reactor Sustainability Program organization.

1.3 Program Research and Development Interfaces

Planning, execution, and implementation of the LWRS Program are done in coordination with the nuclear industry, NRC, universities, and related DOE R&D programs (e.g., Nuclear Energy Advanced Modeling and Simulation, Consortium for Advanced Simulation of LWRs, and the Fuel Cycle R&D Program) to assure relevance and effective management of the work (Figure 6).

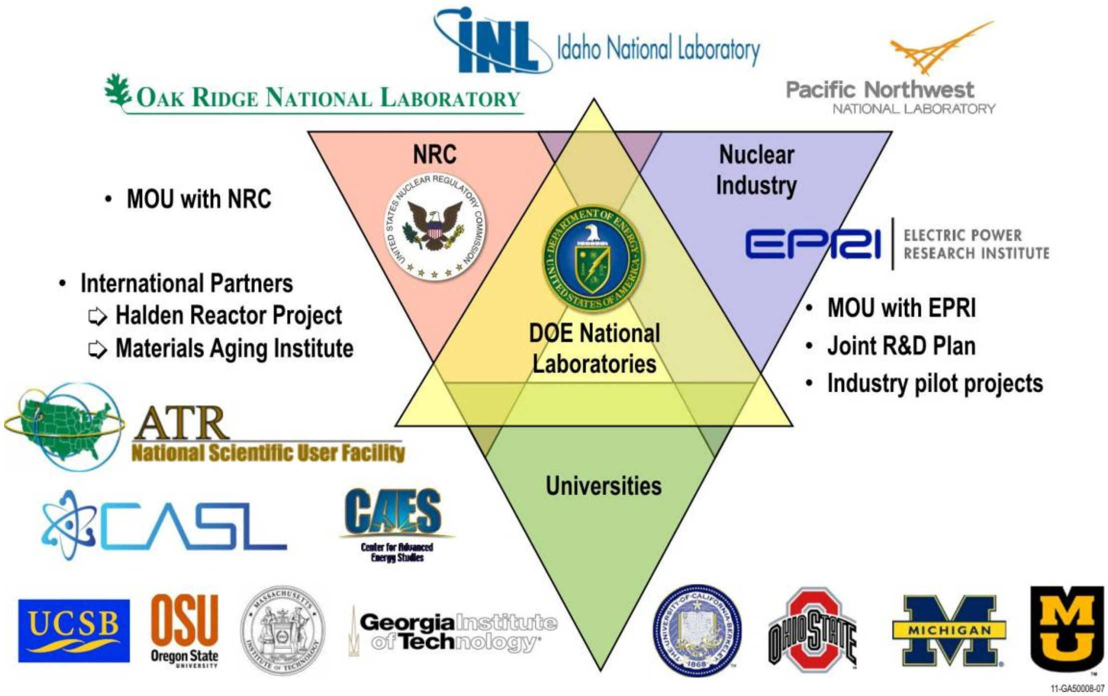

Figure 6. Light Water Reactor Sustainability Program interfaces.

1.3.1 Industry

The LWRS Program works with industry on nuclear energy supply technology R&D needs of common interest. The interactions with industry are broad and include cooperation, coordination, and direct cost-sharing activities. The guiding concepts for working with industry are leveraging limited resources through cost-shared R&D, direct work on issues related to the long-term operation of NPPs, the need to develop state-of-the-art technology to ensure safe and efficient operation, and the need to focus government-sponsored R&D on the higher-risk and/or longer-term projects incorporating scientific and qualitative solutions using the unique expertise and facilities at the DOE laboratories. These concepts are included in memorandums of understanding, nondisclosure agreements, and cooperative R&D agreements. Cost-shared activities are planned and executed on a partnership basis and include significant joint management and funding.

EPRI has established the Long-Term Operations Program, which complements the DOE LWRS Program. EPRI's and industry's interests include applications of the scientific understanding and the tools to achieve safe, economical, long-term operation. Therefore, the government and private sector interests are similar and interdependent, leading to strong mutual support for technical collaboration and cost sharing. The interface between DOE-NE and EPRI for R&D work supporting long-term operations of the existing fleet is defined in a memorandum of understanding. A joint R&D plan defining the collaborative and cooperative R&D activities between the LWRS Program and the Long-Term Operations Program will be issued in 2012 and will be updated annually.[d] Also, contracts with EPRI or other industrial organizations may be used as appropriate for some work.

1.3.2 Nuclear Regulatory Commission

DOE's mission to develop the scientific basis to support both planned lifetime extension up to 60 years and lifetime extension beyond 60 years, and to facilitate high-performance economic operations over the extended operating period for the existing LWR operating fleet in the United States, is the central focus of the LWRS Program. Therefore, more and better coordination with industry and NRC is needed to ensure a uniform approach, shared objectives, and efficient integration of collaborative work for the LWRS Program. This coordination requires that articulated criteria for the work appropriate to each group be defined in memoranda of understanding that are executed among these groups. NRC has a memorandum of understanding[e] in place with DOE, which specifically allows for collaboration on research in these areas. Although the goals of the NRC and DOE research programs may differ, fundamental data and technical information obtained through joint research activities are recognized as potentially of interest and useful to each agency under appropriate circumstances. Accordingly, to conserve resources and to avoid duplication of effort, it is in the best interest of both parties to cooperate and share data and technical information and, in some cases, the costs related to such research, whenever such cooperation and cost sharing may be done in a mutually beneficial fashion.

1.3.3 International

DOE is coordinating LWRS Program activities with several international organizations with similar interests and R&D programs. The LWRS Program participants continue to develop relationships with international partners, including the following international organizations, to gain awareness of emerging issues and their scientific solutions:

- **Organization for Economic Cooperation and Development's Halden Reactor Project**: The Halden Reactor Project is a jointly financed R&D program under the Organization for Economic Cooperation and Development—Nuclear Energy Agency and is comprised of national organizations in 18 countries, including licensing and regulatory bodies, vendors, utilities, and research organizations. The Norwegian Institute for Energy Technology executes the program at its Halden establishment in Norway.

  INL is an associate member of the Halden Reactor Project on behalf of DOE. Membership in the Halden Reactor Project will be maintained over the course of this research program to leverage the wide spectrum of advanced capabilities developed for nuclear operations and support. Halden has been on the cutting edge of new NPP technologies for several decades and their research is directly applicable to the capabilities being pursued under the MAaD, II&C, and Advanced LWR Nuclear Fuels Pathways. In fact, the LWRS Program was well represented with technical presentations at the Enlarged Halden Programme Group Meeting 2011 held in Sandefjord, Norway on October 2 through 7, 2011.[f]

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[d] INL/EXT-12-24562, *DOE-NE Light Water Reactor Sustainability Program and EPRI Long Term Operation Program – Joint Research and Development Plan*, Idaho National Laboratory, draft.

[e] "Memorandum of Understanding Between U.S. Nuclear Regulatory Commission and U.S. Department of Energy on Cooperative Nuclear Safety Research," dated April 22, 2009, and signed by Brian W. Sheron, Director, Office of Nuclear Regulatory Research, NRC, and Rebecca Smith-Kevern, Acting Deputy Assistant Secretary for Nuclear Power Deployment, DOE-NE.

[f] Halden Reactor Project, "Enlarged Halden Programme Group Meeting 2011," *Sandefjord, Norway, October 2 through 7, 2011*.

- **Materials Aging Institute**: The Materials Aging Institute was founded as a partnership between Électricité de France, EPRI, and the Tokyo Electric Power Company and is dedicated to understanding and modeling materials degradation. The collaborative interface with the LWRS Program is coordinated through EPRI, which is a founding member of the Materials Aging Institute.

  A current activity being performed in cooperation with NRC, EPRI, and the Materials Aging Institute is development of a concrete performance database, including support to partners in modeling activities, surveillance, and testing criteria. This activity should provide understanding of the roles of composition, history, and the environment associated with the mechanisms of concrete degradation. Additional cooperative activities also are being evaluated.

- **International Atomic Energy Agency Plant Life Management:** The International Atomic Energy Agency is the world's center of cooperation in the nuclear field. The Agency works with its member states and multiple partners worldwide to promote safe, secure, and peaceful nuclear technologies.

  The Third International Conference on NPP Life Management for Long Term Operations will be held on May 14 through 18, 2012, in Salt Lake City, Utah.[g] This conference is being organized by the International Atomic Energy Agency in cooperation with the European Commission Joint Research Centre and the Organization for Economic Cooperation and Development—Nuclear Energy Agency and will be hosted by the DOE LWRS Program and the NRC Subsequent License Renewal Program.

- **International Forum for Reactor Aging Management:** The International Forum for Reactor Aging Management facilitates the appropriate exchange of information among those parties and organizations around the world that presently are planning to address or are addressing issues of NPP SSCs aging management.

  During the inaugural International Forum for Reactor Aging Management meeting held on August 4 and 5, 2011, in Colorado Springs, Colorado, the working group provided recommendations on collaborative research topics. Topics identified by the LWRS Program MAaD Pathway include (1) concrete performance and surveillance techniques (2) online monitoring, (3) condition assessment and sensor placement, (4) irradiated materials welding, and (5) cables (coatings and polymeric materials).

- **European Nuclear Plant Life Prediction:** The European network of excellence Nuclear Plant Life Prediction has been launched under the Euratom Framework Programme with a clear focus on integrating safety-oriented research on materials, structures, and systems and using the results of this integration through the production of consistent lifetime assessment methods.

  The RISMC Pathway participated in the Workshop on Deterministic and Probabilistic Safety Assessment in Helsinki on October 3 through 5, 2011.[h] The Deterministic and Probabilistic Safety Assessment Group is closely associated with the European Nuclear Plant Life Prediction.

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[g] International Atomic Energy Agency, "Third International Conference on NPP Life Management for Long-Term Operations," *Salt Lake City Utah, May 14 through 18, 2012*.

[h] European Nuclear Plant Life Prediction, "Workshop on Deterministic and Probabilistic Safety Assessment," *Helsinki on October 3 through 5, 2011*.

- **U.S.–Argentina Binational Energy Working Group:** The Binational Energy Working Group technical meeting was held on August 1 through 3, 2011, in Albuquerque, New Mexico. Technical teams for both countries discussed collaborative activities in the areas of civilian nuclear power. During the meeting, it was decided that experts from both countries would continue technical discussions and begin collaboration on reactor sustainability. The technical teams consist of members of the LWRS Program and Comision Nacional De Energia Atomica.

- **Nuclear Energy Agency Committee on the Safety of Nuclear Installations**: The mission of the Nuclear Energy Agency Committee on the Safety of Nuclear Installations is to assist member countries in maintaining and further developing the scientific and technical knowledge base required to assess the safety of nuclear reactors and fuel-cycle facilities.

  The LWRS Program periodically participates in the workshops and meetings of this committee.

1.3.4 Universities

Universities participate in the program in at least two ways: (1) through the Nuclear Energy University Program (NEUP) and (2) via direct contracts with the national laboratories that support the LWRS Program. NEUP funds nuclear energy research and equipment upgrades at U.S. colleges and universities and provides scholarships and fellowships to students (see www.neup.gov). In addition to contributing funds to NEUP, the LWRS Program provides descriptions of research activities important to the LWRS Program and the universities submit proposals that are technically reviewed. The top proposals are selected and those universities work closely with the LWRS Program in support of key LWRS Program activities. Universities also are engaged in the LWRS Program via direct subcontracts where unique capabilities and/or facilities are funded by the program.

1.3.5 Advanced Modeling and Simulation Tools

The most common theme for the pathways is use of computer modeling of physical processes or development of a larger system computer model. Extensive use of computer modeling is intended to distill the derived information so that it can be used for further research in other pathways and as the basis for decision-making.

Computer modeling occurs in three forms, with many overlapping aspects within the LWRS Program:

1. Modeling a physical behavior (such as crack initiation in steel) is an example of direct computer modeling. The resulting model is used to store information for use in other pathways and to use in its own right for further research.

2. Development of more detailed computer modeling tools capable of encoding more complex behaviors (such as fuel performance modeling).

3. Creation of larger integrated databases that roll up results and allow decision-making. The large, system-wide, integrated models allow complex behavior to be understood in new ways and new conclusions to be drawn. These integrated databases can be used to further guide physical and modeling research, improving the entire program.

Because of their overlapping nature and numerous interfaces, these modeling activities tend to be naturally cross-cutting activities between pathways.

1.3.5.1 Nuclear Energy Advanced Modeling and Simulation. A critical interaction of the LWRS Program is with the DOE Nuclear Energy Advanced Modeling and Simulation Program. The LWRS Program will take advantage of the detailed, multiscale, science-based modeling and simulation results developed by the DOE Nuclear Energy Advanced Modeling and Simulation Program that will be uniquely valuable to multiple pathways. The modeling and simulation advances will be based on scientific methods, high dimensionality, and high-resolution integrated systems. The simulations will use the most advanced computing programs available. These tools will include fully three-dimensional, high-resolution, modeling-integrated systems based on first-principle physics. To accomplish this, the modeling and simulation capabilities will have to be run on modern, highly parallel processing computer architectures. These advanced computational tools are needed to create a new set of modeling and simulation capabilities that will be used to better understand the safety performance of the aging reactor fleet. These capabilities will be information sources and tools for advancing the LWRS Program’s goals.

1.3.5.2 Department of Energy’s Energy Innovation Modeling and Simulation Hub. The LWRS Program is coordinating with the DOE Energy Innovation Modeling and Simulation Hub managed by the Consortium for Advanced Simulation of Light Water Reactors. The hub is addressing long-term operational challenges faced by U.S. nuclear utilities and will use models under development in the LWRS Program, as well as existing models.

A primary initial product of the hub is a sophisticated integrated model of a LWR (i.e., a virtual reactor with focus on modeling the reactor core). The virtual reactor will be used to address issues for existing LWRs (e.g., life extensions and power uprates). The hub’s challenge problems have been selected principally to demonstrate the capability of the virtual reactor to enable life extensions and power uprates and will require coupling with models under development in the LWRS Program (e.g., systems analysis and component aging models). The enhanced computational capability of the virtual reactor will allow simulated proof of concepts for LWRS Program improvements and identify areas needing additional research. Consortium for Advanced Simulation of Light Water Reactors’ Industry Council has recommended enhanced collaboration with the LWRS Program and discussions on this have begun.

1.4 Summary

The DOE-NE Office of LWR Technologies directs the LWRS Program and closely coordinates with other agencies, the nuclear industry, and international partners to achieve LWRS Program goals. The LWRS Program Technical Integration Office supports DOE-NE in accomplishing these goals. Technical integration and program execution will be accomplished by using facilities and staff from multiple national laboratories, universities, industrial alliance partners, consulting organizations, and research groups from cooperating foreign countries. The Technical Integration Office is responsible for ensuring the necessary memorandum purchase orders, interagency work orders, or contracts are in place to document work requirements, concurrence with work schedules and deliverables, and transfer funds to the performing organizations for R&D activities.

In summary, the electrical energy sector is challenged to supply increasing amounts of electricity in a safe, dependable, and economical manner and with reduced carbon dioxide emissions. Nuclear power is an important part of answering the challenge through long-term, safe, and economical operation of current NPPs and with building new NPPs. Therefore, DOE-NE supports a strong and viable domestic nuclear industry and preserves the ability of that industry to participate in nuclear projects here and abroad. The LWRS Program provides, in collaboration with industry programs, the technical basis for extended safe and reliable operations of the existing commercial fleet of NPPs.

2. MATERIALS AGING AND DEGRADATION

2.1 Background

Nuclear reactors present a very challenging service environment. Components within the containment of an operating reactor must tolerate high-temperature water, stress, vibration, and an intense neutron field. Degradation of materials in this environment can lead to reduced performance and, in some cases, sudden failure. Materials degradation in an NPP is extremely complex due to the various materials, environmental conditions, and stress states. Over 25 different metal alloys can be found within the primary and secondary systems (see Figure 7; source R. Staehle). Additional materials exist in concrete, the containment vessel, II&C equipment, cabling, buried piping, and other support facilities. Dominant forms of degradation may vary greatly between the different SSCs and can have an important role in the safe and efficient operation of an NPP.

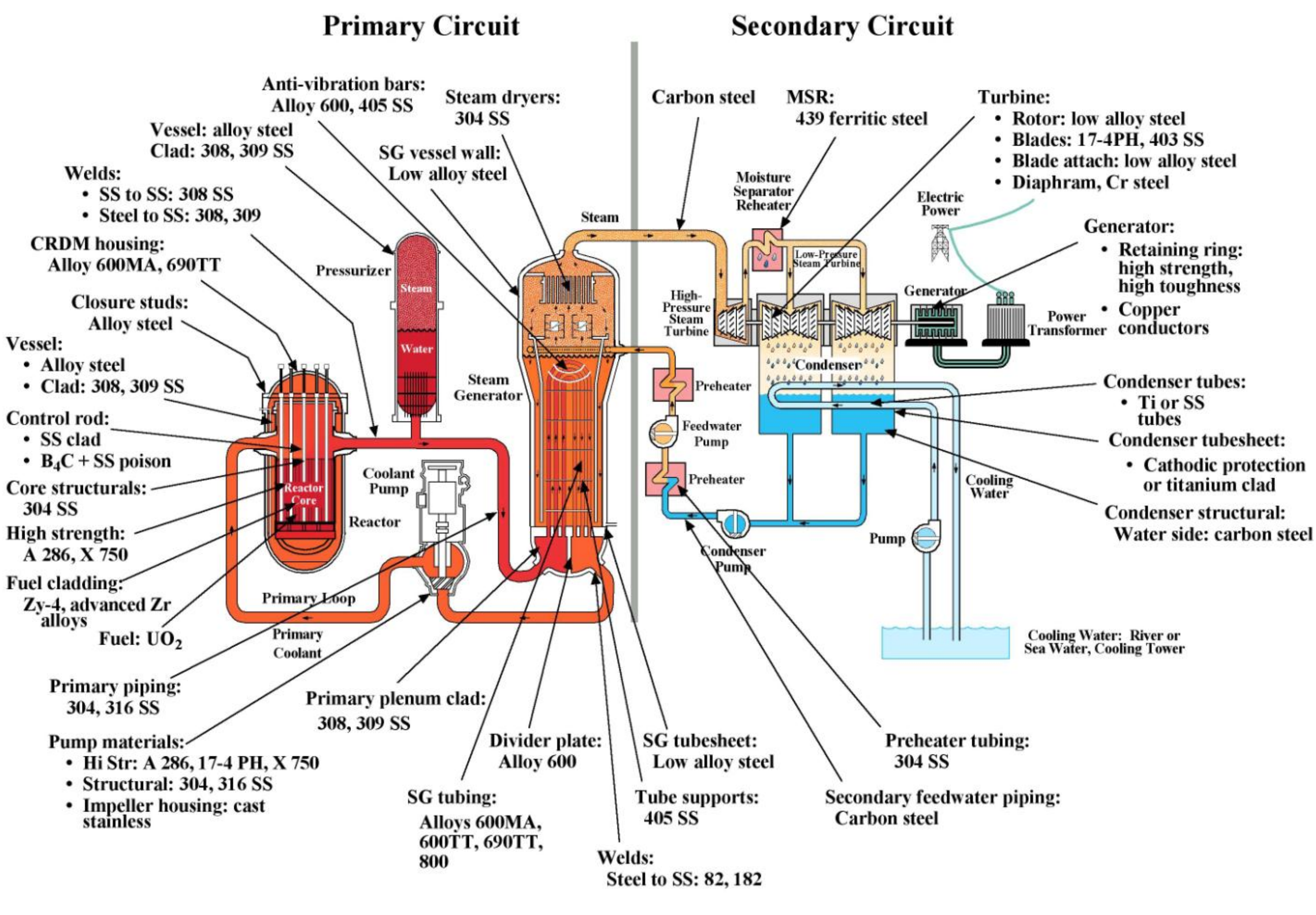

Figure 7. Sampling of the typical materials in a pressurized water reactor.

Clearly, the demanding environments of an operating nuclear reactor may impact the ability of a broad range of materials to perform their intended function over extended service periods. Routine surveillance and repair/replacement activities can mitigate the impact of this degradation; however, failures still occur. With reactors being licensed to operate for periods up to 60 years, with further extensions under consideration, and power uprates being planned, many of the plant SSCs will be expected to tolerate more demanding environments for longer periods. The longer plant operating lifetimes may increase the susceptibility of different SSCs to degradation and may introduce new degradation modes. For example, in the area of crack-growth mechanisms for nickel-based alloys alone, there are up to 40 variables known to have a measurable effect. Further, many variables have complex interactions (see Figure 8; source A Jennsen). In this same instance (i.e., crack-growth mechanisms for nickel-based alloys), a purely experimental approach would require greater than a trillion experiments to address all variables and interactions. Therefore, the application of modern materials science to mechanistic studies and careful inclusion of field service conditions will be required to resolve these issues in a timely manner.

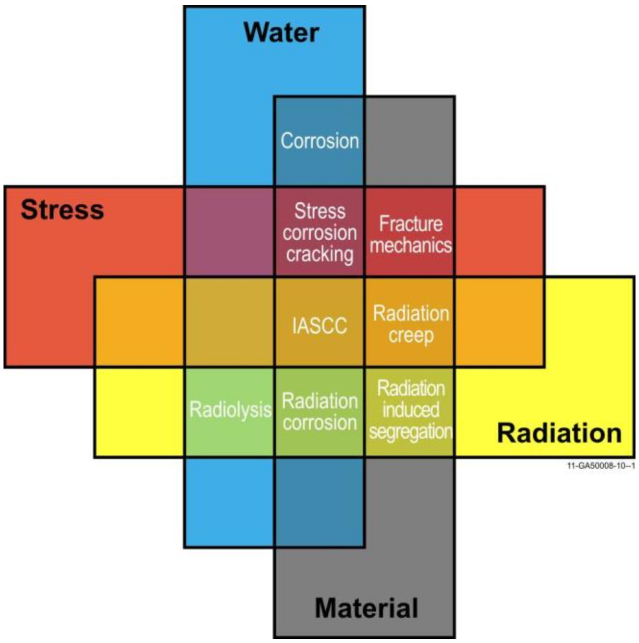

Figure 8. Complexity of interactions between materials, environments, and stresses in an operating nuclear power plant.

In the past two decades, there have been great gains in techniques and methodologies that can be applied to the nuclear materials problems of today. Indeed, modern materials science tools (e.g., advanced characterization tools and computational tools) must be employed. While specific tools and the science-based approach can be described in detail for each particular degradation mode, many of the diverse technical topics and information needs in this area can be organized into a few key areas. These could include mechanisms of materials degradation, mitigation strategies, and modeling and simulation.

While all components potentially can be replaced, decisions to simply replace components may not be practical or the most economically favorable option. Therefore, understanding, controlling, and mitigating materials degradation processes and establishing a sound technical basis for long-range planning of necessary replacements are key priorities for extended NPP operations and power uprate considerations.

2.2 Research and Development Purpose and Goals

The MAaD Pathway provides research in many areas of materials science and technology, all supporting multiple DOE missions and providing unique input to the evaluation of NPP life extension while complementing R&D efforts of the nuclear industry and regulators. The strategic goals of the pathway are to develop the scientific basis for understanding and predicting long-term environmental degradation behavior of materials in NPPs and to provide data and methods to assess performance of SSCs essential to safe and sustained NPP operations.

DOE (through the MAaD Pathway) is involved in this R&D activity for the following reasons:

1. MAaD tasks provide fundamental understanding and mechanistic knowledge via science-based research. Mechanistic studies provide better foundations for prediction tool development and focused mitigation solutions. These studies also are complementary to industry efforts to gain relevant, operational data. The U.S. national laboratory and university systems are uniquely suited to provide this information given their extensive facilities, research experience, and specific expertise. Specific outcomes of these fundamental tasks include mechanistic understanding of key degradation modes, elucidating the role of composition, material history, and environment in degradation. In many of these tasks, models to predict susceptibility over a lifetime will be developed. In some tasks, understanding if a mode of degradation is a true concern is a key outcome.

2. While understanding and predicting failures are extremely valuable tools for management of reactor components, active monitoring of materials degradation and alternatives to component replacement also are invaluable. Improved monitoring techniques will help characterize degradation of core components. Selected MAaD tasks are focused on development of high-risk, high-reward technologies to understand, mitigate, or overcome materials degradation. This type of alternative technology research is uniquely suited for government roles and facilities. These pursuits also are outside the area of normal interest for industry sponsors due to the risk of failure. New nondestructive examination (NDE) techniques may permit a means of monitoring components such as the reactor pressure vessel (RPV), core internals, cables, or concrete. Specific mitigation research tasks in this area include development of advanced welding techniques and annealing processes to overcome component damage. Specific outcomes of these tasks will be the transfer of advanced methodologies to industry and regulatory interests.

3. MAaD tasks support collaborative research with industry and regulators (and meet at least one of the above objectives). The focus of these tasks is on supporting and extending industry capability by providing expertise, unique facilities, or fundamental knowledge.

Combined, these thrusts provide improved mechanistic understanding of key degradation modes and sufficient experimental data to provide and validate operational limits; new methods of monitoring degradation; and development of advanced mitigation techniques to provide improved performance, reliability, and economics. Mechanistic and operational data also will be used to develop performance models for key material systems and components in later years.

2.3 Pathway Research and Development Areas

The MAaD Pathway activities have been organized into five principal areas: (1) reactor metals, (2) concrete, (3) cables, (4) buried piping, and (5) mitigation strategies. These research areas cover material degradation in SSCs that were designed for service without replacement throughout the life of the plant. Management of long-term operation of these components can be difficult and expensive. As NPP licensees seek approval for extended operation, the way in which these materials age beyond 60 years will need to be evaluated and their capabilities reassessed to ensure they maintain the ability to perform their intended functions in a safe and reliable manner.

2.3.1 Reactor Metals

As described above, numerous types of metal alloys can be found throughout the primary and secondary systems of NPPs. Some of these materials (in particular, the reactor internals) are exposed to high temperatures, water, and neutron flux. This challenging operating environment creates degradation mechanisms in the materials that may be unique or environmentally exacerbated. Research projects in this area will provide a greater technical foundation to help determine remaining useful life for materials and components and to establish the ability of those metals to support NPP operations for 60 years and beyond. Deliverables in these areas will include reports detailing experimental results and mechanistic findings that permit reduction in performance uncertainty and gains in basic materials understanding. In addition, predictive models that allow extrapolation of materials degradation to different operating scenarios will be produced; however, great care must be taken to identify and understand the underlying mechanisms. Databases capturing broad laboratory data and operational experiences also will be developed to provide a resource for all stakeholders. A near-term milestone is completion of a gap analysis of the materials degradation modes:

- (2012) Complete the Expanded Proactive Materials Degradation Analysis of the materials degradation modes.

The nine primary activities for this area are listed as follows, along with the key outcomes for each task:

1. Mechanisms of irradiation-assisted stress corrosion cracking (IASCC) in stainless steels provide understanding of the role of composition, history, and the environment on IASCC and model capability. This will be accomplished through a partnership with EPRI by performing tests in simulated water environments (both crack growth and tensile tests) in addition to complementary post-irradiation examination of irradiation effects on a series of service materials and model alloys. Combined, these single variable experiments will provide mechanistic understanding that can be used to identify key operational variables to mitigate or control IASCC, optimize inspection and maintenance schedules to the most susceptible materials/locations, and, in the long-range, design IASCC-resistant materials. The final results of this study (i.e., data and mechanistic understanding) will be delivered in a detailed report in 2014, with preliminary results provided at interim points.

2. High-fluence effects on RPV steels provides a critical evaluation of the risk for high-fluence embrittlement at high fluences; mechanistic understanding of the effects of fluence, flux, and composition on hardening; and a predictive capability for embrittlement of the RPV in extended service conditions. This research task will assess and acquire high-value service materials for testing and analysis (e.g., surveillance coupons from Ginna and a high-fluence capsule from the Palisades NPP); perform mechanical testing on both service materials and model alloys irradiated to conditions relevant to extended service; and provide detailed characterization of the materials, including atom probe tomography, neutron scattering, and other advanced techniques. These research tasks all support development of a predictive model for transition-temperature shifts for RPV steels under a variety of conditions. This tool can be used to predict RPV embrittlement over a variety of conditions key to irradiation-induced changes (e.g., time, temperature, composition, flux, and fluence) and extends the current tools for RPV management and regulation to extended-service conditions. This model will be delivered in 2015 in a detailed report, along with all supporting research data. In addition, the library of assembled materials will be available for examination and testing by other stakeholders.

3. Crack initiation in nickel-based alloys provides mechanistic understanding of precursor states on crack initiation to develop strategies for mitigation. This research task will assess and systematically characterize precursor states (e.g., damage from grinding, polishing, and installation) and their influence on crack-initiation in nickel-based alloys used as piping in NPPs. Research will include crack-initiation testing in simulated reactor water on a series of tensile specimens with controlled microstructures and damage levels. Several test systems have been constructed using a unique design to enable crack-initiation testing at a statistically significant level. These test results will be coupled with a detailed characterization analysis of precursor states to help identify cause-effect for crack initiation. This mechanistic information could provide key operational variables to mitigate or control stress corrosion cracking in these materials, optimize inspection and maintenance schedules to the most susceptible materials/locations, and potentially define stress-corrosion-cracking-resistant materials. The final results of this study (i.e., data and mechanistic understanding) will be delivered in a detailed report in 2016, with preliminary results provided at interim points.

4. High-fluence effects on IASCC of stainless steels provide evaluation of new factors at high fluence, first data for high fluence conditions, and validation of models and mechanisms. This task will build on knowledge from previous years and programs and examine the effects and magnitude of IASCC at very high fluences that will be expected during extended service, but is untested to date. Research will involve a detailed plan to obtain high-fluence specimens for IASCC testing from irradiation of as-received material to high fluence in a test reactor, obtaining high-fluence materials for sample manufacturing, or a combination of those two factors. In addition, both tests (i.e., crack growth and tensile tests) will be performed in simulated water environments in addition to complementary post-irradiation examination of irradiation effects. Results from this task can be used to investigate the potential for IASCC under extended service conditions, extend the mechanistic studies from other tasks in the LWRS Program, and be used to validate any predictive models at high fluence. The results of this effort will be delivered in a final report in the 2017 to 2021 timeframe and will include detailed experimental results and an evaluation of the effects of high fluence on IASCC susceptibility.

5. Evaluation of swelling effects in high-fluence core internals provides evaluation of risk for high-fluence core internal components to swelling and model capability. This task will provide detailed microstructural analysis of swelling in key samples and components (both model alloys and service materials), including transmission electron microscopy and volumetric measurements. These results will be used to develop and validate a phenomenological model of swelling under LWR conditions. This will be accomplished by extension of past models developed for fast reactor conditions. The data generated and mechanistic studies will be used identify key operational limits (if any) to minimize swelling concerns, optimize inspection and maintenance schedules to the most susceptible materials/locations, and, if necessary, qualify swelling-resistant materials for LWR service. The results of this task will be delivered in a final report in 2015 that will include both the experimental results and details of the predictive model for swelling. Full validation of the model will be completed and documented in the 2017 to 2021 timeframe.

6. Evaluation of irradiation-induced phase transformations in high-fluence core internals provides evaluation of risk for high-fluence core internal components to embrittlement due to phase transformations and model capability. This task will provide detailed microstructural analysis of phase transformation in key samples and components (both model alloys and service materials), including transmission electron microscopy, magnetic measurements, and hardness examinations. Mechanical testing to quantify any impacts on embrittlement also may be performed. These results will be used to develop and validate a phenomenological model of phase transformation under LWR conditions. This will be accomplished by use of computational thermodynamics and

extension of models for radiation-induced segregation. The generated data and mechanistic studies will be used to identify key operational limits (if any) to minimize phase transformation concerns, optimize inspection and maintenance schedules to the most susceptible materials/locations, and, if necessary, qualify radiation-tolerant materials for LWR service. The results of this task will be delivered in a final report in 2015 that will include both the experimental results and details of the predictive model for phase transformations. Full validation of the model will be completed and documented in the 2017 to 2021 timeframe.

7. Surrogate and attenuation effects on RPV steels provides mechanistic information on attenuation effects through RPV wall thickness; validation of high-flux irradiations for surveillance capsules; alternative monitoring concepts; and validation of models. This task will build on other RPV tasks and extend the mechanistic understanding of irradiation effects on RPV steels. Specifically, this task will evaluate dose-rate and composition effects for any replacement materials that could be used in surveillance programs by conducting targeted irradiation experiments and providing characterization of the resulting effects through mechanical testing and detailed analysis as described above. In addition, the effects of attenuation of neutron fluxes on embrittlement and damage through the wall thickness also will be examined using similar techniques. The results of these examinations can be used to assess the operational implications of high-fluence effects on RPV. Furthermore, the predictive capability developed in earlier tasks will be modified to address these effects. A final report will be delivered in the 2017 to 2021 timeframe and will detail the experimental results, discuss potential implications on operation, and present any revisions to the RPV model.

8. Environmental fatigue research provides mechanistic understanding of the key variables in environmental fatigue to help predict service-life of components affected by this mechanism. Environmentally assisted fatigue is a growing problem within LWR components and will grow more severe with extended service, even though there is not agreement on mechanisms or directions between regulators and industry. The objective of this task is to develop a model of environmentally assisted fatigue mechanisms to predict life for this mechanism. This will be supported by experimental studies to provide data for identification of mechanisms and key variables and provide valuable data for model validation. The experimental data will inform regulatory and operational decisions, while the model will provide a capability to extrapolate the severity of this mode of degradation to extended-life conditions. A final report will be delivered in the 2017 to 2021 timeframe, providing both the model of fatigue mechanisms and the supporting experimental data.

9. Techniques for NDE of key reactor metals provide new technologies to monitor material and component performance (e.g., evaluation of RPV embrittlement, in-situ testing of swelling, or crack initiation). This task will deliver an R&D plan in 2012 for sensor development to monitor reactor metal performance. An initial step in this R&D plan is to examine the key issues and available technologies. Key issues for consideration will include RPV embrittlement, RPV flaw detection and distribution, fatigue, environmental fatigue, swelling, and crack initiation. Expert panels will develop the R&D plan, ensuring broad input and discussion. In future years, sensor development will be performed with a demonstration of key prototypes by 2016. This ambitious date will require collaboration with other tasks within the LWRS Program and other programs and critical assessment and use of technologies from other industries. Validation and qualification of the sensors will be established and documented in the 2017 to 2021 timeframe.

Milestones to complete these tasks are as follows:

- Deliver mechanistic understanding for key materials and degradation modes, including the following:
  - (2014) Issue a final report on IASCC (data and mechanistic understanding).
  - (2015) Deliver the final model to predict RPV embrittlement over a variety of conditions for extended service (e.g., time, temperature, composition, flux, and fluence) together with all supporting research data.
  - (2016) Issue a final report covering the controlling mechanisms for cable insulation, implications for extended service conditions, and supporting experimental data.
  - (2016) Issue final report on crack initiation in nickel-based alloys for piping (data and mechanistic understanding).
- (2015) Deliver model capability for key core internal issues, including the following:
  - Issue a final report on the experimental results and details of the predictive model of swelling of core internal components.
  - Issue a final report on the experimental results and details of the predictive model for phase transformations of core internal components.
- (2016) Deliver prototype detection and monitoring tools for key material components, including cabling, concrete, RPV, and piping.
- (2017 to 2021) Deliver mechanistic understanding for the key materials and degradation modes, including the following:
  - Issue a final report on environmental fatigue (model and supporting date).
  - Issue a final report on RPV attenuation and surrogate material issues (experimental results for replacement materials, attenuation studies, potential implications on operation and surveillance, and revisions to the RPV model).
  - Issue a final report on high-fluence IASCC (detailed experimental results and an evaluation of the effects).
- (2017-2021) Issue a final report on the validation of modeling capabilities for swelling and phase transformations.
- (2017 to 2021) Deliver model capability for the key materials issues, including the following:
  - Develop a predictive model on IASCC (function of fluence and material properties).
  - Develop a predictive model on nickel-based cracking (statistical analysis of crack probability as a function of time and composition).
  - Develop additional modeling capabilities of RPV (substitute materials and attenuation and extending utility and accuracy).

- (2017 to 2021) Deliver validation data and use criteria for new detection and monitoring tools (technology transfer of NDE sensors).

2.3.2 Concrete

Figure 9 (source NRC) serves as a reminder that large areas of most NPPs have been constructed using concrete and there are some data on performance through the first 40 years of service. However, currently there is little or no data on long-term concrete performance in these plants. Long-term stability and performance of concrete structures within an NPP is a potential concern. As such, the objective of this task is to assess the long-term performance of concrete in nuclear applications. Research task evaluation and prioritization will be performed on an ongoing basis. Plans for research at EPRI and NRC will continue to be evaluated to confirm the complementary and cooperative nature of concrete research under the MAaD Pathway. In addition, the formation of an Extended Service Materials Working Group for concrete issues will provide a valuable resource for additional and diverse input. The two primary activities for this area are listed as follows, along with the key outcomes for each task:

1. Mechanisms of concrete degradation provide understanding of the role of composition, history, and the environment on concrete degradation; development of a concrete performance database; and support to partners in modeling activities, surveillance, and testing criteria. This task is being performed in cooperation with NRC, EPRI, and the Materials Aging Institute. The overall objective of the concrete task is to provide assurances that the NPP concrete structures will continue to meet their functional and performance requirements and maintain adequate structural margins during the current licensing period, as well as for continued service periods beyond the initial operating license period that may extend plant operation to 60, 80, or more years. In meeting this objective, several tasks where concrete-structures-related research is required have been identified: (1) compilation of material property data, including data on irradiation and high-temperature performance, which are currently sparse and where National Institute of Standards and Technology and other databases will be a key resource; (2) assessments of the current condition and estimates of the future condition of the structures (e.g., improved condition assessment methodologies and development of damage models and acceptance criteria for use in condition assessments); (3) improved constitutive models and analytical methods for use in determining nonlinear structural response (e.g., accident conditions); (4) nondestructive methods for thick, heavily reinforced concrete, and global inspections of the containment metallic pressure boundary; (5) data on application and performance (e.g., durability) of repair materials and techniques; and (6) utilization of the structural reliability theory incorporating uncertainties to address time-dependent changes to structures to assure minimum-accepted performance requirements are exceeded; to forecast ongoing component degradation for end-of-life estimations; and to apply probabilistic modeling of component performance to provide risk-based criteria to evaluate how aging affects structural capacity.

   Activities under the LWRS Program presently are being conducted under Tasks 1, 2, 4, and 6. Complementary activities are being conducted under an NRC program at Oak Ridge National Laboratory, addressing Task 2. EPRI has activities under Tasks 2, 3, and 4. Task 5 is being addressed by the Nuclear Energy Standards Coordination Collaborative headed by the National Institute for Standards and Technology.

   To support these activities, a detailed and populated database on concrete performance, with data for performance into the first life-extension period, high-temperature effects, and irradiation effects, will be delivered by 2016.

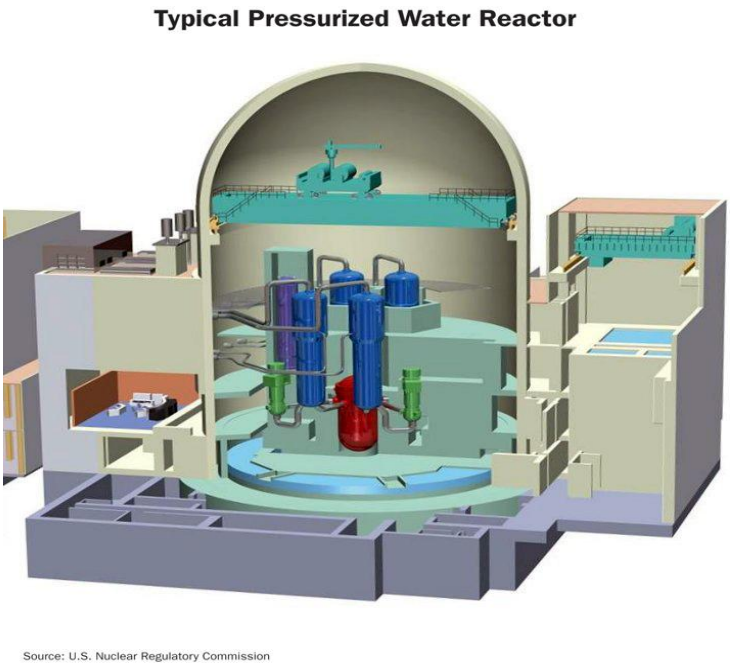

Figure 9. Cut-away of a typical pressurized water reactor, illustrating large volumes of concrete and the key role of concrete performance.

2. Techniques for NDE of concrete provide new technologies to monitor material and component performance. This task will deliver an R&D plan in 2012 for sensor development to monitor reactor metal performance. An initial step in this R&D plan is to examine the key issues and available technologies. Key issues for consideration can include new or adapted techniques for concrete surveillance. Specific areas of interest may include reinforcing steel condition, chemical composition, strength, or stress-state. Expert panels will develop the R&D plan, ensuring broad input and discussion. In future years, sensor development will be performed, with a demonstration of key prototypes by 2016. This ambitious date will require collaboration with other tasks within the LWRS Program and other programs and critical assessment and use of technologies from other industries. Validation and qualification of the sensors will be established and documented in the 2017 to 2021 timeframe.

Milestones that support these tasks include the following:

- (2016) Deliver a detailed database containing relevant and validated data for extended service, high-temperature effects, and irradiation effects on concrete performance.

- (2017 to 2021) Deliver validation data and use criteria for new detection and monitoring tools (technology transfer of NDE sensors).

2.3.3 Cabling

Cable aging is a concern that currently faces the operators of existing NPPs. The plant operators carry out periodic cable inspections using NDE techniques to measure degradation and determine when replacement is needed. Degradation of these cables is primarily caused by long-term exposure to high temperatures. Additionally, stretches of cables that have been buried underground are frequently exposed to groundwater. Wholesale replacement of cables would likely be a “show stopper” for plant operation beyond 60 years because of the cost and difficulty in replacement.

The two primary activities for cable aging research in the LWRS Program are as follows, along with the key outcomes for each task:

1. Mechanisms of cable degradation provide understanding of the role of composition, history, and the environment on cable insulation degradation; understanding of accelerated testing limitations; and support to partners in modeling activities, surveillance, and testing criteria. This task will provide experimental characterization of key forms of cable and cable insulation in a cooperative effort with NRC and EPRI. Tests will include evaluations of cable integrity following exposure to elevated temperature, humidity, and/or ionizing irradiation. This experimental data will be used to evaluate mechanisms of cable aging and determine the validity or limitations of accelerated aging protocols. The experimental data and mechanistic studies can be used to help identify key operational variables related to cable aging, optimize inspection and maintenance schedules to the most susceptible materials/locations, and, in the long-range, design tolerant materials. A final report will be issued in 2016, detailing the controlling mechanisms, implications for extended service conditions, and the supporting experimental data.

2. Techniques for NDE of cables provide new technologies to monitor material and component performance. This task will deliver an R&D plan in 2012 for sensor development to monitor reactor metal performance. An initial step in this R&D plan is to examine the key issues and available technologies. Key issues for consideration will include cable integrity and insulation integrity and ductility. Expert panels will develop the R&D plan, ensuring broad input and discussion. In future years, sensor development will be performed with a demonstration of key prototypes by 2016. This ambitious date will require collaboration with other tasks within the LWRS Program and other programs and critical assessment and use of technologies from other industries. Validation and qualification of the sensors will be established and documented in the 2017 to 2021 timeframe.

Milestones that support cabling include the following:

- (2016) Deliver prototype detection and monitoring tools for key material components, including cabling, concrete, RPV, and piping.

- (2017 to 2021) Deliver validation data and use criteria for new detection and monitoring tools (technology transfer of NDE sensors).

2.3.4 Buried Piping

Maintaining the many miles of buried piping at an NPP is an area of concern when evaluating the feasibility of extended NPP operations. While much of the buried piping is associated with either the secondary side of the plant or other non-safety-related cooling systems, some buried piping serves a direct safety function. Maintaining the integrity of the buried piping in these systems is necessary to ensure the systems continue to perform their intended functions under extended plant service periods. Today, industry and regulators already are investing considerable effort into understanding degradation issues, monitoring techniques, and alternative technologies. Given the breadth and depth of ongoing research elsewhere, the LWRS Program currently does not have any active tasks in this area. However, the LWRS Program will continue to evaluate this area for potential gaps and needs relative to extended service.

2.3.5 Mitigation Technologies

Mitigation technologies include weld repair, post-irradiation annealing, and water chemistry modifications. Welding is widely used for component repair. Weld-repair techniques must be resistant to long-term degradation mechanisms. Extended lifetimes and increased repair frequency welds must be resistant to corrosion, irradiation, and other forms of degradation. The purpose of this research area is to develop new welding techniques, weld analysis, and weld repair. A critical assessment of the most advanced methods and their viability for LWR repair weld applications is needed. Post-irradiation annealing may be a means of reducing irradiation-induced hardening in RPV. It also may be useful for mitigation of radiation-induced degradation of core internals (Figure 10). Water chemistry modification is another mitigation technology that warrants evaluation.

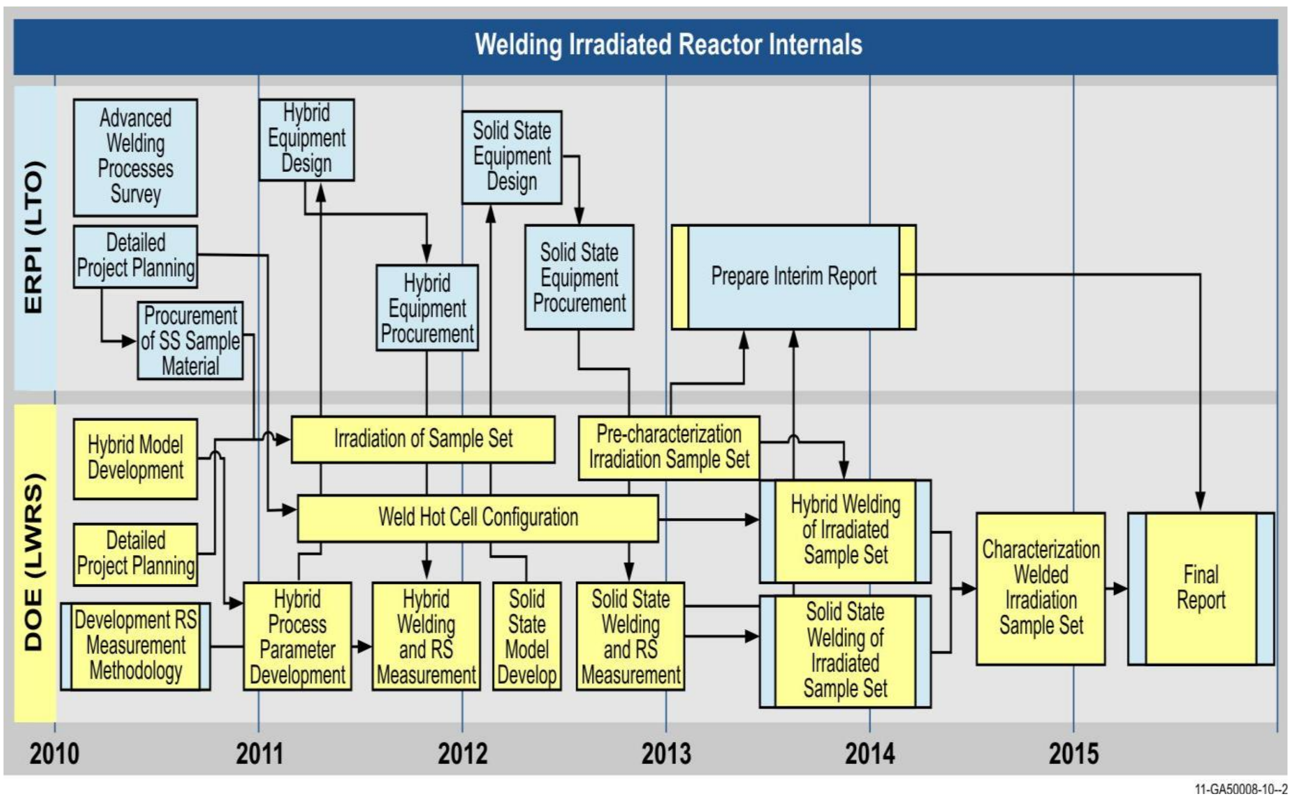

Figure 10. Process flow outline of cooperative research and development efforts between the Department of Energy and the Electric Power Research Institute.

The three primary activities in the LWRS Program's supported mitigation technologies are listed as follows, along with the key outcomes for each task:

1. Weld repair provides understanding and modeling of helium effects under welding, validation of residual stress models currently under development, and deployment of advanced repair welding techniques. This task for developing and demonstrating advanced welding technology for repair applications is being performed collaboratively with EPRI (highlighted in Figure 10). Research includes mechanistic understanding of helium effects in weldments. This modeling task is supported by characterization of model alloys before and after irradiation and welding. This model can be used by stakeholders to further improve best practices for repair welding for both existing technology and advanced technology. In addition, this task will provide validation of residual stress models under development using advanced characterization techniques such as neutron scattering.

Residual stress models also will improve best practices for weldments of NPPs today and under extended service conditions. These tools could be expanded to include other industry practices such as peening. Finally, advanced welding techniques (such as friction-stir welding, laser welding, and hybrid techniques) will be developed and demonstrated on relevant materials (model and service alloys). Characterization of the weldments and qualification testing will be an essential step. This work will culminate in a final report in 2016, detailing mechanistic studies, supporting data, and development of the advanced welding techniques.

2. The thermal annealing task provides critical assessment of thermal annealing as a mitigation technology for RPV and core internal embrittlement and research to support deployment of thermal annealing technology. This task will build on other RPV tasks and extend the mechanistic understanding of irradiation effects on RPV steels to provide an alternative mitigation strategy. This task will provide experimental and theoretical support to resolving technical issues required to implement this strategy. Specifically, this task will provide experimental testing and analysis related to the effects of re-irradiation on annealed RPV materials. The same materials and test techniques used in other tasks will be applied here, extending the value of this work. Successful completion of this effort will provide the data and theoretical understanding to support implementation of this alternative mitigation technology. The LWRS Program currently does not have any activity in this area, but may continue this work if additional funding is available.

3. Advanced replacement alloys provide new alloys for use in LWR application that provide greater margins and performance and support to industry partners in their programs. This task will explore and develop new alloys in collaboration with the EPRI Advanced Radiation-Resistant Materials Program. Specifically, the LWRS Program will participate in expert panel groups to develop a comprehensive R&D plan for these advanced alloys. Future work will include alloy development, alloy optimization, fabrication of new alloys, and evaluation of their performance under LWR-relevant conditions (e.g., mechanical testing, corrosion testing, and irradiation performance among others) and, ultimately, validation of these new alloys. Based on past experience in alloy development, an optimized alloy (composition and processing details) that has been demonstrated in relevant service conditions can be delivered to industry by 2020. A full code-qualification case will be delivered in subsequent years, depending on the exact alloy needs.

Milestones that support mitigation technologies include the following:

- (2016) Issue a final report on the technology transfer of advanced weld repair techniques (mechanistic studies, model development, supporting data, and development).

- (2017 to 2021) Deliver validated advanced replacement alloys (demonstrated improved performance in service-relevant conditions).

- (2022 to 2026) Deliver full code-qualified package for advanced replacement alloys (data and testing).

2.3.6 Integrated Research Activities

Access to service materials from active or decommissioned NPPs provides an invaluable access to materials for which there is limited operational data or experience to inform relicensing decisions and, in coordination with other materials tasks, an assessment of current degradation models to further develop the scientific basis for understanding and predicting long-term environmental degradation behavior.

The Zion Harvesting Project, in cooperation with Zion Solutions, is coordinating the selective procurement of materials, structures, components, and other items of interest to the LWRS Program, ERPI, and NRC from the decommissioned Zion 1 and Zion 2 NPP, as well as possible access to perform limited, onsite testing of certain structures and components. Materials of high interest include low-voltage cabling, concrete core samples, and through-wall thickness sections of RPV.

The Constellation Pilot Project is a joint venture between the LWRS Program, EPRI, and the Constellation Energy Nuclear Group. The project utilizes two of Constellation's nuclear stations, R. E. Ginna and Nine Mile Point 1, for research opportunities to support future licensing of NPPs. Specific areas of joint research have included development of a concrete inspection guideline, installation of equipment for monitoring containment rebar and concrete strain, and additional analysis of RPV surveillance coupons. Opportunities for additional and continued collaboration will be explored in coming years. A document describing containment inspection guidelines for extended service will be developed and delivered collaboratively in 2013.

The milestone that supports this task is as follows:

- (2013) Complete Containment Inspection Guidelines for extended-service conditions through partnership with Constellation Energy and EPRI.

2.4 Research and Development Cooperation

Effective and efficient coordination will require contributions from many different institutions, including input from EPRI's parallel activities in the Long-Term Operation Program's strategic action plan[i] and NRC's subsequent license renewal activities. In addition to contributions from EPRI and NRC, participation from utilities and reactor vendors will be required. Given the breadth of the research needs and directions, all technical expertise and research facilities must be employed to establish the technical basis in this R&D area for extended operations of the current NPP fleet.

The activities and results of other research efforts in the past and present must be considered on a continuous basis. Collaborations with other research efforts may provide a significant increase in cost sharing of research and may speed up research for both partners. This approach also reduces unnecessary overlap and duplicate work. Many possible avenues for collaboration exist, including the following:

- **EPRI:** Considerable research efforts on a broad spectrum of nuclear reactor materials issues that currently are under way to provide a solid foundation of data, experiences, and knowledge. R&D cooperation on selected material's R&D activities is reflected in the LWRS Program/Long-Term Operation Program Joint R&D Plan (see footnote f).

- **NRC:** Broad research efforts of NRC should be considered carefully during task selection and implementation. In addition, cooperative efforts through conduct of the Extended Proactive Materials Degradation Assessment and formation of an Extended Service Materials Working Group will provide a valuable resource for additional and diverse input.

- **Extended Service Materials Working Group:** A joint working group to facilitate discussion and cooperation between the EPRI, NRC, and DOE projects has been formed. The Extended Service Materials Working Group meets at least once per year to discuss recent technical progress in key research areas, topics of common interest, and opportunities for additional cooperation. Discussions range from high-level coordination to detailed technical discussions, allowing for

[i] This document is an internal EPRI document and is not publicly available.

detailed coordination. These meetings have been valuable to date and will be continued in future years.

- **Boiling Water Reactor and Pressurized Water Reactor Owners Groups:** These groups provide a forum for understanding key materials degradation issues for each type of reactor.

- **Materials Aging Institute:** The Materials Aging Institute is dedicated to understanding and modeling materials degradation; a specific example might be the issue of environmental-assisted cracking. The collaborative interface with the Materials Aging Institute is coordinated through EPRI, which is a member of the Materials Aging Institute.

- **Programs in other industries and sectors:** Research in other fields may be applicable in the LWRS Program. For example, efforts in other fields (e.g., the Advanced Cement-Based Materials Program) may provide a valuable starting point for developing a database on concrete performance for structures.

- **Nuclear facilities:** Examining materials from nuclear facilities provides a unique opportunity to evaluate degradation modes in relevant service materials. For example, the primary focus of the Constellation Pilot Project centers on material aging effects (Figure 11). This is a significant project commitment. However, degradation of concrete, buried piping, and cabling are not unique to nuclear reactors; other nuclear facilities (e.g., hot cells and reprocessing facilities) may be a key resource for understanding long-term aging of these materials and systems.

Constellation Pilot Project Activity	LWRS Tasks Supported
Ginna Baffle Bolts	Irradiated-assisted stress corrosion cracking, swelling, phase transformations, and repair welding
Ginna RPV Samples	Reactor pressure vessel embrittlement, thermal annealing, and representative materials
Nine Mile Point Unit 1 RPV Samples	Reactor pressure vessel embrittlement, thermal annealing, and representative materials
Nine Mile Point Unit 1 Top Guide Samples	Irradiated-assisted stress corrosion cracking and repair welding
Concrete Monitoring	Concrete degradation

11-GA50008-10-3

Figure 11. Constellation pilot project activities and related research and development tasks in the Materials Aging and Degradation Pathway.

- **Other nuclear materials programs:** In addition, research within fast reactor and fusion reactor programs may provide key insights into high-fluence effects on materials because the mechanisms and models of degradation for fast reactor applications can be modified and provide a starting and proven framework for degradation issues in this effort. This research element includes (1) international collaboration to conduct coordinated research with international institutions (e.g., the Materials Aging Institute) to provide more collaboration and cost sharing, (2) coordinated irradiation experiments to provide a single integrated effort for irradiation experiments, (3) advanced characterization tools to increase materials testing capability, improve quality, and develop new methods for materials testing, and (4) additional research tasks based on the results and assessments of current research activities.

Participation and collaboration with all of these partners may yield new opportunities for collaboration. Cost sharing is being pursued for each task. Cost sharing can take many forms, including direct sharing of expenses, shared materials (or rescued specimens), coordinated plans, and complementary testing.

2.5 Research and Development Products and Schedule

The main products from the MAaD Pathway are (1) mechanistic understanding of key degradation modes, (2) lifetime performance models, (3) advanced mitigation strategies, and (4) advanced replacement materials.

The implementation schedule is structured to support the following high-level milestones:

- (2012) Complete the Expanded Proactive Materials Degradation Analysis gap analysis of the materials degradation modes.
- (2013) Complete Containment Inspection Guidelines for extended-service conditions through partnership with Constellation Energy and EPRI.
- Deliver mechanistic understanding for key materials and degradation modes, including the following:
  - (2014) Issue a final report on IASCC (data and mechanistic understanding).
  - (2015) Deliver the final model to predict RPV embrittlement over a variety of conditions for extended service (e.g., time, temperature, composition, flux, and fluence) together with all supporting research data.
  - (2016) Issue a final report covering the controlling mechanisms for cable insulation, implications for extended service conditions, and supporting experimental data.
  - (2016) Issue final report on crack initiation in nickel-based alloys for piping (data and mechanistic understanding).
- (2015) Deliver model capability for key core internal issues, including the following:
  - Issue a final report on the experimental results and details of the predictive model of swelling of core internal components.
  - Issue a final report on the experimental results and details of the predictive model for phase transformations of core internal components.
- (2016) Deliver a detailed database containing relevant and validated data for extended service, high-temperature effects, and irradiation effects on concrete performance.
- (2016) Deliver prototype detection and monitoring tools for key material components, including cabling, concrete, RPV, and piping.

- (2016) Issue a final report on the technology transfer of advanced weld repair techniques (mechanistic studies, model development, supporting data, and development).

- (2017 to 2021) Deliver mechanistic understanding for the key materials and degradation modes, including the following:

  – Issue a final report on environmental fatigue (model and supporting data).

  – Issue a final report on RPV attenuation and surrogate material issues (experimental results for replacement materials, attenuation studies, potential implications on operation and surveillance, and revisions to the RPV model).

  – Issue a final report on high-fluence IASCC (detailed experimental results and an evaluation of the effects).

- (2017 to 2021) Issue a final report on the validation of modeling capabilities for swelling and phase transformations.

- (2017 to 2021) Deliver model capability for the key materials issues, including the following:

  – Develop a predictive model on IASCC (function of fluence and material properties).

  – Develop a predictive model on nickel-based cracking (statistical analysis of crack probability as a function of time and composition).

  – Develop additional modeling capabilities of RPV (substitute materials and attenuation and extending utility and accuracy).

- (2017 to 2021) Deliver validation data and use criteria for new detection and monitoring tools (technology transfer of NDE sensors).

- (2017 to 2021) Deliver validated advanced replacement alloys (demonstrated improved performance in service-relevant conditions).

- (2022 to 2026) Deliver full code-qualified package for advanced replacement alloys (data and testing).

3. ADVANCED LIGHT WATER REACTOR NUCLEAR FUELS

3.1 Background

Nuclear fuel performance is a significant driver of NPP operational performance, safety, operating economics, and waste disposal requirements (Figure 12 shows a typical pressurized water fuel assembly). Over the past two decades, the nuclear power industry has improved plant capacity factors with incremental improvements achieved in fuel reliability and use or burnup. However, these upgrades are reaching their maximum achievable impact within the constraints of the existing fuel designs, materials, licensing, and enrichment limits. The development, testing, and licensing cycle for new fuel designs is typically long (i.e., about 10 years from conception through utility acceptance).

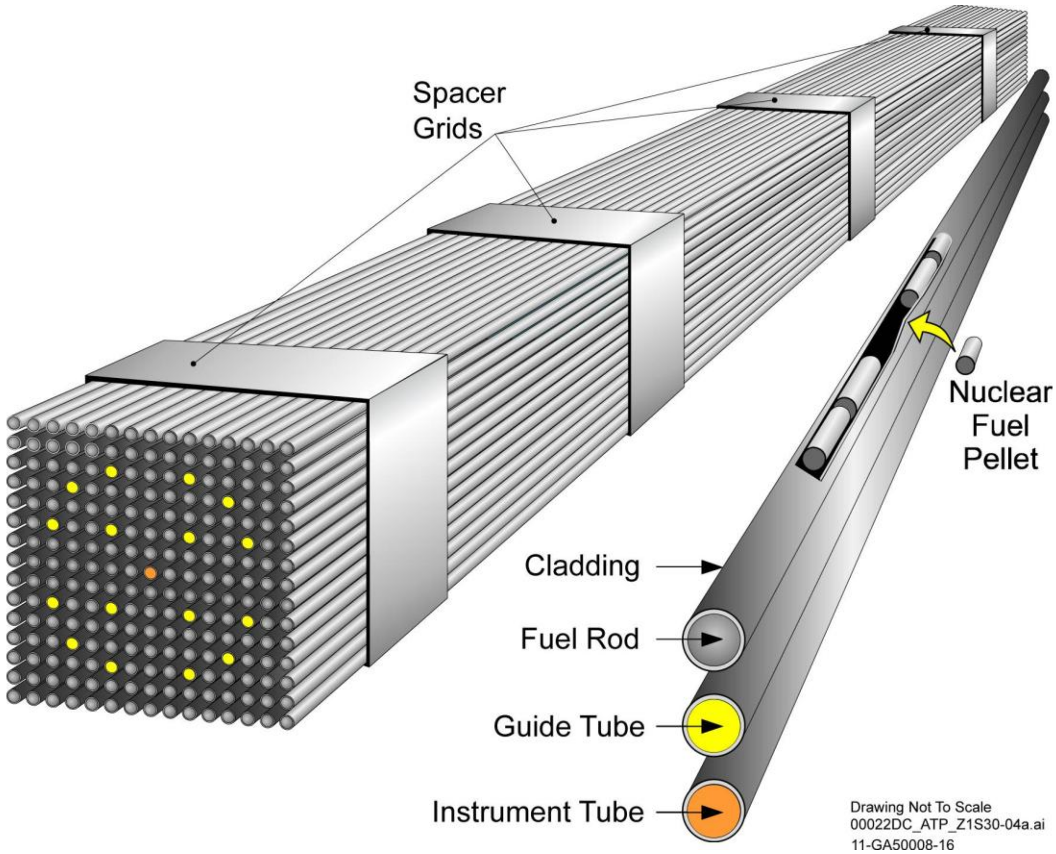

Figure 12. A typical pressurized water reactor fuel assembly.

Continued development of high-performance nuclear fuels through fundamental research is focused on enabling NPP operators to extend plant operating cycles and enhance the safety margins, performance, and productivity of existing NPPs. However, to achieve significant safety margin improvements while improving operating margins and economics, significant steps beyond incremental improvements in the current generation of nuclear fuel are required. Fundamental changes are required in the areas of nuclear fuel composition, cladding integrity, and the fuel/cladding interaction to reach the next levels of fuel performance. The technological improvements being developed in the Advanced LWR Nuclear Fuels Pathway center on development of revolutionary cladding materials supported by enhanced fuel mechanical designs and alternate fuel compositions. If realized, the changes would have substantial beneficial improvements in NPP economics, operation, and safety.

3.2 Research and Development Purpose and Goals

The Advanced LWR Nuclear Fuels Pathway performs research on improving reactor safety, increasing fuel economics, producing advanced cladding designs, and developing enhanced computational models to predict fuel performance. Strategic R&D goals are directed at improving the scientific knowledge basis for understanding and predicting fundamental nuclear fuel and cladding performance in NPPs, and applying the information to development of high-performance, high-burnup fuels with improved safety, cladding, integrity, and nuclear fuel cycle economics. This research is further designed to demonstrate each of the technology advancements while satisfying all safety and regulatory limits through rigorous testing and analysis. Silicon carbide (SiC) ceramic matrix composite (CMC) materials have been chosen as the cladding material for fuels under investigation in this pathway because of their potential for significant improvements in performance. The technology selected for development and deployment intentionally was chosen to minimize developmental risk. The research schedule derived from the technology development assumptions is optimistic and could change if significant development issues arise.

There are other nuclear fuel research programs that focus on a broader range of LWR fuel technologies and topics. Many different nuclear fuel materials and cladding concepts are being investigated. Studies related to reactor performance; fuel cycles studies, including storage issues; and economics of advanced nuclear fuels also are being performed. DOE activities that benefit the LWRS Advanced LWR Nuclear Fuels Pathway are described in Section 3.4.

DOE (through the Advanced LWR Nuclear Fuels Pathway) is involved in this R&D activity for the following reasons:

- This development of a fundamentally new fuel is technically high risk and long term compared to incremental development of existing technology. Federal efforts are essential to stimulate and encourage industry efforts and to address the longer-term, high-risk research that industry is not equipped to address.

- Development of SiC CMC cladding requires technology that does not exist within the nuclear industry. The LWRS Program's Advanced LWR Nuclear Fuels Pathway is drawing heavily on the unique cooperation of INL's National and Homeland Security organization, where CMC materials are extensively developed for armor and structures.

- The application of SiC CMC materials to nuclear fuel requires significant scientific understanding, testing, and technology integration. This integrating effort requires significant long-term R&D suited to the national laboratory mission.

- This advanced fuel technology has the potential to address national interests by directly increasing safety in the current generation of NPPs. Improved economics and reliability for NPPs allow the existing units to remain online and contribute to price stability and low carbon power generation.

- The DOE laboratory infrastructure is being used to rapidly develop the technology. This pathway is using multiple laboratories, test reactors, and universities to quickly and efficiently develop unique advanced fuel cladding.

- The nuclear fuel vendors are very conservative when introducing new fuel technology. The extreme need for nuclear fuel reliability makes introducing any new technology a significant risk to a nuclear fuel vendor. This is coupled with the high cost for implementation of a new fuel technology, discouraging the vendors from introducing new, unproven technologies.

- This technology will improve the safety and economics of the national and worldwide NPP fleets and advanced reactor concepts.

3.3 Pathway Research and Development Areas

The LWRS Program's Advanced LWR Nuclear Fuels Pathway is separated into three R&D tasks: (1) SiC CMC designs and concepts, (2) mechanistic understanding of fuel behavior, and (3) advanced tools. These tasks were selected to balance development of new knowledge, verify developed knowledge, and create new advanced fuel technology. The scope of the pathway includes all aspects important to fuel design and performance, including fuel design, exposure effects, and cladding material performance and development.

3.3.1 Silicon Carbide Ceramic Matrix Composite Designs and Concepts

The purpose of this task is to increase the understanding of advanced LWR fuel design concepts and apply this understanding to create safer and more economic nuclear fuel. This development centers on the use of new cladding materials (Figure 13) to increase safety margins, fuel lifetimes, and expand the allowable fuel performance envelope. The advanced cladding material (SiC CMC) has the potential to maintain strength and resist chemical reactions at very high temperatures. These improvements will allow fuel performance-related plant operating limits to be optimized in areas such as operating temperatures, power densities, power ramp rates, and coolant chemistry. Accomplishing these goals will lead to increased operating safety margins and improved economic benefits.

Figure 13. Silicon carbide clad test rodlets.

The LWRS Program's Advanced LWR Nuclear Fuels Pathway is seeking to demonstrate the advanced LWR SiC fuel cladding. The demonstration will show that the technology is capable of being developed into a commercial nuclear fuel. The basic nuclear performance, fabrication technologies, and an understanding of the data needed to license the fuel will be determined.

To maximize the understanding of advanced nuclear fuel and demonstrate the performance of the developed fuel, an extensive reactor test program is being developed. The reactor test program will perform increasingly complex reactor tests in defining the performance of the advanced nuclear fuel.

Initial tests on a prototype of an all-ceramic system are being performed at the Oak Ridge National Laboratory High-Flux Isotope Reactor. These tests are essentially static and demonstrate basic SiC CMC performance. Further tests are being planned for the INL Advanced Test Reactor. Testing will start using unfueled samples to create initial understanding. Further fueled tests will define how the nuclear fuel cladding responds to steady-state and operationally transient conditions. Later tests at a national laboratory (e.g., the Advanced Test Reactor or High-Flux Isotope Reactor) or the Halden Test Reactor in Norway will expand the known operating envelop to severe transient and accident performance. These tests will be used to benchmark the computational nuclear fuel models created in the mechanistic understanding of fuel behavior activity.

Milestones that support the SiC CMC designs and concepts include the following:

- (2012) Complete the initial characterization of the SiC CMC clad fuel performance to allow design activities. Characterization will allow an understanding of what technology is needed to meet the performance requirements.

- (2013) Complete an analysis to support fueled SiC CMC matrix fuels in-pile testing to demonstrate practical operation. Demonstration of advanced cladding performance with simulated nuclear fuel heating.

- (2014) Conduct transient testing of SiC CMC cladding with simulated nuclear fuel heating to define an operating envelope in advance of in-pile testing.

- (2015) Perform accident scenario and reactivity insertion tests with simulated nuclear fuel heating to assess performance and provide data for verification and validation.

- (2015) Perform in-pile testing of extended-length SiC CMC cladding to demonstrate in-reactor performance of extended length rods.

- (2016) Perform in-pile testing of rods at higher exposure limits to demonstrate long-term performance of SiC CMC cladding.

- (2016) Begin an evaluation of vendor-specific nuclear fuel rod features to establish critical operating limits for advanced commercial fuel designs.

3.3.2 Mechanistic Understanding of Fuel Behavior

This task area includes the testing and modeling of specific aspects of LWR fuel, cladding, and coolant behavior. Examples include pellet cladding interaction, fission gas release, coolant chemistry effects on corrosion, and crud (oxide) formation. Improved understanding of fuel behavior can be used in fuel design, licensing, and performance prediction.

An improved fundamental understanding of phenomena that impose limitations on fuel performance will allow fuel designers, fabricators, plant chemists, and code developers to optimize the performance of current fuels and the designs of advanced fuel concepts. A life-cycle concept will be applied so that optimization applies to fabrication, in-reactor use, and storage after removal from the reactor. Fundamental mechanistic models will provide a foundation for supporting the LWRS Program's strategic objectives in developing advanced fuels. The following models will be included in this task: (1) fuel mechanical property change model as a function of exposure, (2) pellet cladding interaction model development, and (3) mesoscale models of microstructure fuel behavior. Fuel modeling depends on the DOE-NE sponsored work (in the Nuclear Energy Advanced Modeling and Simulation Program and the Fuel Cycle R&D Program) on the BISON[j] (implicit simulation of nuclear fuel) fuel performance code (Figure 14).

The results from the BISON code will allow prediction of fuel performance under a variety conditions. The modeling will allow fuel performance predictions under conditions that are not experimentally demonstrated. Advanced modeling also will allow prediction of nuclear fuel performance in advance of complex experiments, maximizing the benefit of the experimental work.

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[j] "Three dimensional coupled simulation of thermomechanics, heat, and oxygen diffusion in UO2 nuclear fuel rods," Chris Newman, Glen Hansen, Derek Gaston, *Journal of Nuclear Materials* 392 (2009) 6–15.

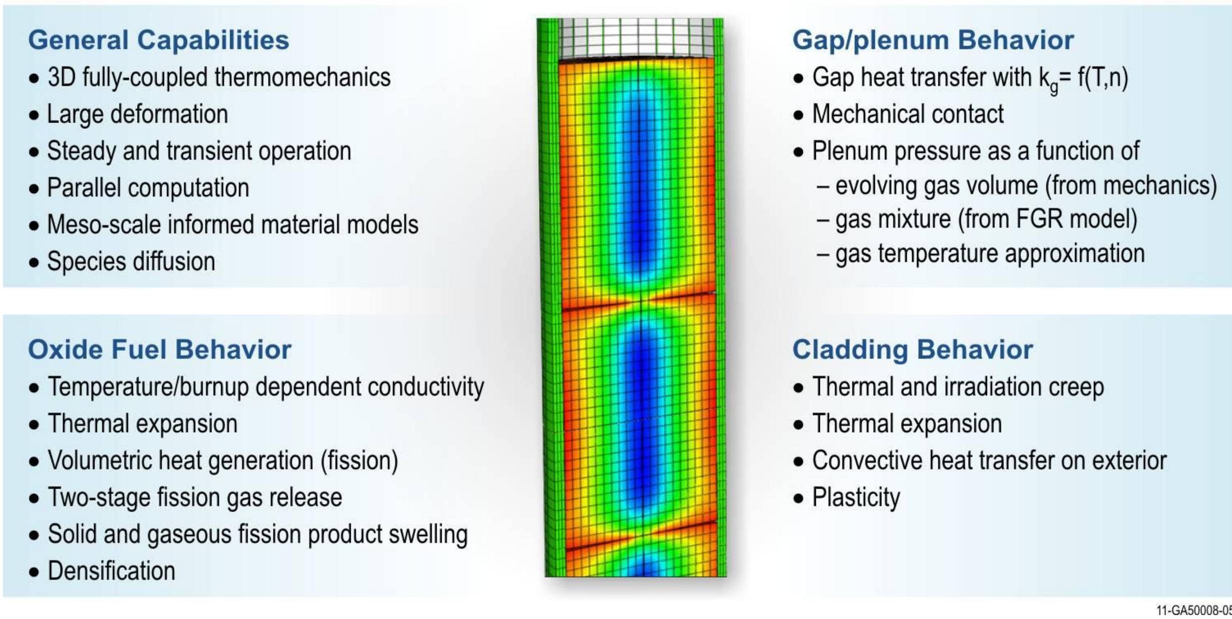

Figure 14. BISON nuclear fuel performance code features.

Milestones that support the mechanistic understanding of fuel behavior activity include the following:

- (2013) Predict fuel interaction with cladding to demonstrate adequate performance for operating conditions using advanced fuel models of SiC CMC cladding.

- (2014) Deliver a computational model of an advanced SiC CMC fuel system to predict performance during accident scenarios in advance of in-pile demonstration tests.

3.3.3 Advanced Tools

This task area uses increased understanding of specific fuel performance phenomena that will be integrated into encompassing fuel performance advanced tools. These advanced tools should help minimize the time required for materials development and fuel qualification. The following activities will be included in this task: (1) engineering design and safety analysis tool, (2) mechanical models of composite cladding, (3) design studies of advanced silicon carbide cladding, and (4) experiments to verify design and safety margin calculation tools.

Advanced designs are being developed under this task area. The needed technical knowledge to establish a licensing basis is developed here. The basis for the NRC licensing requirements and how they apply to advanced SiC CMC cladding is evaluated here. Work to solve current and anticipated technical problems are addressed here. The use of metallic liners to overcome the near-term problem of hermetic sealing, pellet and clad chemical interactions, and reliable end-plug sealing was performed in this task. Stress–to-strain performance curves, fatigue strength, and chemical reactions will be developed to support mechanical design activities. Advanced measurements to support SiC CMC cladding are being developed in this task area. The measurement will provide both scientific information and the necessary quality assurance measurements. A micro-tomographic image of the current prototype test rodlet is shown in Figure 15.

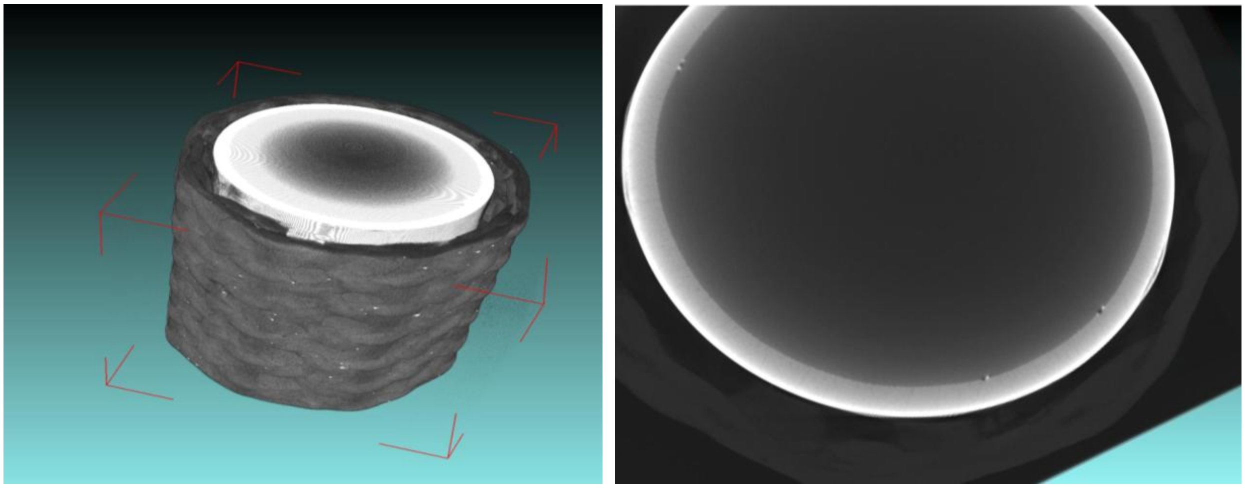

Figure 15. Micro-tomographic image of silicon carbide ceramic matrix composite test rodlet, showing the zirconium liner and silicon carbide ceramic matrix composite.

Milestones that support the advanced tools activity include the following:

- (2012) Issue a fuel development plan for SiC CMC nuclear fuel systems, including technology challenges, development schedule, and approximate costs for implementation.
- (2012) Complete an SiC CMC material technology tradeoff study on advanced LWR fuels cladding material to guide program development.
- (2013) Fabricate a second generation of advanced SiC CMC cladding that incorporates high-performance features.
- (2014) Fabricate extended-length fuel cladding that represents commercial nuclear fuel rods to demonstrate economic and technical practicality.
- (2014) Issue a report on licensing requirements and research program requirements to guide transfer to industrial development.
- (2016) Begin an evaluation of vendor-specific nuclear fuel rod features to establish critical operating limits for advanced commercial fuel designs.

3.4 Research and Development Cooperation

The final industry-supplied nuclear fuel will have to come from a combination of national laboratory research, nuclear fuel vendor development, the vendor licensing program, and NPP operator requirements. To achieve this combined development, it is critical that the technology be adopted and developed into unique nuclear fuel designs by the nuclear fuel vendors to suit NPP operator requirements. The vendors will, by necessity, lead the transfer of technology into unique nuclear fuel products. The direct involvement of the vendors will ensure successful nuclear fuel products are developed. The requirement for commercially successful fuel also will ensure the utility requirements are addressed in the development of advanced nuclear fuel products. The leading role of the vendors will grow as the program continues to advance nuclear fuel technology and indicate success of the program.

Since the initial decision to pursue SiC cladding, the Advanced LWR Nuclear Fuels Pathway has engaged EPRI as a research partner. Both of EPRI's Advanced Fuels and Fuel Reliability groups have been involved directly in the program. The Advanced Fuels group supports the program as part of the program guidance group with Oak Ridge National Laboratory. The Advanced Fuels group also is supporting the LWRS Program with code support, experimental facilities, and independent fuel behavior research. This interaction has led to EPRI requesting that the LWRS Program directly support an EPRI research task on SiC CMC boiling water reactor fuel channels. The goal is to demonstrate the potential for low bow SiC fuel channels. In turn, the DOE laboratory will receive a contract to produce prototypes and test samples. Further, the LWRS Program will gain fundamental SiC fuel swelling models and knowledge.

The Advanced LWR Nuclear Fuels Pathway leads an industry phone call with participants drawn from industry (e.g., TVA, Edison Welding Institute, and Ceramic Tubular Products), nuclear fuel vendors (e.g., Westinghouse and General Atomics), material suppliers (e.g., HITCO and Saint-Gobain), national laboratories (INL and Oak Ridge National Laboratory), and universities (e.g., Massachusetts Institute of Technology). The conference call has lead to greater communication and understanding within the nuclear SiC community.

The Advanced LWR Nuclear Fuels Pathway is sponsoring an industry engagement request for proposal in Fiscal Year 2012. This request for proposal centers on developing industry experience and capabilities related to ceramic cladding to end plug joining. The work will help overcome a significant technical challenge facing the development of mature SiC CMC cladding. The current technology used in ceramic material joining has not been successful in LWR environments.

Westinghouse Electric Company has entered into a nondisclosure agreement with INL/Battelle Energy Alliance, LLC that should lead to cooperative R&D agreements on specific research tasks. Currently, INL is receiving commercial zirconium cladding research results. In the future, Westinghouse will supply uranium dioxide fuel pellets and access to testing and irradiation facilities. These commitments will greatly advance the program. The LWRS Program provides irradiation facilities, materials, and research results.

GE-Hitachi Nuclear Energy has created a DOE-sponsored, advanced LWR nuclear material white paper. The white paper[k] includes the recommendation to develop SiC CMC materials for nuclear fuel cladding with advanced fuel forms. This suggestion led to direct talks on cooperative work.

Industry is working on manufacturing issues of a specific technology related to producing quality functional components that can be used in a commercial reactor. Industry is required to focus on near-term proof of concepts that can lead directly to licensed commercial products. DOE's research is focused on the needed science-based knowledge to confidently understand, design, predict performance, and license advanced fuel. In the case of the LWRS Program, advanced designs using unique technologies are being developed. The LWRS Program provides the scientific understanding to extrapolate a successful demonstration to eventual commercial applications.

These interactions are models for industry interaction going forward. The Advanced LWR Nuclear Fuels Pathway will provide infrastructure for testing and advanced technology to leverage activities by industry partners. The planned near-term results and direct testing programs provide significant value to industry.

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[k] NEDO-33670, *Assessment of Advanced Material Options for BWR Fuel*, GE Hitachi Nuclear Energy for DOE, Revision 0, August 2011.

It also should be noted that advanced nuclear fuel development is not restricted to the LWRS Program. The Advanced LWR Nuclear Fuels Pathway is working in conjunction with other nuclear fuel programs. Direct cooperation with the DOE Fuel Cycle R&D Program is ongoing. The Fuel Cycle R&D program investigates additional fuel and cladding options, and performs evaluations of fuel cycle issues related to economics, fabrication, recycling, and storage of advanced fuel options. The LWRS Program has benefited from fuel cycle R&D industry meetings and nuclear fuel technology separate from the advanced cladding being developed by the LWRS Program. This interaction and cooperation will continue to grow as samples are tested and work to integrate an advanced fuel cladding with an advanced nuclear fuel occurs. Principal investigators are sharing work packages and attend meetings for both programs. Specific tasks for both programs are being coordinated to avoid overlap, but also to promote progress on required tasks.

The Advanced LWR Nuclear Fuels Pathway also is gaining benefit from the Nuclear Energy Advanced Modeling and Simulation Program in development of advanced nuclear fuel computer models. Currently, research for the LWRS Program and the Nuclear Energy Advanced Modeling and Simulation Program use common staff. Close coordination and cooperation among the three fuels-related R&D activities ensures information sharing and avoids duplication of effort.

3.5 Research and Development Products and Schedule

The goal of this pathway is to develop an advanced nuclear fuel with significantly improved performance characteristics relative to current LWR fuel. The focus is on SiC CMC clad fuels, which have the potential to provide the desired significant improvements in performance.

The implementation schedule is structured to support the following high-level milestones:

- (2012) Issue a fuel development plan for SiC CMC nuclear fuel systems, including technology challenges, development schedule, and approximate costs for implementation.

- (2012) Complete an SiC CMC material technology tradeoff study on advanced LWR fuels cladding material to guide program development.

- (2012) Complete the initial characterization of SiC CMC clad fuel performance to allow design activities. Characterization will allow an understanding of what technology is needed to meet the performance requirements.

- (2013) Complete an analysis to support fueled SiC CMC matrix fuels in-pile testing to demonstrate practical operation. Demonstration of advanced cladding performance with simulated nuclear fuel heating.

- (2013) Fabricate a second generation of advanced SiC CMC cladding that incorporates high-performance features.

- (2013) Predict fuel interaction with cladding to demonstrate adequate performance for operating conditions using advanced fuel models of SiC CMC cladding.

- (2014) Conduct transient testing of SiC CMC cladding with simulated nuclear fuel heating to define an operating envelope in advance of in-pile testing.

- (2014) Fabricate extended-length fuel cladding that represents commercial nuclear fuel rods to demonstrate economic and technical practicality.

- (2014) Deliver a computational model of an advanced SiC CMC fuel system to predict performance during accident scenarios in advance of in-pile demonstration tests.

- (2014) Issue a report on licensing requirements and research program requirements to guide transfer to industrial development.

- (2015) Perform accident scenario and reactivity insertion tests with simulated nuclear fuel heating to assess performance and provide data for verification and validation.

- (2015) Perform in-pile testing of extended length SiC CMC cladding to demonstrate in-reactor performance of extended-length rods.

- (2016) Perform in-pile testing of rods at higher exposure limits to demonstrate long-term performance of SiC CMC cladding.

- (2016) Begin an evaluation of vendor-specific nuclear fuel rod features to establish critical operating limits for advanced commercial fuel designs.

- (2017 to 2021) In cooperation with industry, obtain approval for lead test rod or assembly testing in a commercial reactor.

- (2017 to 2021) In cooperation with industry, conduct analysis of vendor reload analysis capabilities to support licensing of advanced fuel reload.

- (2022 to 2026) Industry receives first approval for a full core reload of advanced fuel in a commercial reactor.

- (2022 to 2026) Start evaluation to support increased enrichment/higher burn-up commercial fuel reloads.

4. ADVANCED INSTRUMENTATION, INFORMATION, AND CONTROL SYSTEMS TECHNOLOGIES

4.1 Background

Reliable II&C systems technologies are essential to ensuring safe and efficient operation of the U.S. LWR fleet. These technologies affect every aspect of NPP and balance-of-plant operations. In 1997, the National Research Council conducted a study concerning the challenges involved in modernization of digital I&C systems in NPPs. Their findings identified the need for new II&C technology integration.

Digital II&C technologies are deployed in a number of power generation settings worldwide. Current instrumentation and human-machine interfaces employ analog systems in the nuclear power sector. These systems, though generally considered by other industries to be obsolete, continue to function reliably, but do not enable utilities to take full advantage of digital technologies to achieve performance gains.

The NPP owners and operators realize that this analog technology represents a significant challenge to sustaining safe and economic operation of the current fleet of NPPs. Beyond control systems, new technologies are needed to monitor and characterize the effects of aging and degradation in critical areas of key SSCs. The objective of these efforts is to develop, demonstrate, and deploy new digital technologies for II&C architectures and provide monitoring capabilities to ensure the continued safe, reliable, and economic operation of the nation's 104 NPPs.

Today, digital technologies are implemented as point solutions to performance concerns with individual II&C components. This reactive approach is characterized by planning horizons that are short and typically only allow for 'like-for-like' replacements. This results in a fragmented, non-optimized approach that is driven by immediate needs. As a long-term strategy, this is inefficient in light of the evolution of II&C technology, the availability of skills needed to maintain this legacy technology, and the associated high costs and uncertainties.

To displace the piecemeal approach to digital technology deployment, a new vision for efficiency, safety, and reliability is needed that leverages the future potential of a range of digital options. This includes consideration of goals for NPP staff numbers and types of specialized resources; targeting operation and management costs and the plant capacity factor to ensure commercial viability of proposed long-term operations; improved methods for achieving plant safety margins and reductions in unnecessary conservatisms; and leveraging expertise from across the nuclear enterprise. This last point is especially noteworthy because mergers and acquisitions have redefined NPP ownership and nuclear energy supply in the United States and Europe. NPP ownership is spread across a smaller number of utilities due to mergers and acquisitions, and ownership is no longer typically characterized by regional location or even national boundaries. Digital technology can enable plant owners to effectively manage the ongoing operations and support of the NPPs from wherever the owner resides.

A technology-driven approach in this R&D area alone will be insufficient to yield the type of transformation that is needed to secure a long-term source of nuclear energy base load; a new approach is needed. An effective R&D initiative must engage the stakeholders (i.e., plant owners, regulators, vendors, and R&D organizations) to initiate relevant R&D activities. This calls for development and execution of a long-term strategy for NPP II&C technology modernization based on the unique characteristics of the U.S. nuclear industry and its regulatory environment. In the near term, this strategy should lead to the ability to transition to a business model for NPP operation, employing a new technology base that becomes less labor intensive, facilitates greater digital application deployments, and can be deployed seamlessly across the operational enterprise. The execution of this R&D approach will lay the foundation for a technology base that is more stable and sustainable over the long term and assures the continued safety of power generation from nuclear energy systems.

4.2 Research and Development Purpose and Goals

The purpose of the research pathway is to enable the modernization of the legacy II&C systems in a manner that creates a seamless digital environment encompassing all aspects of plant operations and support – building a three-dimensional information architecture that integrates plant systems, plant processes, and plant workers in an array of interconnected technologies as follows:

- Plant systems – beyond the monitoring and control functions of these systems, extend plant information within these systems directly into the processes that support the plant work activities and directly to the workers performing these activities.

- Plant processes – integrate processes with real-time plant information to enable task automation, plant status control, more accurate procedure and work package usage, enhanced risk management, and other such functions, based on actual plant configuration, performance, and operational constraints.

- Plant workers – immerse plant workers in an information-rich environment that provides immediate, accurate plant information and allows the workers to conduct plant processes directly at the plant location, using mobile technologies, augmented reality (e.g., "seeing" radiation fields), and real-time video, enabling virtual collaboration and collective situational awareness among all participants in a work activity, both at the job site and in remote locations.

This development will transform the current NPP operating model from one that relies on a large plant staff and predominately manual activities to one based on smaller, technology-empowered staff conducting largely automated activities. Such an operating model will significantly enhance nuclear safety, worker productivity, and overall plant performance. This digital transformation is critical to addressing an array of difficult issues currently facing the plants, including the aging of legacy II&C systems, the need for long-term plant asset management, a potential shortage of technical workers, susceptibility to consequential human error, ever-increasing expectations for nuclear safety improvement, and relentless pressure to reduce cost.

The development and collaborations through this pathway are intended to overcome the inertia that sustains the current status quo of today's II&C systems technology and to motivate transformational change and a shift in strategy – informed by business objectives – to a long-term approach to II&C modernization that is more sustainable. Accordingly, DOE (through the LWRS Program Advanced II&C Systems Technologies Pathway) recognizes the following issues and needs for a long-term R&D program in II&C technologies.

- I&C modernization is critical to the sustainability of the operating nuclear fleet.

- Because of its short-term operational focus, the U.S. commercial nuclear industry could modernize its legacy I&C systems and still miss the opportunity to transform its operating model, thereby missing out on efficiencies in the advanced technologies that could reduce the costs of plant operations and outages.

- A national research program is needed to develop the transformative technologies and implementation roadmap for a performance-based I&C replacement strategy.

- DOE's national laboratories maintain unique capabilities to develop and deliver a strategy for modernization that can be successfully deployed by the private sector:

  – A federally funded and industry cost-shared program is technologically and organizationally neutral.

– Utilities must own the solution to successfully producing a plant-specific licensing case for modernized I&C and monitoring technologies.

– National laboratories will collaborate with utilities to overcome barriers to technology deployment.

An overriding objective of this pathway is to ensure that legacy I&C equipment does not become a limiting factor in the decisions on long-term operation of these NPPs. Goals for technology introduction are to enhance efficiency, safety, and reliability; improve characterizations of the performance and capabilities of passive and active components during periods of extended operation; and facilitate introduction of new advanced II&C systems technologies by demonstrating performance and reducing regulatory uncertainties. The R&D activities are intended to set the agenda for a long-term vision of future operations, including fleetwide integration of new technologies.

4.3 Pathway Research and Development Areas

4.3.1 Overview

R&D activities are being proposed to develop needed capabilities through digital technologies to support long-term NPP operations and management. The supporting technologies will enable the large integrated changes that industry cannot achieve without direct R&D support. This includes comprehensive programs that achieve the following:

- Support creation of new technologies that can be deployed to address the sustainability of today's II&C systems technologies

- Improve understanding of, confidence in, and facilitate transition to these new technologies

- Support development of the technical basis needed to achieve technology deployments

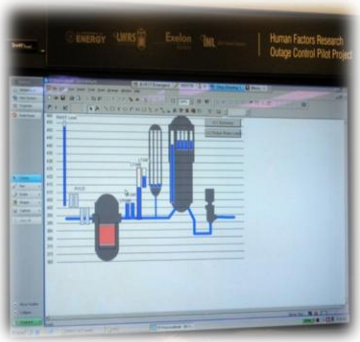
- Create or renew infrastructure needed for research, education, and testing.

4.3.2 Advanced Instrumentation, Information, and Control Systems Technologies Research Program

This research program will address aging and long-term reliability issues of the legacy II&C systems used in the current LWR fleet by demonstrating new technologies and operational concepts in actual NPP settings. This approach drives the following two important outcomes:

- Reduces the technical, financial, and regulatory risk of upgrading the aging II&C systems to support extended plant life beyond 60 years.

- Provides the technological foundation for a transformed NPP operating model that improves plant performance and addresses the challenges of the future business environment.



The research program is being conducted in close cooperation with the nuclear utility industry to ensure that it is responsive to the challenges and opportunities in the present operating environment. The scope of the research program is to develop a seamless integrated digital environment as the basis of the new operating model.

The program is advised by a Utility Working Group (UWG) composed of leading nuclear utilities across the industry and EPRI. The UWG developed a consensus vision of how a more integrated approach to modernizing plant II&C systems could address a number of challenges to the long-term sustainability of the LWR fleet. A strategy was developed to transform the NPP operating model by first defining a future state of plant operations and support based on advanced technologies and then developing and demonstrating the needed technologies to individually transform the plant work activities. The collective work activities were grouped into the following major areas of enabling capabilities:

1. Highly integrated control room

2. Highly automated plant

3. Integrated operations

4. Human performance improvement for field workers

5. Outage safety and efficiency

6. Centralized online monitoring and information integration.

Within these areas of enabling capabilities, a series of 18 pilot projects were defined as the roadmap for industry to collectively integrate new technologies into NPP work activities. For online monitoring, two broad areas of development have been defined at the present, which will be further defined into a series of additional pilot projects.

A pilot project is an individual demonstration that is part of a larger strategy needed to achieve modernization according to a plan. It is small enough to be undertaken by a single utility, it demonstrates a key technology or outcome required to achieve success in the higher strategy, and it supports scaling that can be replicated and used by other plants.

The pilot projects were defined as the appropriate points to introduce enabling technologies across the spectrum of plant work activities. These technologies serve as the stepping stones to the eventual seamless digital environment that enables a transformed NPP operating model. In a September 2011 workshop, the UWG prioritized the pilot projects in terms of value to the utilities and validated the development order. The sequence of development is designed to achieve progressively greater benefits as the growing aggregate of integrated technologies enables higher degrees of automation and innovation. The pilot projects were scheduled over a 12 year period (i.e., 2010 to 2021) as depicted in Figure 16.

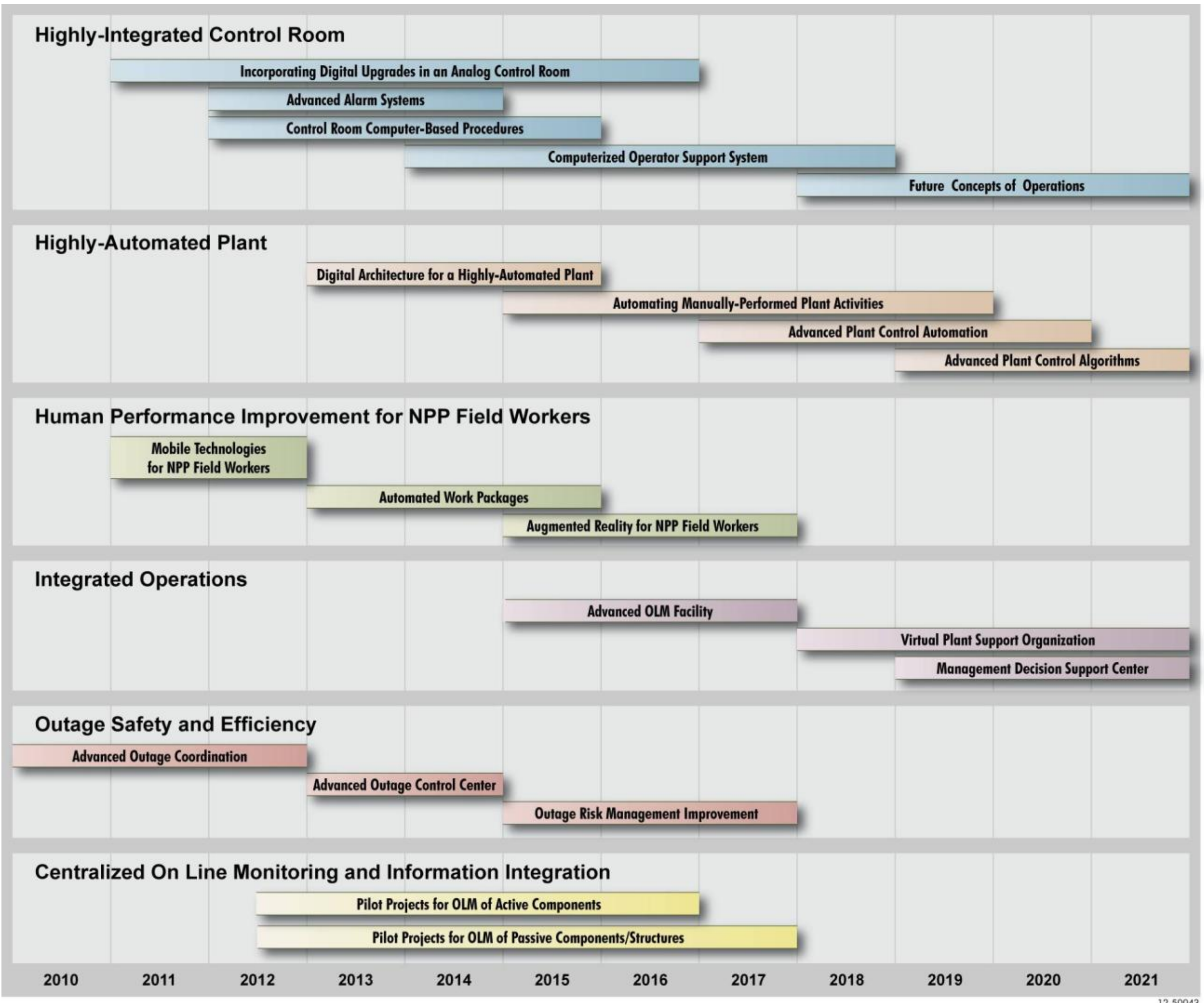


Figure 16. Pilot projects for the Advanced Instrumentation, Information, and Control Systems Technologies Pathway.

Prior to the time the individual pilot projects are scheduled to begin, members of the UWG are solicited to serve as host utilities for the R&D activities in which the new technologies are demonstrated and validated for production usage. This arrangement has a number of advantages as follows:

- It assures the end-state vision for plant modernization is shared by a significant portion of the LWR fleet.

- It assures the near-term technologies are immediately beneficial while they comprise the long-term building blocks of a more comprehensive digital environment.

- It greatly reduces the risk of implementation for any one utility, and the oversight of the working group provides a competent peer review.

- It allows the utilities to move forward together in transforming their operating model to fully exploit these technologies, providing a transparent process for coordinated assistance from the major industry support organizations of EPRI, Institute of Nuclear Power Operations, and Nuclear Energy Institute.

The LWRS Program provides the structured research program and expertise in plant systems and processes, digital technologies, and human factors science as it applies to NPP human performance. The utilities provide a cost share in the form of their time, expenses, expertise in plant functions, plant documentation, and access to plant facilities, including the plant simulator. The products of the pilot projects are technology demonstrations and technical basis reports that can be cited in regulatory filings, vendor specifications, and utility feasibility studies.

4.3.3 Human Systems Simulation Laboratory

The Human Systems Simulation Laboratory (HSSL) at the INL is used to conduct research in the design and evaluation of advanced reactor control rooms, integration of intelligent support systems to assist operators, development and assessment of advanced human performance models, and visualizations to assess advanced operational concepts across various infrastructures. This advanced facility consists of a reconfigurable simulator that supports human factors research, including human-in-the-loop performance, human-system interfaces, and analog and digital hybrid control displays. It is applicable to the development and evaluation of control systems and displays for complex systems such as existing and advanced NPP control rooms, command and control systems, and advance emergency operations centers. The facility also can be linked to a virtual reality system (known as the Computer-Aided Virtual Environment) (Figure 17) for expanded overview displays, to perform virtual walkthroughs of work environments, or to evaluate human interaction in simulated virtual environments.

Figure 17. Human Systems Simulation Laboratory.

For this research project, HSSL will be used to study human performance in a near-realistic operational context for advanced NPP control room design. The facility is equally suitable for human performance measurement in other NPP control centers such as an outage control center, a centralized online monitoring center, and emergency response facilities. Assessment of human performance in a naturalistic setting includes studies in a range of the following focus areas:

1. Human-system performance relationships between the reliability of the operator, the time available to perform an action, performance success criteria, and the influence of the performance characteristics of the plant or system on task performance and outcome(s).

2. Usability of the human systems interface, which includes the effectiveness, efficiency, safety, and reliability with which an operator can perform specific tasks in a specific operational context (e.g., normal or emergency). This includes the effect on human performance with different technologies and different human-system interface configurations.

3. Human performance expressed as physical and cognitive workload under different operational conditions, including the following:

    a. Monitoring of plant status and system performance

    b. Human error, human reliability, and human error mechanisms

    c. Task completion (e.g., accuracy, speed, tolerance, and variability)

    d. Procedure following

    e. Problem diagnosis:

        1) Decision making

        2) Response times.

4. Situational awareness with a given human-system interface and control configuration under different operational conditions.

5. Crew communication effectiveness with given technologies under different operational conditions.

6. Human performance with different staffing configurations and a given control room configuration.

HSSL provides the simulation, visualization, and evaluation capabilities needed for pilot projects involving development and evaluation of new technologies for the main control room and other control centers. As such, the new technologies will first be staged in HSSL for proof-of-concept prior to demonstration at host utility NPPs. HSSL facilities will be configured in a variety of settings according to the functional context of each type of plant control center.

To meet the needs of each type of control center, HSSL will continually be upgraded with new capabilities as the research program progresses. A major upgrade will be implemented in 2013, which will enable research on function allocation, staffing, situational awareness, and workload in multiple-unit control rooms. Over time, this will result in an HSSL of highly complex and sophisticated features that will enable realistic modeling of the tasks and functions required of the various plant control centers. It is envisioned that HSSL will be the leading facility in the United States for validation of new operational concepts and technologies for the LWR fleet, thereby ensuring that NPP modernization of II&C systems is based on demonstrated and validated scientific principles.

4.3.4 Cyber Security

Cyber security is recognized as major concern in implementing advanced digital II&C technologies in NPPs in view of the considerable security requirements necessary to protect these facilities from potential adversaries, as well as protect company-proprietary information. The members of the UWG have expressed the need to ensure that cyber security vulnerabilities are not introduced through adoption of these advanced digital technologies. Furthermore, these utilities have internal cyber security policies and regulatory obligations that must be upheld during implementation of the project technologies.

To this end, a project task has been created to address cyber security issues arising from the technology developments in the pilot projects. INL has significant cyber security expertise and resources that have been developed to address the security concerns of the laboratory, as well as those of many security-critical U.S. government facilities. INL's experience in identifying, characterizing, and mitigating cyber security threats is highly applicable to the type of concerns that potentially would be created in technology developments of the pilot projects.

A cyber security assessment template will be developed to identify possible threat vectors introduced by the new technologies. An individual assessment will be conducted for each pilot project to identify the threats specific to its technologies, characterize the degree of cyber security risk, and recommend effective mitigation measures. The assessment will be discussed with the host utility for the pilot projects and the information will be provided to the UWG in general.

Responsibility for cyber security ultimately lies with the utilities that implement technologies from this research program. They must ensure their own policies and regulatory commitments are adequately addressed. However, the cyber security resources, expertise, and experience of INL will provide a sound information basis to guide utilities in prudent technology implementation practices and mitigation measures.

4.4 Research and Development Cooperation

A systematic engagement activity is underway with NPP owner/operators, suppliers, industry support organizations, and NRC. Together, these engagement activities are intended to ensure that R&D activities focus on issues of challenge and uncertainty for NPP owners and regulators alike, the products of research can be commercialized, and roadblocks to deployment are systematically addressed.

4.4.1 Utility Working Group

The Advanced II&C Systems Technologies Pathway sponsors a UWG to define and host a series of pilot projects that, together, will enable significant plant performance gains and minimize operating costs in support of the long-term sustainability of the LWR fleet. At this time, the UWG consists of 12 leading U.S. nuclear utilities. Additional membership will be pursued for the UWG with the intent to involve every U.S. nuclear operating fleet in the program.

EPRI also is a member of the UWG, in addition to their direct role in collaborative research with II&C Pathway. EPRI has conducted numerous R&D activities over the past several decades in support of NPP digital implementation and related issues and has made relevant reports and guidelines available to this research pathway. EPRI technical experts directly participate in the formulation of the project technical plans and in the review of the pilot project results, bringing to bear the accumulated knowledge from their own research projects and collaborations with nuclear utilities. In addition, EPRI sponsors a utility advisory group on productivity improvements through advanced technology that is investigating digital technologies of interest to this program and has created an open dialogue for cooperation with the UWG through joint meetings and shared documentation.

To achieve the full potential of digital technology to improve performance, the industry must work together to collectively transform the operating/support model, using these same practices of rapidly adopting proven innovations across the industry. The working group will foster this digital transformation in a manner that reduces technical and financial risk, while providing a pathway to this new operating/support model. It also will cooperate with the major industry support organizations to facilitate all aspects of the transformation.

The UWG is directly involved in defining the objectives and research projects of this pathway. The UWG meets regularly several times annually. Criteria have been developed for identifying, prioritizing, and selecting potential advanced II&C pilot projects performed by this pathway.

The pilot project partner will make the results of the R&D available and accessible to other commercial nuclear utilities and participate in efforts to support deployment of systems, technologies, and lessons learned by other NPP owners. Host utilities regularly make presentations in key industry technical meetings to describe their motivations and efforts in the pilot projects and to communicate important findings to the industry.

The UWG sponsors four special interest groups in the areas of outage safety and efficiency, human performance improvement for NPP field workers, computer-based procedures, and control room modernization. These special interest groups are self-forming, based on the topics that the utilities want to engage in. The purpose of the special interest groups is to provide a means of focused engagement for utilities in the areas of their interests and provide the means of broad peer review of the technologies developed by the research program.

The special interest groups hold separate conference calls and meetings to review specific technology developments, particularly in association with demonstrations at a host utility. This facilitates direct communication and collaboration among utility representatives with similar development responsibilities and provides a much broader base for identifying utility requirements, such that the developments will have broad applicability across the LWR fleet.

Additional special interest groups will be formed as new areas of technology development are undertaken through the future pilot projects.

4.4.2 Halden Reactor Project

The Halden Reactor Project's programs extend to many aspects of NPP operations; however, the area of interest to this R&D program is the man-machine-technology research program that conducts research in the areas of computerized surveillance systems, human factors, and man-machine interaction in support of control room modernization. Halden has been on the cutting edge of new NPP technologies for several decades and their research is directly applicable to the capabilities being pursued under the pilot projects. In particular, Halden has assisted a number of European NPPs in implementing II&C modernization projects, including control room upgrades.

The II&C Pathway will work closely with Halden to evaluate their advanced II&C technologies to take advantage of the applicable developments. In addition to the technologies, the validation and human factors studies conducted during development of the technologies will be carefully evaluated to ensure similar considerations are incorporated into the pilot projects. Specific Halden developments of interest to the pilot projects are as follows:

- Advanced control room layout
- Computer-based procedures
- Advanced, state-based alarm systems
- Integrated operations
- Plant worker mobile technologies.

In addition, INL will enter into a bilateral agreement in areas of research where collaborative efforts with Halden will accelerate development of the technologies associated with the pilot projects.

4.4.3 Major Industry Support Organizations

The LWR fleet is actively supported by major industry support groups; namely EPRI, the Nuclear Energy Institute, and the Institute of Nuclear Power Operations. All of these organizations have active efforts in the I&C area, including technical developments, regulatory issues, and standards of excellence in conducting related activities. It is important that these organizations be informed of the purpose and scope of this research program, and that activities be coordinated to the degree possible.

It is a task of this research program to engage these organizations to enable a shared vision of the future operating model based on an integrated digital environment and to cooperate in complementary activities to achieve this vision across the industry with the maximum efficiency and effectiveness.

There are additional industry support groups (such as the Pressurized Water Reactor and Boiling Water Reactor Owners Groups) that need similar engagement for more focused purposes. These groups sponsor I&C working groups that will similarly benefit from communications about the research program and coordination of activities where warranted.

4.4.4 Nuclear Regulatory Commission

Periodic informational meetings are held between DOE Headquarters personnel and members of NRC management to communicate about aims and activities of individual LWRS Program pathways. Briefings and informal meetings will continue to be provided to inform staff from NRC's Office of Nuclear Regulatory Research about technical scope and objectives of the LWRS Program.

4.4.5 Suppliers

Ultimately, it will be the role of nuclear industry II&C suppliers to provide commercial products based on technologies developed under this research program. In the absence of an industry-wide II&C modernization strategy, products currently offered by these suppliers reflect the more limited approach of fragmented, like-for-like digital implementations as driven by the market. As a collective vision for an improved operating model based on an integrated digital environment takes hold within the LWR fleet, leading suppliers will seize the market opportunity to provide products that enact this vision.

An engagement strategy for nuclear industry II&C suppliers will be conducted with the following tasks:

- Communicate to suppliers the objectives of the research program and the specific technologies and operational concepts that are being developed and validated through the pilot projects.

- Obtain input from suppliers on how they are developing their products with respect to this market.

- Set up a mechanism for ongoing communications.

- Facilitate a long-term commercialization strategy for the program's developed technologies.

4.5 Research and Development Products and Schedule

The R&D activities associated with each of the six areas of enabling capabilities result in key outcomes from each of the pilot projects.

4.5.1 Highly-Integrated Control Room

Today's LWR control rooms consist of an array of discrete devices such as gauges, indicators, displays, alarms, and operator controls located on multiple large control boards. A highly-integrated control room is one in which these functions are integrated into operator workstations and overview displays that provide a compact and rich set of control functions and information presentations that greatly enhance operator performance. A hybrid control room is one in which there is a mixture of these concepts as the control rooms are progressively modernized.

The II&C Pathway will conduct R&D activities to determine the optimum layout and concepts for an NPP hybrid control room based on engineering and human factors principles. The control room upgrades will be implemented and studied in INL's HSSL to ensure that new concepts are sound and will uphold all nuclear safety requirements. The II&C Pathway will assist a host utility in implementing the concepts in an actual NPP control room, conducting further studies on actual control room performance. Further work will develop the strategy into several tiers of control room modernization end-states, up to a highly-integrated control room. Planning activities are underway to define and schedule the following key outcomes:

- (2012) Develop a digital, full-scale mockup in HSSL of a conventional NPP control room.

- (2013) Publish guidelines for an optimized, human-factored control board layout for integrating digital operator interface screens with analog controls and indicators.

- (2013) Implement an upgrade of HSSL, enabling research on function allocation, staffing, situational awareness, and workload in multiple-unit control rooms.

- (2014) Publish a guideline standard for an advanced alarm management system in an NPP control room and a methodology for integrating diverse alarms and annunciators across all systems and digital platforms.

- (2015) Publish implementation guidelines for computer-based procedures that enhance worker productivity, human performance, plant configuration control, risk management, regulatory compliance, and nuclear safety margin.

- (2016) Develop an end-state vision and strategy, based on human factors engineering principles, for the implementation of both a hybrid and a full highly-integrated control room as new digital technologies and operator interface systems are introduced into traditional control rooms.

- (2018) Develop an end-state vision and implementation strategy for an advanced computerized operator support system, providing real-time situational awareness for operators and prediction of the future plant state based on current conditions and trends.

- (2021) Develop validated future concepts of operations for improvements in control room protocols, staffing, operator proximity, and control room management, enabled by new technologies that provide mobile information and control capabilities.

4.5.2 Highly Automated Plant

The concept of a highly automated plant is one where important, safety-critical activities are automated using advanced technologies under the direction of a competent staff. Automation on a large scale enables a shift from a labor-intensive operating/support model to one that is technology-based. This transformed NPP operating model will address an array of future challenges facing the LWR fleet.

The II&C Pathway will develop an advanced digital architecture that integrates plant systems, plant processes, and plant workers in a manner that maximizes efficiency and shared-use of plant information. Opportunities for plant activity automation will be identified through a top-down analysis of NPP plant activities and define a transformed NPP operating model based on a highly-automated plant. Further, to improve nuclear safety margins and plant capacity factors, the II&C Pathway will develop strategies and guidance for specific automation improvements in plant control functions. Planning activities are underway to define and schedule the following key outcomes:

- (2015) Develop an advanced digital architecture integrating plant systems, plant work processes, and plant workers in a seamless digital environment, and publish guidelines to implement the architecture using industry open standards.

- (2019) Develop a transformed NPP operating model and organizational design derived from a top-down analysis of NPP operational and support activities, quantifying the efficiencies that can be realized through highly automated plant activities using advanced digital technologies.

- (2020) Develop the strategy and priorities and publish implementation guidelines for automating operator control actions for important plant state changes, transients, and power maneuvers, resulting in nuclear safety and human performance improvements founded on engineering and human factors principles.

- (2021) Develop the strategy and priorities and publish implementation guidelines for improving plant control algorithms based on greater availability of sensed and derived plant parameters through the advanced digital architecture, resulting in more anticipatory, adaptive, and resilient control functions.

4.5.3 Human Performance Improvement for Nuclear Power Plant Field Workers

To improve human performance for NPP field workers, a fundamental shift in approach is needed. Digital technology can be applied in a manner to perform the tedious error-prone tasks in NPP field activities, leaving the worker in more of a cognitive role. It has the potential to eliminate human variability in performing routine actions such as identifying the correct components to be worked on. In short, the technology can perform tasks at much higher reliability rates, while the plant worker remains in a role of correctly applying the technology and validating the results.

The II&C Pathway will develop integrated mobile technologies for NPP field workers that connect the worker to plant information and plant processes in a manner that significantly enhances human performance and productivity. Human factors studies will be conducted, resulting in guidelines for utilities to use in applying these technologies to field activities. Additional work will be conducted in developing guidelines for providing augmented reality technologies to field workers, allowing workers to view invisible phenomena (such as radiation fields) as a means of reducing worker dose. Planning activities are underway to define and schedule the following key outcomes:

- (2012) Publish a technical report for implementing integrated mobile technologies for NPP field workers that provide real-time connections to plant information and processes, thereby reducing human error, improving human performance and productivity, enabling distance collaboration, and maximizing the "collective situational awareness."

- (2013) Publish guidelines for implementing integrated mobile technologies for NPP field workers to improve human performance and worker productivity.

- (2014) Develop human factors evaluations and an implementation strategy for deploying automated field activity work packages built on mobile technologies, resulting in more efficient and accurate plant work processes, adherence to process requirements, and improved risk management.

- (2017) Publish implementation guidelines for augmented reality technologies for NPP field workers, enabling them to visualize abstract data and invisible phenomena, resulting in significantly improved situational awareness, access to context-based plant information, and generally improved effectiveness and efficiency in conducting field work activities.

4.5.4 Integrated Operations

Many industries have taken advantage of new digital technologies to consolidate operational and support functions for multiple production facilities to improve efficiency and quality. This concept is sometimes referred to as integrated operations. It basically means using technology to overcome the need for onsite support, thereby allowing the organization to centralize certain functions and concentrate the company's expertise in fewer workers. These workers, in turn, develop higher levels of expertise because they are exposed to a larger variety of challenges and issues than if they supported just a single facility. The concept also enables standardized operations and economy of scale in maintaining a single organization instead of duplicate capabilities at each location.

The II&C Pathway will conduct human factors studies of various types of integrated operations in HSSL and, ultimately, at a host utility to maximize human, process, and organizational effectiveness using virtual collaboration technologies to connect remote parties supporting plant operations. This project will address the looming concerns on cost and availability of future plant staff by enabling nuclear utilities to build virtual organizations of trusted partners (fleet-level or external) rather than having to rely on onsite resources for time-critical support. Planning activities are underway to define and schedule the following key outcomes:

- (2017) Develop a digital architecture and publish implementation guidelines for an advanced online monitoring facility, providing long-term asset management, and providing real-time information directly to control room operators, troubleshooting and root cause teams, suppliers and technical consultants involved in component support, and engineering in support of the system health program.

- (2021) Publish human and organizational factors studies and implementation guidelines for a virtual plant support organization technology platform consisting of data sharing, communications (voice and video), and collaboration technologies that will compose a seamless work environment for a geographically-dispersed NPP support organization.

- (2021) Publish human and organizational factors studies and implementation guidelines for a management decision support center consisting of advanced digital display and decision-support technologies, thereby enhancing nuclear safety margin, asset protection, regulatory performance, and production success.

4.5.5 Outage Safety and Efficiency

NPP refueling outages are perhaps the most challenging times in the ongoing operations of the facilities, executing typically more than 10,000 activities in a 20 to 30-day work period. Many of these activities are safety critical. This presents enormous challenges in controlling the timing, quality, and cost of individual work activities in the face of shifting schedules, emergent problems, and strained human and equipment resources. This dynamic work mix must be analyzed continually to detect and avoid threats to nuclear safety margins, regulatory compliance, and outage schedule adherence.

The II&C Pathway will conduct R&D activities for the application of advanced digital technologies that integrate outage control centers, field work crews, and real-time plant information to achieve collective situational awareness and enable timely decision-making to effectively allocate resources in an optimized manner. The II&C Pathway will use HSSL to develop concepts for an advanced outage control center specifically designed to maximize the use of digital technology for information analysis and shared understanding in outage control center team decision-making. The II&C Pathway will conduct further research and produce implementation guidance for technologies that improve outage risk management, especially in the area of configuration control for changing plant states, by integrating plant status information with configuration changes imposed by ongoing and near-term outage work activities. Planning activities are underway to define and schedule the following key outcomes:

- (2012) Publish a technical report for implementing digital technologies that facilitate communications, coordination, and collaboration in obtaining accurate outage activity status, managing the flow of information through the outage control center, and enabling the resolution of emergent problems in an efficient and effective manner, resulting in improved work efficiencies, production success, and nuclear safety margins.

- (2013) Publish guidelines for implementing digital technologies to improve outage communications, coordination, and collaboration.

- (2014) Develop human factors studies and publish implementation guidelines for an advanced outage control center that is specifically designed to maximize the usefulness of communication and collaboration technologies for outage coordination, problem resolution, and outage risk management.

- (2017) Develop a real-time outage risk management strategy and publish implementation guidelines to improve nuclear safety during outages by detecting configuration control problems caused by work activity interactions with changing system alignments.

4.5.6 Centralized Online Monitoring and Information Integration

As NPP systems begin to be operated during periods longer than originally anticipated, the need arises for more and better types of monitoring of material and system performance. This includes the need to move from periodic, manual assessments and surveillances of physical systems to online condition monitoring. This represents an important transformational step in the management of NPPs. It enables real-time assessment and monitoring of physical systems and better management of active components based on their performance. It also provides the ability to gather substantially more data through automated means and to analyze and trend performance using new methods to make more informed decisions about NPP management and safety management. Of particular importance will be the capability to determine the “remaining useful life” of a component to justify its continued operation over an extended plant life.

Working closely with the MAaD Pathway and EPRI, this pathway will develop technologies to complement sensor development and monitoring of materials to assess the performance of SSC materials during long-term operation for purposes of decision making and asset management. This includes development of algorithms, methods, and automated tools to process sensor signals to derive parameter estimates of specific aging and performance features and analytic capabilities to characterize the state and condition of material properties. These developments will be used to produce new types of assessments of ‘diagnostic’ accuracy about material aging and degradation. This will yield new capabilities that enable a move from mechanisms of change, their progression in materials, and a description of the specific transformations that affect a material or system’s ability to achieve its design function, in turn, leading to ‘prognostic’ assessments of the rate of degradation and the types and timing of needed interventions.

A series of pilot projects will be conducted to develop the diagnostic and prognostic analysis framework for a representative set of large plant components, both active and passive, for which extended life is highly important to LWR sustainability. This will include the ability to predict the remaining useful life for these components. These capabilities will enable industry to implement online monitoring for these components and will establish the methodology for industry to extend the concept to other plant components where aging and degradation mechanisms must be managed for extended life. The product of the pilot projects will be technical reports that describe the technical basis and analysis framework to enable online monitoring for these components. These technical reports will be used further to develop guidelines for utilities to implement centralized online monitoring and information integration for the components/structures important to plant life extension. Included in these guidelines will be a survey of additional sensors, NDE technologies, and signal processing techniques that will need development to enable the industry to extend online monitoring to other important components/structures.

Planning activities are underway to define and schedule the specific key outcomes:

- (2013) Publish a technical report on measures, sensors, algorithms, and methods for monitoring active aging and degradation phenomena for Generation Step-Up transformers as an important passive component, including the diagnostic and prognostic analysis framework to support utility implementation of online monitoring for the component type.

- (2014) Publish a technical report on measures, sensors, algorithms, and methods for monitoring active aging and degradation phenomena for a large active component, including the diagnostic and prognostic analysis framework to support utility implementation of online monitoring for the component type.

- (2015) Publish a technical report on measures, sensors, algorithms, and methods for monitoring active aging and degradation phenomena for a large passive plant component/structure, involving NDE-related online monitoring technology development and including the diagnostic and prognostic analysis framework to support utility implementation of online monitoring for the component type.

- (2016) Publish a technical report on measures, sensors, algorithms, and methods for monitoring active aging and degradation phenomena for a second large active plant component, including the diagnostic and prognostic analysis framework to support utility implementation of online monitoring for the component type.

- (2017) Publish guidelines on utility implementation of centralized online monitoring and information integration for the component/structure types addressed by the pilot projects, including a survey of an additional sensor, NDE technologies, and signal processing techniques required for industry development of online monitoring capabilities for other plant components/structures important to LWR sustainability.

4.6 Research and Development Products and Schedule

The following depicts the key outcomes by year:

- (2012) Publish a technical report for implementing digital technologies that facilitate communications, coordination, and collaboration in obtaining accurate outage activity status, managing the flow of information through the outage control center, and enabling the resolution of emergent problems in an efficient and effective manner, resulting in improved work efficiencies, production success, and nuclear safety margins.

- (2012) Publish a technical report for implementing integrated mobile technologies for NPP field workers that provide real-time connections to plant information and processes, thereby reducing human error, improving human performance and productivity, enabling distance collaboration, and maximizing the "collective situational awareness."

- (2012) Develop a digital full-scale mockup in HSSL of a conventional NPP control room.

- (2013) Publish guidelines for an optimized, human-factored control board layout for integrating digital operator interface screens with analog controls and indicators.

- (2013) Implement an upgrade of HSSL, enabling research on function allocation, staffing, situational awareness, and workload in multiple-unit control rooms.

- (2013) Publish guidelines for implementing digital technologies to improve outage communications, coordination, and collaboration.

- (2013) Publish guidelines for implementing integrated mobile technologies for NPP field workers to improve human performance and worker productivity.

- (2013) Publish a technical report on measures, sensors, algorithms, and methods for monitoring active aging and degradation phenomena for Generation Step-Up transformers as an important passive component, including the diagnostic and prognostic analysis framework to support utility implementation of online monitoring for the component type.

- (2014) Publish a guideline standard for an advanced alarm management system in an NPP control room and a methodology for integrating diverse alarms and annunciators across all systems and digital platforms.

- (2014) Develop human factors evaluations and an implementation strategy for deploying automated field activity work packages built on mobile technologies, resulting in more efficient and accurate plant work processes, adherence to process requirements, and improved risk management.

- (2014) Develop human factors studies and publish implementation guidelines for an advanced outage control center that is specifically designed to maximize the usefulness of communication and collaboration technologies for outage coordination, problem resolution, and outage risk management.

- (2014) Publish a technical report on measures, sensors, algorithms, and methods for monitoring active aging and degradation phenomena for a large active component, including the diagnostic and prognostic analysis framework to support utility implementation of online monitoring for the component type.

- (2015) Publish implementation guidelines for computer-based procedures that enhance worker productivity, human performance, plant configuration control, risk management, regulatory compliance, and nuclear safety margin.

- (2015) Develop an advanced digital architecture integrating plant systems, plant work processes, and plant workers in a seamless digital environment, and publish guidelines to implement the architecture using industry open standards.

- (2015) Publish a technical report on measures, sensors, algorithms, and methods for monitoring active aging and degradation phenomena for a large passive plant component/structure, involving NDE-related online monitoring technology development and including the diagnostic and prognostic analysis framework to support utility implementation of online monitoring for the component type.

- (2016) Develop an end-state vision and strategy, based on human factors engineering principles, for the implementation of both a hybrid and a full highly integrated control room as new digital technologies and operator interface systems are introduced into traditional control rooms.

- (2016) Publish a technical report on measures, sensors, algorithms, and methods for monitoring active aging and degradation phenomena for a second large active plant component, including the diagnostic and prognostic analysis framework to support utility implementation of online monitoring for the component type.

- (2017) Publish implementation guidelines for augmented reality technologies for NPP field workers, enabling them to visualize abstract data and invisible phenomena, resulting in significantly improved situational awareness, access to context-based plant information, and generally improved effectiveness and efficiency in conducting field work activities.

- (2017) Develop a digital architecture and publish implementation guidelines for an advanced online monitoring facility, providing long-term asset management and providing real-time information directly to control room operators, troubleshooting and root cause teams, suppliers and technical consultants involved in component support, and engineering in support of the system health program.

- (2017) Develop a real-time outage risk management strategy and publish implementation guidelines to improve nuclear safety during outages by detecting configuration control problems caused by work activity interactions with changing system alignments.

- (2017) Publish guidelines on utility implementation of centralized online monitoring and information integration for the component/structure types addressed by the pilot projects, including a survey of an additional sensor, NDE technologies, and signal processing techniques required for industry development of online monitoring capabilities for other plant components/structures important to LWR sustainability.

- (2018) Develop an end-state vision and implementation strategy for an advanced computerized operator support system, providing real-time situational awareness for operators and prediction of the future plant state, based on current conditions and trends.

- (2019) Develop a transformed NPP operating model and organizational design derived from a top-down analysis of NPP operational and support activities, quantifying the efficiencies that can be realized through highly automated plant activities using advanced digital technologies.

- (2020) Develop the strategy and priorities and publish implementation guidelines for automating operator control actions for important plant state changes, transients, and power maneuvers, resulting in nuclear safety and human performance improvements founded on engineering and human factors principles.

- (2021) Develop validated future concepts of operations for improvements in control room protocols, staffing, operator proximity, and control room management, enabled by new technologies that provide mobile information and control capabilities.

- (2021) Develop the strategy and priorities and publish implementation guidelines for improving plant control algorithms, based on greater availability of sensed and derived plant parameters through the advanced digital architecture, resulting in more anticipatory, adaptive, and resilient control functions.

- (2021) Publish human and organizational factors studies and publish implementation guidelines for a virtual plant support organization technology platform consisting of data sharing, communications (voice and video), and collaboration technologies that will compose a seamless work environment for a geographically dispersed NPP support organization.

- (2021) Publish human and organizational factors studies and publish implementation guidelines for a management decision support center consisting of advanced digital display and decision-support technologies, thereby enhancing nuclear safety margin, asset protection, regulatory performance, and production success.

5. RISK-INFORMED SAFETY MARGIN CHARACTERIZATION

5.1 Background

Safety is central to the design, licensing, operation, and economics of NPPs. As the current LWR NPPs age beyond 60 years, there are possibilities for increased frequency of SSC failures that initiate safety-significant events, reduce existing accident mitigation capabilities, or create new failure modes. Plant designers commonly “over-design” portions of NPPs and provide robustness in the form of redundant and diverse engineered safety features to ensure that, even in the case of well-beyond design basis scenarios, public health and safety will be protected with a very high degree of assurance. This form of defense-in-depth is a reasoned response to uncertainties and is often referred to generically as "safety margin." Historically, specific safety margin provisions have been formulated, primarily based on "engineering judgment."

The ability to better characterize and quantify safety margin holds the key to improved decision making about LWR design, operation, and plant life extension. In a sense, contemplation of LWR operation beyond 60 years does represent a kind of "beyond design basis" operation. A systematic approach to characterization of safety margins represents a vital input to the licensee and regulatory analysis and decision making that will be involved. In addition, as R&D in the LWRS Program and other collaborative efforts yield new data and improved scientific understanding of physical processes that govern the aging and degradation of plant SSCs (and concurrently support technological advances in nuclear reactor fuels and plant II&C systems) needs and opportunities to better optimize plant safety and performance will become known.

5.2 Research and Development Purpose and Goals

The purpose of the RISMC Pathway is to develop and deploy approaches to support the management of uncertainty in safety margins quantification to improve decision making for NPPs. Management of uncertainty implies the ability to (a) understand and (b) control risks related to safety. Consequently, the RISMC Pathway is dedicated to improving both aspects of safety management.

Central to this pathway is the concept of a safety margin. In general terms, a "margin" is characterized in one of two ways:

- A *deterministic* margin. For example, we test a pressure tank to failure where the tank design is for X, it failed at pressure Y, thus the margin is Y-X (safety margin) or Y/X (safety factor).

- A *probabilistic* margin. For example, we model failure of a pressure tank where the tank design capacity is a distribution f(X), its loading condition is a second distribution f(Y), thus the margin is described by either:

  – Pr[X-Y < 0] (safety margin or the probability the load is larger than the capacity)

  – Pr[X/Y < 1] (safety factor or the probability the load is larger than the capacity).

Because one LWRS objective is to develop technologies that can improve the reliability, sustain the safety, and extend the life of the current reactors, any safety margin focus would need to consider realistic "load" and "capacity" implications for operating NPPs. For example, the notional diagram shown in Figure 18 illustrates that a safety impact, as represented by a load distribution, is a complex function that varies from one accident scenario to the next. However, the capacity part of the evaluation may not vary as much from one accident to the next because the safety capacity is determined by design elements such as fuel and material properties (which are common across a spectrum of accidents).

The goals of the RISMC Pathway are twofold:

1. Develop and demonstrate a risk-assessment method tied to safety margins quantification.

2. Create advanced tools for safety assessment that enable more accurate representation of a NPP safety margin.

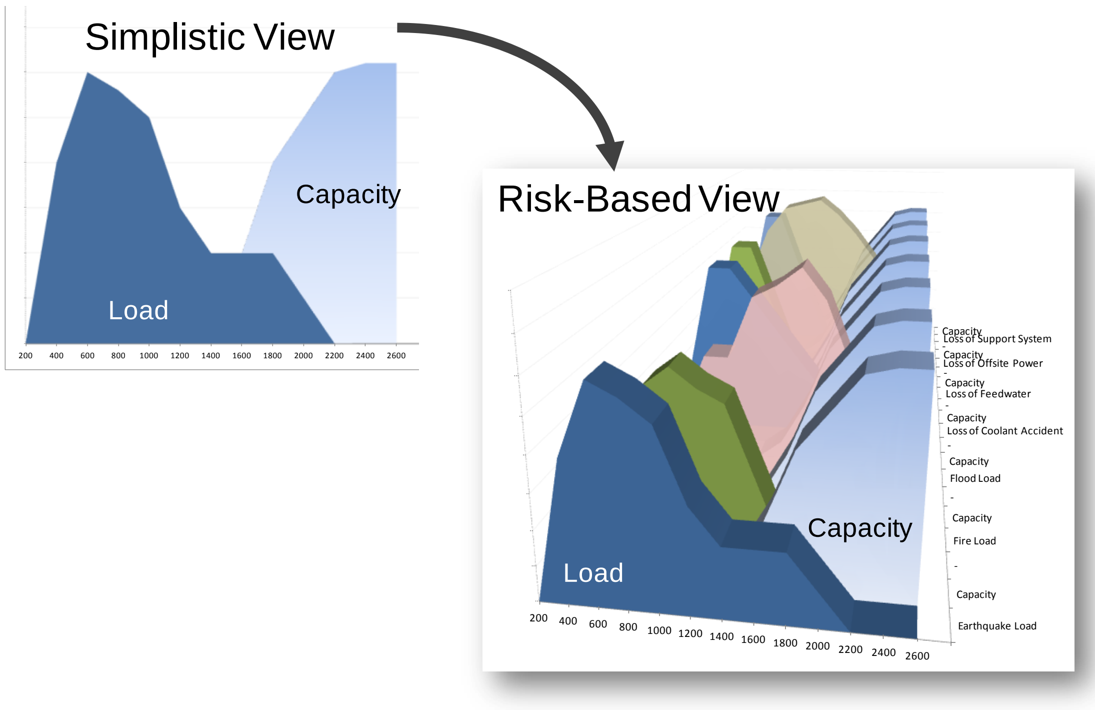


Figure 18. Family of load and capacity distributions representing different accident conditions.

To successfully accomplish Goal 1, the RISMC Pathway will clearly define and demonstrate the safety margin approach. The determination of the degree of a safety margin requires an understanding of risk-based scenarios. Within a scenario, an understanding of plant behavior (i.e., operational rules such as technical specifications, operator behavior, and SSC status) and associated uncertainty will be required to interface with a systems code (i.e., RELAP-7; see Section 5.3.3.2). Then, to characterize safety margin for a specific performance metric of consideration (e.g., peak clad temperature), the plant simulation will determine time and scenario-dependent outcomes for both the load and capacity. Specifically, the safety margin approach will use the physics-based plant results (the "load") and contrast these to the capacity (for the associated performance metric) to determine if safety margins have been exceeded (or not) for a family of accident scenarios. Engineering insights will be derived based on the scenarios and associated outcomes (both load and capacity).

To successfully accomplish Goal 2, the RISMC Pathway will develop a significantly improved plant physics code (i.e., RELAP-7) and a suite of simulation methods for driving RELAP-7 to analyze safety margin. These tools will use advanced computational techniques to simulate the behavior of NPPs in a way that develops more comprehensive safety insights and enables a more useful risk-informed analysis of plant safety margin than can be done using existing tools. RELAP-7 is a systems code, meaning it will simulate behavior at the plant level (i.e., it will address a broad range of phenomena at a level of detail that is feasible and appropriate for a plant scale of modeling) as opposed to analyzing highly localized phenomena in great detail at every point in the plant (which is still infeasible today). However, as a systems code, RELAP-7 will function as an environment within which user-supplied, highly detailed models of selected subsystems (e.g., the Consortium of Advanced Simulation of Light Water Reactors model of the reactor core) can be applied.

DOE (through the RISMC Pathway) is involved in this R&D activity for the following reasons:

- The development of RELAP-7 is high-risk, requiring multiphysics modeling capabilities developed in the DOE national laboratory system. Moreover, RELAP-7 is highly multi-disciplinary, making RELAP-7 development a good match for the institutional conditions at DOE.

- The DOE national laboratory system has broad experience in validation, verification, and uncertainty quantification, which are essential components for successful development of RELAP-7.

- Numerous academic institutions across the United States support RELAP-7 development, fulfilling a government responsibility to help train the next generation of nuclear scientists and engineers.

- RELAP-7 will be a very significant component of the U.S. industry capability that will promote investment in the U.S. nuclear power industry by reducing technical and, potentially, regulatory uncertainty.

- RELAP-7 development will significantly benefit the entire operating fleet and important classes of new facilities (e.g., small modular reactors).

- Government and industry are sharing work on methods and tools for characterizing safety margin.

    - The DOE role is to lead the development of advanced techniques, including building on uncertainty analysis methodology that has been under development for years at government laboratories and internationally.

    - Industry, under EPRI's Long-Term Operation Program, is carrying out simplified case studies to better understand the issues and to provide feedback and comparative results to DOE on both RELAP-7 development and the methods and tools for analysis of safety margin.

One outcome of a risk-informed approach advocated in the RISMC Pathway is the use of "performance-based" controls. These controls will be informed by the risk assessment and will focus on desired, measurable outcomes, rather than prescriptive processes, techniques, or procedures, with the aim of identifying performance measures that ensure an adequate safety margin. In addition to the activities identified above in this pathway, RISMC will be working with the MAaD, Advanced Light Water Reactor Nuclear Fuels, and the Advanced II&C Systems Technologies Pathways to introduce RISMC-thinking into each pathway.

5.3 Pathway Research and Development Areas

The purpose of the RISMC Pathway is to develop and deploy approaches to support the management of uncertainty in safety margins quantification to improve decision making for NPPs.

To better understand the approach to determine safety margins, we first describe the two types of analysis used in this pathway (see Figure 19). Note that in actual applications, a blended approach is used where both types of analysis are used to support any one particular decision. For example, the approach could be either mostly probabilistic, mostly mechanistic, or both in nature.

Types of Analysis Used in Safety Margin Evaluations	
PROBABILISTIC	**MECHANISTIC**
Pertaining to stochastic (non-deterministic) events, the outcome of which is described by a probability.	**Pertaining to predictable events, the outcome of which is known with certainty if the inputs are known with certainty.**
Probabilistic analysis uses models representing the randomness in the outcome of a process. Because probabilities are not observable quantities, we rely on models to estimate probabilities for certain specified outcomes.	**Mechanistic analysis (also called "deterministic") uses models to represents situations where the observable outcome will be known given a certain set of parameter values.**
An example of a probabilistic model is the counting of *k* number of failures of an operating component in time *t*: Probability(k=1) = $\lambda e^{-\lambda t}$.	**An example of a mechanistic model is the one-dimensional transfer of heat (or heat flux) through a solid: $q = -k\partial T/\partial x$.**

Figure 19. Types of analysis that are used in the Risk-Informed Safety Margin Characterization Pathway.

The use of both types of analysis, probabilistic and mechanistic, is shown in Figure 20. Safety margin and uncertainty quantification rely on plant physics (e.g., thermal-hydraulics and reactor kinetics) coupled with probabilistic risk simulation. The coupling takes place through the interchange of physical parameters (e.g., pressures and temperatures) and operational or accident scenarios. This "margins analysis techniques" (i.e., methods for applying modeling and simulation tools to plant decision-making) is discussed further under Section 5.3.2. Development of tools for the representation of plant performance is discussed further in Section 5.3.3.

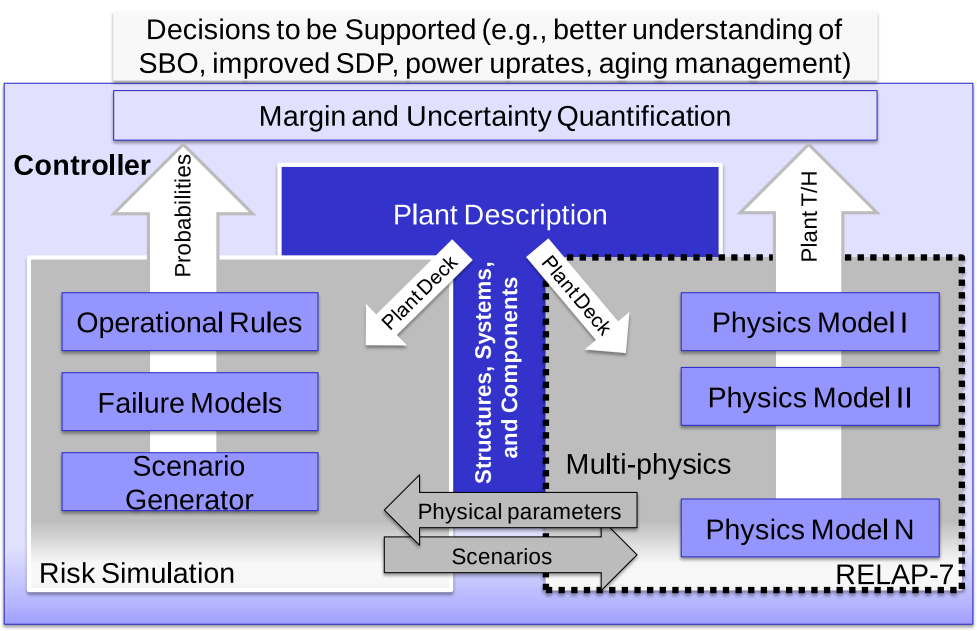


Figure 20. Attributes of the Risk-Informed Safety Margin Characterization approach for supporting decision-making.

5.3.1 The Safety Case

While definitions may vary in detail, "safety case" essentially means the following:

> *A structured argument, supported by a body of evidence that provides a compelling, comprehensible and valid case that a system is adequately safe for a given application in a given environment.*[1]

The realization of a safety case for RISMC applications will be an output when applying the method shown notionally in Figure 20. The safety-margin claims will do the following:

1. Make an explicit set of safety claims about the facility and SSCs

2. Produce evidence that supports the claims from #1 (e.g., representative operating history, redundancy in design, or results of analysis)

3. Provide a set of safety margin arguments that link the claims to the probabilistic and mechanistic evidence

4. Make clear the assumptions, models, data, and judgments underlying the arguments

5. Allow different viewpoints and levels of detail in a graded fashion for decision making.

The safety case of a facility or SSC should be regarded as having fundamental significance as opposed to being mere documentation of facility or SSC features. For practical purposes, "safety margin" is not observable in the way that many other operational attributes are (e.g., core temperature or embrittlement of pressure vessels). In decision-making regarding the facility or SSC, the safety case is, in practice, a proxy for the safety attribute. And, regardless of context, the formulation of a safety case is about developing a body of evidence and marshaling that evidence to inform a decision. All RISMC activities support these aspects.

5.3.2 Margins Analysis Techniques

This research area develops techniques to conduct margins analysis, including methodology for carrying out simulation-based studies of safety margin, using the following generic process steps (as shown in Figure 21) for RISMC applications. Also, two example applications of margins analysis follow.

1. Characterize the issue to be resolved in a way that explicitly scopes the modeling and analysis to be performed. Formulate an "issue space" that describes the safety figures of merit to be analyzed and the model parameter space that needs to be sampled.

2. Quantify the decision-maker and analyst's state-of-knowledge (uncertainty) of the key variables (and models relevant to the issue.

3. Determine issue-specific, risk-based scenarios and accident timelines (as shown in Figure 22).

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[1] Bishop, P. and R. Bloomfield, "A Methodology for Safety Case Development," Safety-Critical Systems Symposium, Birmingham, UK. 1998.

4. Represent plant operation probabilistically using the scenarios identified in Step 3. For example, plant operational rules (e.g., operator procedures, technical specifications, maintenance schedules) are used to provide realism for scenario generation. Because numerous scenarios will be generated, the plant and operator behavior cannot be manually created like in current risk assessment using event/fault trees. In addition to the *expected* operator behavior (plant procedures), the probabilistic plant representation will account for the possibility of failures.

5. Represent plant physics mechanistically. The plant systems level code (e.g., RELAP-7) will be used to develop distributions for the loads applied to the subject SSCs and their capacities to withstand those loads for the scenarios identified in Step 4. Because there is a coupling between Steps 4 and 5, they each can impact the other. For example, a calculated high pressure in an SSC may disable a component, thereby impacting an accident scenario.

6. Construct and quantify probabilistic load and capacity curves relating to the figures of merit analyzed to determine the safety margin.

7. Determine, to the degree possible, how to manage uncharacterized risk. Because there is no way to guarantee that all scenarios, hazards, failures, or physics are addressed, the decision maker should be aware of limitations in the analysis and adhere to protocols of "good engineering practices" to augment analysis.

8. Identify and characterize the factors and controls that determine safety margin within this issue to determine (and support) the safety case. Determine whether additional work to reduce uncertainty would be worthwhile or if additional (or relaxed) safety control is justified.

The following subsections present two example applications of the margins analysis process steps. The examples are greatly simplified and meant only to be representational. The first example involves a cable aging issue. The second example involves feed-and-bleed operation in a hypothetical loss of main feedwater transient.

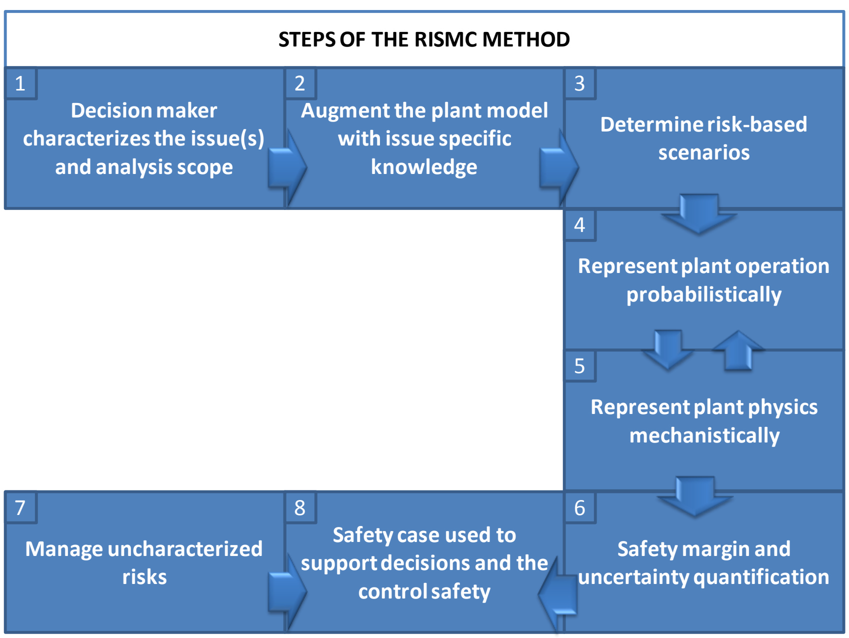

Figure 21. Depiction of the high-level steps required in the Risk-Informed Safety Margin Characterization method.

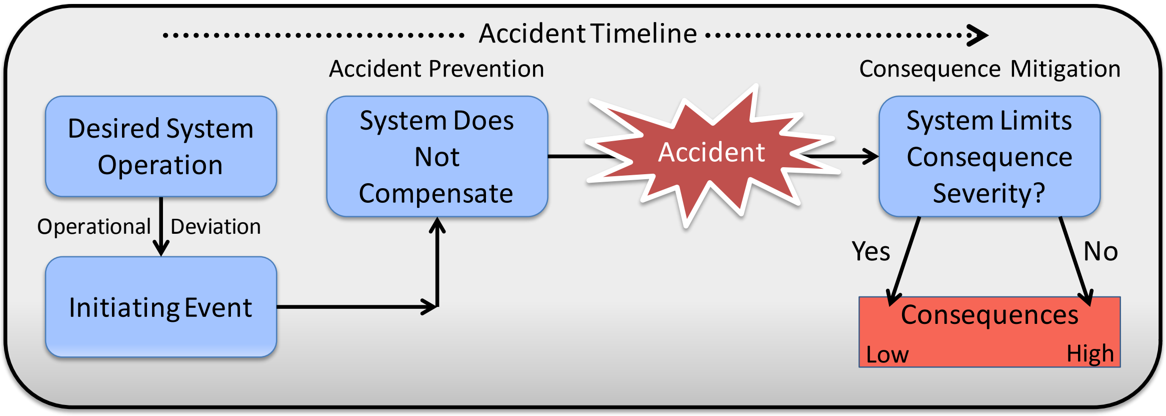

Figure 22. Accident scenario representation.

5.3.2.1 Process example one. The first example of the margins analysis generic process steps involves a RISMC application to cable aging/environmental qualification (after Blanchard and Youngblood[m]).

1. Characterize the Issue – Specific Step Taken for Example 1: Hypothetical plant operator issue – "Aging cables may be an issue at my plant. Degradation due to aging (or other effects) may be reducing our capacity for dealing with harsh accident-induced environments. There are a lot of cables potentially affected. What can I do to minimize the safety and economic impacts of this uncertainty?"

   Possible approach – if we can identify a subset of cables that provide enough functionality and focus monitoring or replacement on them, a very significant savings in resources could result. Therefore, such subsets should be identified.

2. Augment the Model with Issue Specific Knowledge – Specific Step Taken for Example 1: For cable failure probability in severe environments, start with a presumption of significant uncertainty in cable resistance to harsh environments.

3. Determine Risk-Based Scenarios – Specific Step Taken for Example 1: For this example, it is feasible to use a static probabilistic risk assessment to identify a subset of all cables whose performance suffices to maintain safety, even if all other cables were to degrade significantly. Identify candidate subsets, rank them according to other resource implications (e.g., cost of monitoring or replacement).

4. Represent the Plant Probabilistically – Specific Step Taken for Example 1: Used a plant static probability risk assessment model to represent applicable SSC failures. Focused on core damage frequency as the safety metric.

5. Represent the Plant Physics – Specific Step Taken for Example 1: Used a "harsh environment" model that represented component failure if its qualification temperature is exceeded for a specific probability risk assessment sequence.

[m] Risk Informed Safety Margin Characterization Case Study: Selection of Electrical Equipment To Be Subjected to Environmental Qualification, M2L11IN07020105, "Report on Trial Method and Case Study and Improvements," D. Blanchard (ARE) and R. Youngblood (INL), September 2011.

6. Safety Margin and Uncertainty Quantification – Specific Step Taken for Example 1: Used the internal events probability risk assessment to identify components inside containment for which demonstrating margin with respect to environmental qualification may be worthwhile.

7. Manage Uncharacterized Risk – Specific Step Taken for Example 1: None, but consider a simulation-based analysis to characterize harsh environments in more detail and determine whether degraded cables might credibly perform in a real accident (e.g., they may be needed only early in the accident, when the harsh environment has not had sufficient time to cause failure).

8. Safety Case to Support Decisions – Specific Step Taken for Example 1: The result of this kind of analysis is a collection of options, each option being a subset of all cables that, together, are capable of providing the necessary functionality even if all other cables degrade. In general, these options will have different advantages and disadvantages (e.g., different costs, different replacement costs, and different monitoring issues). These options should be presented to the decision-maker, and the decision-maker can choose one and focus the resources accordingly.

5.3.2.2 Process example two. The second example is a simulation-based RISMC application for functional reliability of feed and bleed (after Gabor et al.[n]).

1. Characterize the issue – Specific Step Taken for Example 2: Hypothetical plant operator issue – Feed and bleed is a core-cooling method that is only required in certain beyond-design-basis conditions and is not analyzed in the formal safety analysis report (Chapter 15). Probabilistic risk assessment makes "mission success" assumptions about it, but it always has been a gray area. For example, questions include the following: Under what conditions can it work at our plant? How reliable is it? What components do we need? What do operators need to do and how long do they have to accomplish these actions? How well do we know all this? How much does it change with power uprate?

   Possible approach – Conduct a thorough, simulation-based analysis of the performance of the feed-and-bleed function, generating time histories that sample appropriately over the space of epistemically uncertain variables, as well as variations in the performance of plant components and plant operators.

2. Augment the Model with Issue Specific Knowledge – Specific Step Taken for Example 2: Develop state-of-knowledge distributions of key parameters such as operator response times, component reliability parameters, pump characteristics, pressurizer power-operated relief valve, and safety valve relief capacity.

3. Determine Risk-Based Scenarios – Specific Step Taken for Example 2: Representative scenarios from a static probability risk assessment model for a loss-of-feedwater event tree were extracted and recast as a simple simulation (time based) model in Step 4.

4. Represent the Plant Probabilistically – Specific Step Taken for Example 2: Simulate enough time histories to cover issue space adequately. This will be iterative; it is still necessary to expend simulation resources judiciously to maximize the information gain from each run. Therefore, the strategy for covering the issue space will be issue space specific. In the feed-and-bleed example, it was expedient to discretize the space according to the availability of certain key components (e.g., pumps) and then sample the continuous variables conventionally.

[n] J. Gabor, R. Sherry and D. True, "Technical Framework for Management of Safety Margins--Loss of Main Feedwater Pilot Application," EPRI 1023032, Final Report, November 2011.

5. <u>Represent the Plant Physics – Specific Step Taken for Example 2</u>: In the feed-and-bleed example, probabilistic load and capacity curves were generated, parsed, and interpreted. The figure of merit used for analysis was "peak node temperature" essentially meant to correspond to "peak clad temperature." Modular Accident Analysis Program (MAAP)[o] was used to determine the plant physics for each scenario that was generated.

6. <u>Safety Margin and Uncertainty Quantification – Specific Step Taken for Example 2</u>: The capacity curve used was a triangle distribution centered at 2200°F and going linearly to zero at 2200 ±200°F. The load curves were histograms of simulation results for peak node temperature. The analyst was able to parse these results to show that within the simulations done, all instances in which a charging pump worked were successful, independent of power-operated relief valve operability. However, at least some instances of safety injection did not always succeed for reasons that are not yet clear. Both of these aspects are different from assumptions widely used in reactor risk analysis.

7. <u>Manage Uncharacterized Risk – Specific Step Taken for Example 2</u>: It would be useful to know how much time the operator has (after loss of all feedwater) to accomplish this task. It also would be useful to know how all of this changes with power uprate, which would change the allowable time at least somewhat and might move some pump/power-operated relief valve combinations from the "probable success" column to the "probable failure" column.

8. <u>Safety Case to Support Decisions – Specific Step Taken for Example 2</u>: The results suggest that the function is extremely reliable provided that a charging pump works. This has implications for procedure improvement (e.g., stress the charging pumps) and for operations (e.g., make sure a charging pump is operational and consider diesel-backing them if they are not already). The high reliability of this function also serves to reduce the downside risk significance of possible future performance issues associated with auxiliary feedwater (i.e., if a performance issue is ever identified with auxiliary feedwater, its risk/ regulatory significance will be less because of this work due to the backup function being highly reliable).

Work in 2012 will develop and test methods for carrying out these steps in case studies coordinated with industry. The following margins analysis techniques deliverables are planned:

- (2012) Demonstrate the RISMC methodology using a test case based on the INL Advanced Test Reactor.

- (2012) Assist EPRI in defining the station blackout conditions for a postulated event in a boiling water reactor with analysis focusing on the impact on safety margins associated with an extended power uprate.

- (2013) Demonstrate RELAP-7 capability to simulate boiling water reactor station blackout with the RAVEN system controller.

- (2014) Demonstrate current margins analysis techniques on selected case studies using the completed software structure. The case studies will be selected in consultation with external stakeholders and will be chosen based on their potential to address an issue important to LWR sustainability and/or to achieve widespread stakeholder acceptance of the RISMC approach.

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[o] The Modular Accident Analysis Program is a computer code developed by EPRI that simulates the response of light water and heavy water moderated NPPS, both current designs and advanced LWRs, during severe accident sequences, including actions taken as part of the severe accident management guidelines.

- (2015) The margins analysis techniques will be sufficiently mature to enable industry to conduct margins quantification exercises for their own plants, including using RELAP-7/RAVEN/Grizzly (component aging module)/others (multiscale system analysis of plant performance, such as coupling to localized fuel behavior for a boiling water reactor station blackout and other defined LWR scenarios).

- (2016) Use margins analysis techniques, including use of RELAP-7/RAVEN/Grizzly (component aging module)/others, to analyze an industry-important issue (e.g., assessment of major component degradation in the context of life extension or assessment of the safety benefit of advanced fuel forms). Test case will be chosen in consultation with external stakeholders.

- (2020) Ensure development and validation to the degree that by the end of 2020, RELAP-7 and the margins analysis techniques are the generally accepted approach for safety analysis support to plant decision-making, covering analysis of design-basis events and events within the technical scope of internal events probabilistic risk assessment.

5.3.3 Modeling and Simulation Activities in Support of RISMC

5.3.3.1 Simulation controller. Simulation of a time history of plant performance requires a thermal-hydraulics simulation that is carried out conditionally, based on the postulated states of the plant components (e.g., which pumps are working, which pumps are not working, the positions of the various valves, and so on). The thermal-hydraulics portion of this is performed by RELAP-7, with the determination of plant component states done by the simulation controller. The RAVEN controller will determine component states based on the following:

- Plant control system actions (e.g., control logic generating a safety injection signal and ensuing component changes of state)

- Operator performance, considering procedurally required actions, and operator responses to technical specifications

- Component reliability coupled to current plant conditions.

To determine and manage these states, the controller will need to store plant physical properties, including SSCs. Inside the controller will be a component library, which stores component information such as component type, dimensions, materials, age, and failure models.

5.3.3.2 RELAP-7. Although incremental advances have been made continuously over the past two decades to improve modeling of plant components and transient/accident phenomena, the system (plant) analysis tools used in the industry’s engineering applications remain based on a decades-old modeling framework and computational methodology that do not take advantage of modern developments in computers and in computational science and engineering. Although the codes have served as an adequate basis to address traditional safety margin analysis, significant enhancements will be necessary to support the challenges of plant decision-making on extended and enhanced plant operations. RELAP-7 is a systems code that will simulate behavior at the plant level.

5.3.3.3 Aging simulation. A simulation tool called Grizzly will be developed to model component aging and damage evolution in LWRs. Grizzly will couple with RELAP-7 and RAVEN to provide aging analysis in support of the RISMC methodology.

Modeling and simulation deliverables include the following:

- (2012) Deliver software development and quality assurance plans for RELAP-7.
- (2013) Develop a reactor loop capability in RELAP-7 for two-phase flow, including the representation of several simplified major physical components for a boiling water reactor's primary and safety systems.
- (2013) Demonstrate RELAP-7 capability to simulate boiling water reactor station blackout with the RAVEN system controller.
- (2013) Deliver the RELAP-7 verification and validation plan.
- (2013) Demonstrate RELAP-7 capability to simulate loss-of-coolant accident of both small and large break events.
- (2014) Complete software structure, allowing rapid and scalable development. At this time, RELAP-7 can be fully controlled by RAVEN for complete systems analysis. RELAP-7/RAVEN will have the capability to be coupled to other applications (e.g., aging and fuels modules) and perform as a balance-of-plant capability for the multidimensional core simulators under development in other DOE programs.
- (2015) The margins analysis techniques will be sufficiently mature to enable industry to conduct margins quantification exercises for their own plants, including using RELAP-7/RAVEN/Grizzly (component aging module)/others (multiscale system analysis of plant performance, such as coupling to localized fuel behavior for a boiling water reactor station blackout and other defined LWR scenarios).
- (2015) RELAP-7 will be validated against an accepted set of data.
- (2016) Complete full-scope analysis of a power uprate using RELAP-7/RAVEN (test case will be chosen in consultation with external stakeholders).
- (2016) Use margins analysis techniques, including use of RELAP-7/RAVEN/Grizzly (component aging module)/others, to analyze an industry-important issue (e.g., assessment of major component degradation in the context of life extension or assessment of the safety benefit of advanced fuel forms). Test case will be chosen in consultation with external stakeholders.
- (2020) Ensure development and validation to the degree that by the end of 2020, RELAP-7 and the margins analysis techniques are the generally accepted approach for safety analysis support to plant decision-making, covering analysis of design-basis events and events within the technical scope of internal events probabilistic risk assessment.

5.4 Research and Development Cooperation

Industry is significantly engaged in RISMC activities, and the level of engagement is increasing. Up to now, industry engagement in RISMC (primarily through EPRI) has taken place at two levels: (1) input into program planning and (2) active participation in RISMC Working Group activities. One effect of this influence has been strengthening the RISMC team consensus that RISMC developments should be driven by "use cases" (i.e., explicitly planned eventual applications that are used to formulate requirements on development of the next-generation capability) and “case studies” (i.e., actual applications that scope particular developments and, once completed, support assessment of the current phase of development). EPRI and other industry representatives are becoming increasingly involved in detailed technical planning of the case studies that now drive development activities and are expected to support actual execution. This has two effects: (1) it helps to ensure the program moves in a direction that addresses practical industry concerns, and (2) it provides the RISMC team with access to engineering expertise that is needed in development of enabling methods and tools.

Coordination of RISMC activities includes the following:

- **EPRI:** EPRI will continue to play an important role in high-level technical steering and in detailed planning of RISMC case studies. RISMC work is coordinated with EPRI Long-Term Operation Program work.

- **Other industry partners:** Involvement of engineering and analysis support from industry is presently foreseen in the performance of case studies to drive next-generation analysis development and in formulation of component models for implementation in next-generation analysis capability. The level of analysis effort to be provided and the source of funding for that effort remain to be determined. The individuals prospectively involved are either industry consulting firms or currently independent consultants who have working relationships with current licensees. All individuals are experts in applying traditional safety analysis tools and are conversant with risk-informed analysis.

5.5 Research and Development Products and Schedule

The main products of the RISMC Pathway are as follows:

- A risk-assessment method tied to safety margins quantification, including a next-generation plant simulation approach that will address plant safety issues, ranging from NPP protection up to, and including, regulatory issues.

- Advanced tools for safety assessment that enable more accurate representation of a NPP safety margin, including RELAP-7, RAVEN, Grizzly, and other capabilities, as applicable.

It has been agreed upon with industry that the focus in the near term will be on negotiated case studies that specify a scope of phenomena, components, and simulation capabilities needed to address the given issue space, yielding a product at the end of the first round of development that only will have a partial scope of applicability, but will be testable and verifiable within that scope.

It is expected that development of the safety margins analysis techniques will be largely complete in the first round, including illustrations of margin characterization and methods for driving RELAP-7 to assess margin within the scope of first-round case studies. Refinement of the associated methods and tools would continue thereafter at a level of effort significantly reduced compared to the effort associated with RELAP-7 development.

In the first round, RELAP-7-compatible models of passive SSCs also will be developed. As other pathways develop models and results to be input to margins assessments, they will be addressed beginning in the first round and continuing more intensively in the second round. Application of test and operating data to RELAP-7 calibration and model testing will begin in the first round with data used to validate existing safety analysis codes. As newer data become available to address issues not covered by the old data, comparison with those data will support RELAP-7 refinement.

Beginning in the second round of near-term development, inputs from other pathways are expected to become available and will begin to inform RISMC development work.

Assuming a funding profile commensurate with that in the current program plan, RELAP-7 development is expected to be substantially complete in 2015 at the end of the second round. This does not mean that RELAP-7 would be frozen as of 2015, any more than previous-generation safety analysis codes have been frozen, but its development would be more evolutionary in nature.

Beginning in 2013 and continuing thereafter, increasing effort will be devoted to training a broader user community of practice and supporting their applications.

The implementation schedule is structured to support the following high-level milestones:

- (2012) Deliver software development and quality assurance plans for RELAP-7.
- (2012) Demonstrate the RISMC approach using a test case based on the INL Advanced Test Reactor.
- (2012) Assist EPRI in defining the station blackout conditions for a postulated event in a boiling water reactor with analysis focusing on the impact on safety margins associated with an extended power uprate.
- (2013) Develop a reactor loop capability in RELAP-7 for two-phase flow, including the representation of several simplified major physical components for a boiling water reactor's primary and safety systems.
- (2013) Demonstrate RELAP-7 capability to simulate boiling water reactor station blackout with the RAVEN system controller.
- (2013) Deliver the RELAP-7 verification and validation plan.
- (2013) Demonstrate RELAP-7 capability to simulate loss-of-coolant accident of both small and large break events.
- (2014) Complete software structure, allowing rapid and scalable development. At this time, RELAP-7 can be fully controlled by RAVEN for complete systems analysis. RELAP-7/RAVEN will have the capability to be coupled to other applications (e.g., aging and fuels modules) and perform as a balance-of-plant capability for the multidimensional core simulators under development in other DOE programs.
- (2014) Demonstrate current margins analysis techniques on selected case studies using the completed software structure. The case studies will be selected in consultation with external stakeholders and will be chosen based on their potential to address an issue important to LWR sustainability and/or to achieve widespread stakeholder acceptance of the RISMC approach.
- (2015) The margins analysis techniques will be sufficiently mature to enable industry to conduct margins quantification exercises for their own plants, including using RELAP-7/RAVEN/Grizzly (component aging module)/others (multiscale system analysis of plant performance, such as coupling to localized fuel behavior for a boiling water reactor station blackout and other defined LWR scenarios).

- (2015) RELAP-7 will be validated against an accepted set of data.

- (2016) Complete full-scope analysis of a power uprate using RELAP-7/RAVEN (test case will be chosen in consultation with external stakeholders).

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- (2020) Ensure development and validation to the degree that by the end of 2020 RELAP-7 and the margins analysis techniques are the generally accepted approach for safety analysis support to plant decision-making, covering analysis of design-basis events and events within the technical scope of internal events probabilistic risk assessment.