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Light Water Reactor Sustainability Program — A Summary of Collaborative Research and Development Activities

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U.S. Department of Energy

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EXECUTIVE SUMMARY

This report describes the collaborative research and development projects in which the U.S. Department of Energy's Light Water Reactor Sustainability (LWRS) Program engaged with industry, regulatory agencies, and other organizations during Fiscal Year 2018. One way that this Program accomplishes its objectives—to develop technologies and other solutions that can improve the reliability, sustain the safety, enhance the economic performance, and extend the life of current reactors—is by conducting research together with industry and key organizations through cooperative arrangements and plans, through coordinated planning and management of resources and activities, through periodic technical exchanges of data and information, or by other means of interaction (i.e., contracts, memoranda of understanding, non-disclosure agreements, etc.). Broadly, these interactions represent different types of collaborations—formal or informal agreements between two or more organizations to work on something together that may be for a short or extended duration and may involve a single purpose or broad set of goals. DOE's research, development, and demonstration role focuses on enhancing the safe, efficient, and economical performance of the nation's nuclear fleet while studying and mitigating aging phenomena and issues that are applicable to the service environments of operating reactors and require unique DOE laboratory expertise. Often, research and development (R&D) and demonstration activities are cost-shared, coordinated, or otherwise jointly conducted with industry, regulatory agencies, or other organizations through the aforementioned or other collaborative mechanisms.

Operation of the existing fleet of plants to 60 years, extending the operating lifetimes of those plants beyond 60 years and, where practical, making further improvements in their productivity are essential to support the nation's energy needs. Recently, several utilities have submitted or announced plans to submit applications to the U.S. NRC to begin the subsequent license-renewal process, extending the operating license period beyond 60 years from the date of their initial licensing. This marks an important planned milestone in the history of commercial nuclear power operations in the U.S.—one that underscores the long-term dependability of these plant designs and the commitment to their long-term performance by the organizations that operate them. The LWRS Program will continue to work with owner-operators to address the key issues needed to support the technical bases for continued safe long-term operation of our nation's nuclear power assets.

The U.S. Department of Energy's Office of Nuclear Energy's (DOE-NE's)[a] primary mission is to advance nuclear power as a resource capable of making major contributions in meeting the nation's energy supply, environmental, and energy security needs. DOE-NE is working to revitalize the nuclear energy sector by addressing three main priorities:

1. Expand the lifespan of the nation's existing fleet,
2. Develop a new pipeline of advanced nuclear reactors, and
3. Strengthen the nation's fuel-cycle infrastructure

a. https://www.energy.gov/ne/about-us.

The LWRS Program is the primary programmatic activity that addresses Priority 1. For the LWRS Program, sustainability is defined as the ability to maintain safe and economic operation of the existing fleet of nuclear power plants for as long as possible and practical. It has two facets with respect to long-term operations: (1) to provide science-based solutions to the industry to implement technology to exceed the performance of the current labor-intensive business model; and (2) to manage the aging of plant systems, structures, and components (SSCs) so that nuclear power plant lifetimes can be extended and the plants can continue to operate safely, efficiently, and economically. The LWRS Program carries out its mission through a set of four distinct R&D pathways that are summarized below:

- ***Materials Research.*** R&D to develop the scientific basis for understanding and predicting long-term environmental degradation behavior of materials in nuclear power plants. This work will provide data and methods to assess the performance of SSCs essential to safe and sustained nuclear power plant operations. The R&D products will be used to define operational limits and aging mitigation approaches for materials in nuclear power plant SSCs subject to long-term operating conditions, providing key input to both regulators and industry.
- ***Plant Modernization.*** R&D to address nuclear power plant economic viability in current and future energy markets through innovation, efficiency gains, and business-model transformation through digital technologies. This includes addressing the long-term aging and modernization or replacement of legacy instrumentation and control technologies (I&C) by R&D and research, development, and testing of new I&C technologies and advanced condition-monitoring technologies for more automated and reliable plant operation. The resulting R&D products will enable modernization of plant systems and processes while building a technology-centered business-model platform that supports improved performance at lower cost.
- ***Risk-informed Systems Analysis (RISA).*** R&D to optimize safety margins and minimizing uncertainties to achieve high levels of safety and economic efficiencies. The pathway will: (1) deploy the method and tools of technologies that enable better representation of safety margins and the factors that contribute to cost and safety; and (2) conduct advanced risk-assessment applications with industry to support margin management strategies that enable more cost-effective plant operation. The methods and tools provided by the pathway will support effective safety margin management for both active and passive SSCs.
- ***Reactor Safety Technologies.*** R&D to improve the understanding of beyond-design-basis events and reduce uncertainty in severe accident progression, phenomenology, and outcomes, using existing analytical codes and information gleaned from severe accidents—in particular, the Fukushima Daiichi events. This information has been used to aid in the development of mitigating strategies and improving severe accident-management guidelines for the current light-water reactor fleet. In addition, methods for enhancing plant resilience to accident-initiating events have also been explored.

CONTENTS

ACRONYMS

ABSI	auxiliary beam stress improved
AMS	Analysis and Measurement Services
ASR	alkali-silica reaction
ASSW	austenitic stainless steel welds
ATF	Accident Tolerant Fuel
ATR	Advanced Test Reactor
BWROG	Boiling Water Reactor Owners’ Group
BWR	boiling water reactor
CASS	cast austenitic stainless steel
CFR	Code of Federal Regulations
CGR	crack growth rate
CNWG	Civil Nuclear Working Group
CRIEPI	Central Research Institute of Electric Power Industry
DOE	Department of Energy
DOE-NE	Department of Energy Office of Nuclear Energy
EdF	Électricité de France
EMDA	Expanded Materials Degradation Assessment
EPR	ethylene-propylene rubber
EPRI	Electric Power Research Institute
FLEX	Diverse and Flexible Coping Strategy
FSW	friction stir welding
GE	General Electric
GWM	guided-wave monitoring
HFE	human-factors engineering
HSSL	Human Systems Simulation Laboratory
IAE	Institute for Applied Energy
IASCC	irradiation-assisted stress corrosion cracking
ICIC	International Committee on Irradiated Concrete
I&C	instrumentation and control

II&C	instrumentation, information, and control
INERI	International Nuclear Energy Research Initiative
INL	Idaho National Laboratory
INPO	Institute of Nuclear Power Operations
JAEA	Japan Atomic Energy Agency
KAIST	Korean Advanced Institute of Science and Technology
LOCA	loss of coolant accident
LTO	long-term operations
LWR	light-water reactor
LWRS	Light Water Reactor Sustainability
MBDBE	mitigation of beyond-design-basis event
METI	Ministry of Economy, Trade, and Industry
MsS	magnetostrictive sensor
NDE	non-destructive examination
NEA	Nuclear Energy Agency
NEAMS	Nuclear Energy Advanced Modeling and Simulation
NEI	Nuclear Energy Institute
NEUP	Nuclear Energy University Program
NRC	U.S. Nuclear Regulatory Commission
NUREG	NRC Technical Report
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
PRA	probabilistic risk assessment
PWROG	Pressurized Water Reactor Owners' Group
PWR	pressurized water reactor
QA	quality assurance
R&D	research and development
RCIC	Reactor Core Isolation Cooling
RIAR	Research Institute of Atomic Reactors
RIMM	Risk-Informed Margins Management
RISA	Risk-Informed Systems Analysis

RPV	reactor pressure vessel
RST	Reactor Safety Technologies
SAMG	severe accident management guideline
SAWM	severe accident water management
SCC	stress corrosion cracking
SHM	structural health monitoring
SNL	Sandia National Laboratories
SSC	system, structure, and component
SwRI	Southwest Research Institute
TIP	Top Innovative Practice (Award)
TSC	Technical Support Center
TSG	Technical Support Guidance
U.S.	United States
UTK	University of Tennessee–Knoxville
WGEV	Working Group on External Hazards
XLPE	cross-linked polyethylene

1. INTRODUCTION

Sustainability in the context of this program is the ability to maintain the safe and economic operation of the existing fleet of nuclear power plants now and in the future. It has two objectives with respect to long-term operations: (1) to provide science and technology-based solutions to industry to overcome the current labor-intensive business model and associated practices; and (2) to manage the aging of systems, structures, and components (SSCs) so nuclear power plants can continue to operate safely and cost effectively.

The Light Water Reactor Sustainability (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 existing nuclear power plants.
2. Applying this fundamental knowledge to develop and demonstrate methods and technologies that support the safe and economical long-term operation of existing nuclear power plants.
3. Researching new technologies to address enhanced nuclear power plant performance, economics, and safety.

The LWRS Program consists of the following primary technical areas of research and development (R&D):

1. **Materials Research:** R&D to develop the scientific basis for understanding and predicting long-term environmental degradation behavior of materials in nuclear power plants. This work will provide data and methods to assess the performance of SSCs essential to safe and sustained nuclear power plant operations. The R&D products will be used to define operational limits and aging-mitigation approaches for materials in nuclear power plant SSCs subject to long-term operating conditions, providing key input to both regulators and industry.
2. **Plant Modernization:** R&D to address nuclear power plant economic viability in current and future energy markets through innovation, efficiency gains, and business-model transformation through digital technologies. This includes addressing the long-term aging and modernization or replacement of legacy instrumentation and control (I&C) technologies by R&D and testing of new I&C technologies and advanced condition-monitoring technologies for more automated and reliable plant operation. The R&D products will enable modernization of plant systems and processes while building a technology-centered business-model platform that supports improved performance at a lower cost.
3. **Risk-informed Systems Analysis (RISA):** R&D to optimize safety margins and minimizing uncertainties to achieve high levels of safety and economic efficiencies. The pathway will: (1) deploy the method and tools of technologies that enable better representation of safety margins and the factors that contribute to cost and safety; and (2) conduct advanced risk-assessment applications with industry to support margin management strategies that enable more cost-effective plant operation. The methods and tools provided by the pathway will support effective safety margin management for both active and passive SSCs.
4. **Reactor Safety Technologies (RST):** R&D to improve understanding of beyond-design-basis events and reduce uncertainty in severe-accident progression, phenomenology, and outcomes using existing analytical codes and information gleaned from severe accidents—in particular, the Fukushima Daiichi events. This information has been used to aid in the development of mitigating strategies and improving severe-accident management guidelines for the current light-water reactor (LWR) fleet. In addition, methods for enhancing plant resilience to accident-initiating events have been explored.

Nuclear energy is an important part of supplying our nation's electricity safely, dependably, and economically, with reduced carbon dioxide emissions, through the long-term safe and economical operation of current nuclear power plants. The United States (U.S.) Department of Energy Office of Nuclear Energy (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, reliable, and economical operations of the existing commercial fleet of nuclear power plants.

This report describes the collaborative activities in which the U.S. Department of Energy's LWRS Program engaged with industry, regulatory agencies, and other organizations during Fiscal Year 2018. One of the ways that this program accomplishes its objectives—to develop technologies and other solutions that can improve the reliability, sustain the safety, enhance the economic performance, and extend the life of current reactors—is by conducting research together with industry and key organizations either through cooperative arrangements and plans, through coordinated planning and management of resources and activities, through periodic technical exchanges of data and information, or by other means of interaction (i.e., contracts, memoranda of understanding, non-disclosure agreements, etc.). Broadly, these interactions represent different types of collaborations—formal or informal agreements between two or more organizations to work on something together that may be for a short or extended duration and may involve a single purpose or broad set of goals. DOE's research, development, and demonstration role focuses on enhancing the safe, efficient, and economical performance of the nation's nuclear fleet and by studying aging phenomena and issues that are applicable to the service environments of operating reactors and require unique DOE laboratory expertise. Often, the costs of R&D and demonstration activities are shared or the R&D work is coordinated or otherwise jointly conducted with industry, regulatory agencies, or other organizations through a variety of the aforementioned or other collaborative mechanisms.

Although this report provides a description and summary of the collaborative activities between the LWRS Program and other programs and organizations, it is not the intent of the report to take credit for these collaborations or the products of these efforts. Rather, it is written as an acknowledgment of the efforts and contributions of the organizations with whom the LWRS Program collaboratively conducts research or has had the opportunity to conduct technical information exchanges or other interactions. This report is written and organized from the perspective of the LWRS Program, in addition to its own role in supporting the sustained operation of the existing fleet of U.S. LWRs. The report also provides a crosswalk between the R&D planning documents developed by the LWRS Program and the extension of those plans to understand how the program engages other organizations, programs, and the commercial nuclear power industry and suppliers to achieve vital outcomes for the sustainability of the U.S. nuclear power industry.

Other participants involved in collaborative activities reported herein may not be engaged in research or may have markedly different goals from those of the LWRS Program and other participants in a collaborative activity. It does, then, underscore the importance of the topics that are addressed through such collaborative efforts that organizations with different aims and goals support such activities. The LWRS Program is fortunate to be able to collaborate in mature R&D and related efforts that have been ongoing for many years by other research organizations. Likewise, through this program and the products of its collaborations, the LWRS Program and other collaborators have developed and continue to enhance new and innovative capabilities that can be brought to bear on the challenges facing the current fleet of operating LWRs. The activities reported herein are also vital to ensure the most efficient use of fiscal resources, coordinate between organizations on the prioritization and use of key facilities and personnel, and ensure the production of technical information and technologies on timelines and schedules needed to support key decision-making activities important to the industry, regulators, and other stakeholders.

The following sections of this report summarize the means by which R&D is being supported or accomplished through activities and interactions in the R&D pathways of the LWRS Program. Each section provides a summary of the individual R&D pathway, the R&D collaborative activities, the participant and their roles or contributions in those activities, and the overall purpose of the collaboration, that is, the outcomes they are aimed to support or address. Where feasible, participating organizations involved in these activities are explicitly identified in these summaries. In some instances, the state of the collaboration with respect to roles, specific contributions, and other relevant details of the agreements may be under development, limiting the summary to the information that is available at this time.

2. MATERIALS RESEARCH PATHWAY

Nuclear reactors present a very challenging service environment to materials. Many components in an operating reactor must tolerate high-temperature water, stress, vibration, and an intense neutron field. Degradation of materials in this environment can affect component performance and, without accurate predictive knowledge of component lifetime or if degradation is left unmitigated, can lead to unexpected and costly repairs. Over 25 different metal alloys can be found within the primary and secondary systems, along with additional materials in concrete, the containment vessel, I&C equipment, cabling, and elsewhere. Such variability in material types, challenging environment conditions, stress states, and many other factors make material degradation in a nuclear power plant a complex phenomenon. Dominant forms of degradation may vary greatly between the different SSCs and can have an important role in the safe and efficient operation of a nuclear power plant.

The continued operation of the existing nuclear power fleet beyond 60 years will place enormous demands on materials and components in their in-service environments. Understanding the performance of these materials during these longer periods of operation entails the characterization of the materials as they age under the demands of in-service conditions and relating that knowledge to the performance characteristics of the different SSCs. The research conducted through the activities described here is intended to provide data, models, methods, and techniques to inform industry on long-term materials performance. NRC Technical Report (NUREG)/CR-7153, "Expanded Materials Degradation Assessment (EMDA)," gives a detailed assessment of many of the key issues in today's reactor fleet and provides a starting point for evaluating those degradation forms particularly important for consideration during continued operation. While extending operation will add additional time and neutron fluence, the primary impact will be increased susceptibility to degradation mechanisms. The application of modern materials science to mechanistic studies and the development of technology and materials are critical to resolve challenging issues in a timely and practical manner to produce results that can be used by industry to monitor, predict, and plan for the effective management of materials in their in-service environments.

2.1 Purpose, Goals, and R&D Activities

The Materials Research Pathway provides an important foundation and gateway for performing R&D activities that are critical for licensing and managing the long-term, safe, and economical operation of nuclear power plants. Materials aging mechanisms and their influence on nuclear power plant SSCs must be understood with sufficient predictable confidence to support planning, investment, and licensing for necessary component evaluation and structural repair and replacement needs for continued plant operation. Understanding, managing, and mitigating materials degradation processes are key priorities for the Materials Research Pathway. Proactive management is essential to ensure that any degradation from long-term operation of nuclear power plants does not affect the public's confidence in the safety and reliability of U.S. operating nuclear power plants. The strategic goals of the pathway are to understand and predict the environmental and service mechanisms that age and degrade materials during continued operation, predict their effects on the performance of SSCs, and develop methods and tools for characterizing and mitigating damage to achieve safe and economic operation of nuclear power plants. Such strategic goals are critical in meeting the primary mission of DOE-NE to ensure that nuclear power will remain a viable option for the U.S. energy needs for generations to come.

Identifying, formulating, and prioritizing all of the competing needs for effective aging materials management is done in a collaborative manner with other organizations who provide annual input. This involves obtaining input from technical experts representing broad institutional experience on identified materials issues and topics and assessing their priorities in order to maintain an effective and responsive Materials Research Pathway. Previous workshops identified research needs that are summarized in joint publications, such as NUREG/CR-7153. Continued dialogue with the Electric Power Research Institute (EPRI), NRC, vendors, utilities, and other institutions around the world is used to prioritize emerging needs that are addressed by the Materials Research Pathway. Through its collaborative and cooperative research activities with industry, other R&D organizations, regulatory agencies, universities, and others, the Materials Research Pathway has been focused on the following four principal area of activities:

1. Reactor Metals:
    A. Performance of Reactor Pressure Vessel Steels
    B. Mechanisms of Irradiation-Assisted Stress Corrosion Cracking
    C. Stress Corrosion Cracking Initiation in Nickel-Base Alloys
    D. Aging and Radiation-Induced Damage of Structural Materials
    E. Environmentally Assisted Fatigue
    F. Thermal Aging of Cast Austenitic Stainless Steel.
2. Concrete and Civil Structure Degradation:
    A. Radiation and Environmental Induced Damage of Concrete Structures
    B. Alkali-Silica Reactions in Concrete Structures
    C. Nondestructive Evaluation of Concrete and Civil Structures.
3. Cable Systems:
    A. Mechanisms of Cable Insulation Aging and Degradation
    B. Nondestructive Evaluation of Cable Insulation.
4. Mitigation Technologies:
    A. Advanced Weld Repair of Irradiated Materials
    B. Advanced Replacement Materials.

2.2 Collaborative Research and Development Activities

The interactions with industry, the NRC, and other organizations are broad and include cooperation, coordination, and direct cost-sharing activities. The pathway, through cost-sharing, leverages resources from industry participants and R&D organizations to achieve common objectives and ensure that the right priority and focus are employed in LWRS research activities.

Through collaborative and cooperative cost-sharing efforts, the Materials Research Pathway and the EPRI Long-Term Operations (LTO) Program, for example, have established separate, but complementary R&D programs to address a broad spectrum of nuclear reactor materials issues and the long-term operation challenges facing the current operating fleet. Since 2010, the Materials Research Pathway and LTO Program have cooperatively pursued extensive, long-term R&D activities related to the ability of operating the existing fleet for periods beyond 60 years. Considerable research efforts are underway on a cost-sharing collaborative and cooperative agreement to provide a solid foundation of data, experiences, and knowledge.

Since the inception of the LWRS Program, the Materials Research Pathway has worked with the NRC closely to coordinate on research needs and activities to address them. Research efforts of the NRC are considered carefully during annual planning in order to best coordinate. In addition, cooperative efforts such as NUREG/CR-7153 and the formation of an Extended Service Materials Working Group have provided valuable sources of additional input to planning. The Materials Research Pathway also coordinates research activities with the LTO and Materials Reliability Programs of EPRI.

The following sections provide brief descriptions of collaborative research projects in which the Materials Research Pathway is actively engaged and the manner in which they are being conducted with other organizations.

2.2.1 Reactor Metals

2.2.1.1 Performance of Reactor Pressure Vessel Steels

To ensure that commercial nuclear power plants can be safely and reliably operated for extended service periods, it will be necessary to demonstrate that the reactor pressure vessels (RPVs) for those plants can maintain adequate safety margins against radiation-induced embrittlement, manifested as increases in the ductile-brittle fracture temperature (ΔT) for the duration of the plant's service life. A primary objective of the LWRS Program's research efforts on this topic is to develop a robust physical model to accurately predict transition temperatures at high fluence (i.e., at least 10^{20} n/cm^2, E >1 MeV) for vessel-relevant fluxes pertinent to extended plant operations. This research involves experimental testing of representative and archival heats of steel used in RPV construction, modeling of the microstructural processes that occur during extended operations that influence the mechanical properties, and the larger, engineering-scale modeling of the changes to RPV fracture tolerance with aging under normal-operating and accident-scenario conditions. This topic incorporates the examination of RPV materials harvested from the Zion Unit 1 nuclear power plant between 2015 and 2016 to provide material in addressing gaps in knowledge and use that material towards benchmarking model predictions. Furthermore, work in this subject area addresses new techniques in materials testing to improve fracture property evaluations of RPV materials and address potential biases in the materials-surveillance database.

Key interactions include the following:

- **Westinghouse** has provided eight archival heats of materials currently used in operating commercial reactor surveillance capsules for accelerated test-reactor irradiations (Advanced Test Reactor [ATR]-2 Project), currently being examined in the LWRS Program to determine high-fluence effects on material properties. Westinghouse and the Pressurized Water Reactor Owners Group (PWROG) have provided high-copper surveillance material from a currently operating nuclear power plant that was irradiated to various doses for microstructural characterization. Also, a large piece of archived surveillance weld for Zion Unit 1 has been provided to Oak Ridge National Laboratory (ORNL) for characterization of the Zion WF-70 weld in the unirradiated condition to complement current LWRS efforts in characterizing the beltline weld from decommissioned Zion Unit 1 by Westinghouse and PWROG.
- **Rolls Royce** has provided collaborative support for the testing of new advanced steels that may be less sensitive to embrittlement over long service lifetimes or high fluences. This includes providing material used in experimental reactor tests (e.g., ATR-2 Project) and financial support to an LWRS Program university contractor for the post-irradiation examination and testing of advanced steel alloys.
- A **nuclear laboratory partner** has provided both model RPV alloys for the high-fluence experimental testing of RPV steels and continued technical support to the program on RPV performance.
- **Central Research Institute of Electric Power Industry (CRIEPI, Japan)** has provided complementary testing of mini-compact tension specimens as part of an international round-robin led by the LWRS Program. CRIEPI is also performing comparative testing on the harvested Zion RPV base-metal specimens through a coordinated effort with the LWRS Program. Involvement by CRIEPI in these tasks is through the DOE Civil Nuclear Working Group (CNWG) agreement.
- A **commercial nuclear utility** has contributed technical information and support towards the development and planning of future work involving the recovery of reactor surveillance capsules that

will provide additional information on radiation-sensitive RPV weld materials and the long-term thermal aging effects that are difficult to evaluate through accelerated aging conditions.

Research generated in this work will permit the development of embrittlement models for RPV steels for extended operating conditions. The validation of codes, standards, and models is based on results obtained from experimental reactor test data, plant surveillance data, and the examination of service-aged (harvested) materials. This research will provide industry and regulators with a comprehensive tool to evaluate the performance of RPVs, which will help utilities and regulators make more-informed decisions on nuclear power plant aging-management decisions and identify options for extended operations.

2.2.1.2 Irradiation-Assisted Stress Corrosion Cracking

The objective of this work is to determine the mechanisms of irradiation-assisted stress corrosion cracking (IASCC) in austenitic stainless steels through the evaluation of materials performance as a function of various metallurgical (alloy chemistry, heat treatment, etc.) and environmental (irradiation, water chemistry) stressor conditions. This work also evaluates post-irradiation annealing as a means for reducing IASCC susceptibility. The goal of this work is to apply the knowledge gained through testing towards models for improved prediction of IASCC-related failures of in-service materials in extended commercial reactor operations.

Key interactions include the following:

- **Électricité de France (EdF, France)** has coordinated the transfer of ownership of the high-fluence irradiated stainless steel samples used in the LWRS Program on IASCC crack initiation. These materials were originally irradiated in the Research Institute of Atomic Reactors BOR-60 experimental test reactor as part of a larger EdF-sponsored project. Additional contributions by EdF include technical specifications for the materials and the supply of archival materials for comparative testing.
- **Research Institute of Atomic Reactors (RIAR, Russian Federation)** was the source and initial owner of the high-fluence samples used in the LWRS Program on IASCC initiation. These materials were shipped from RIAR to the Halden Reactor Project as part of a larger set of test materials for EdF-sponsored work at Halden. RIAR has provided technical information and shipped samples to Halden.
- **Halden Reactor Project (Norway)** provided the repackaging and final shipping, including costs, of the RIAR/EdF test specimens to ORNL for the LWRS Program.
- **Westinghouse** provided Experimental Breeder Reactor II, 304L stainless steel hex-block material used in an LWRS Program study evaluating the influence of radiation-induced void swelling on crack growth rate (CGR) in austenitic stainless steel. Westinghouse has also provided 304L stainless steel control-rod material from the Barsebäck 1 boiling water reactor (BWR) in Sweden that is used in LWRS Program research to evaluate the mitigating effect of post-irradiation annealing on CGR.
- **Nippon Nuclear Fuel Development Corporation (Japan)** has provided test materials and facility resources for the CGR testing of austenitic stainless steel to evaluate the effectiveness of hydrogen water chemistry over normal water chemistry in BWR conditions as a function of fluence and stress intensity factor.

Completing research to identify the mechanisms of IASCC is an essential step to predicting the extent of this form of degradation under extended service conditions. Understanding the mechanism of IASCC will enable more-focused material inspections and allow for more-informed decisions by utilities on when component replacement is necessary.

2.2.1.3 Stress Corrosion Crack Initiation in Ni-Base Alloys

This research project addresses one of the least-understood aspects of stress corrosion cracking (SCC) for LWR pressure-boundary components: crack initiation. The focus of the work is to investigate important material (e.g., composition, processing, microstructure, strength) and environmental (e.g., temperature, water chemistry, electrochemical potential, stress) effects on the SCC susceptibility in nickel-base alloys.

Key interactions include the following:

Wood [formerly AMEC Foster Wheeler] (UK), Rolls Royce (UK), General Electric (GE) Global, EdF (France), EPRI (U.S.), Studsvik (Sweden), CIEMAT (Spain), and UJV Rez (Czech Republic) were active industry participants in round-robin testing on the SCC initiation response of Ni-base Alloy 600 to discern lab-to-lab variations in SCC initiation data from a common set of test materials. These organizations have provided their own costs in concept-development activities, providing materials and/or performing the testing and data analysis. **Korea Hydro and Nuclear Power (Korea)** and **Kinectrics (Canada)** also served as industry participants. Other participants in this effort include **University of Michigan, Shanghai Jiao Tong University (China), Paul Scherrer Institute (Switzerland),** and **VTT (Finland)**. This work was coordinated through the International Cooperative Group on Environmentally Assisted Cracking and was organized and led by researchers at Wood, GE Global, Paul Scherrer Institute, EdF, and Pacific Northwest National Laboratory (PNNL, the last supported by the LWRS project).

- **EPRI:** The LWRS SCC initiation project at PNNL collaborates with an EPRI co-sponsored project with the U.S. NRC on quantitative characterization of SCC initiation times in Ni-base alloys in simulated PWR primary water that is also being conducted at PNNL. Selected LWRS test systems have been improved, expanding experimental capabilities for both projects. The LWRS Program SCC initiation program laid the groundwork for advancing the state of the art in SCC-initiation testing, and scientific insights gained through LWRS research are often readily applicable to results obtained in the EPRI co-sponsored project. At the same time, LWRS benefits from having access to a greater range of SCC initiation data that assists in co-developing mechanistic understanding.
- **EPRI** and the **NRC** coordinate work on SCC initiation testing through independent projects on Ni-base weld alloys, for which data are shared with the LWRS Program.

Identifying the mechanisms of SCC is an essential step in predicting the extent of this form of degradation under extended service conditions. Understanding underlying causes for crack-initiation may allow for more-focused material inspections and maintenance, new SCC-resistant alloys, and development of new mitigation strategies, all of which are of high interest to the nuclear industry. This mechanistic understanding may also drive more-informed regulatory guidelines and aging-management programs.

2.2.1.4 Aging and Radiation-induced Damage in Structural Materials

This subject area covers several research projects that include analysis of experimental reactor test data, examination of harvested core internals (i.e., baffle former bolts from a pressurized water reactor [PWR]), and modeling of radiation-induced changes occurring in structural metal alloys. The degradation mechanisms examined include radiation-induced swelling, phase transformations, and solute segregation that occur during long-term aging in nuclear environments. These mechanisms can have a significant effect on materials behavior that creates changes in mechanical strength, susceptibility to embrittlement, reduced corrosion resistance, and increased sensitivity to SCC initiation. This research relies on developing codes for physical changes to materials under long-term, LWR-relevant conditions, which are difficult to experimentally simulate using accelerated test conditions.

Key interactions include the following:

- **EPRI** provided experimental data and participated in discussions on LWRS Program model predictions for the stability of ordered phases in Ni-base alloys.

- **Rolls Royce** has provided materials used in irradiation experiments (ATR-2 Project) and has been part of technical discussions on the cluster-dynamics modeling work on the development and evolution of precipitate phases in high-fluence steels.
- **CRIEPI**, through the CNWG agreement, has shared experimental data and information on model development of radiation-induced defects in stainless steel. CRIEPI also contributes to analysis of ex-service, high-fluence baffle former bolts by performing atom probe tomographic studies of specimens.

The generated data and mechanistic modeling studies will be used to identify key operational limits based on phase evolution or defect generation and development in irradiated materials that are subjected to long-term reactor environments. Research will help optimize the inspection of components, identify limits of use, identify possible techniques towards mitigation of embrittlement, or minimize susceptibility to other forms of degradation. The projects in this subject area directly support the high-fluence studies on RPV and stainless steel IASCC efforts.

2.2.1.5 Environmentally Assisted Fatigue

The objective of this task is to model environmentally assisted mechanisms for fatigue through a mechanistic approach supported by experimental studies to develop a finite-element component-fatigue model. This will provide a capability to extrapolate the severity of the mode of degradation under realistic reactor-environment loading cycles and under multiaxial stress states. Current work involves the assessment of fatigue life behavior of a 316L stainless steel surge-line pipe.

Key interactions include the following:

- **Westinghouse** has provided in-kind technical support to the environmentally assisted fatigue model of a surge-line pipe through technical reviews of the model during its development, as well as recommendations for the LWRS Program’s effort in environmentally assisted fatigue.

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. In 2017, a thermomechanical model for Grade 508 low-alloy steel was developed to assess thermal fatigue associated with RPV cycling.

2.2.1.6 Thermal Aging of Cast Austenitic Stainless Steels

Cast austenitic stainless steel (CASS) and austenitic stainless steel welds (ASSW) are extensively used for many massive primary-coolant-system components of LWRs, including coolant piping, valve bodies, pump casings, and piping elbows. The performance of these materials beyond 40 years is not well defined and is a concern identified in the EMDA. The objective of this work is to provide conclusive predictions for the behavior of CASS and ASSW components in LWR environments by resolving uncertainties in scientific understanding and performance during extended (i.e., beyond 60 years) nuclear plant operations.

Key interactions include the following:

- **EPRI** provided archival heats of CASS materials of different composition and solidification processes to the LWRS Program, which deliver a range of conditions that represent typical materials in use in commercial plants.
- **Korean Advanced Institute of Science and Technology (KAIST, Republic of Korea)** performs collaborative work with the LWRS Program through an International Nuclear Energy Research Initiative (INERI) project on the testing and evaluation of ASSW materials. KAIST has supplied the LWRS Program with select heats of weld materials that are incorporated as a part of the aging and testing campaign of CASS materials. KAIST is also conducting additional studies on ASSW aging and characterization of materials.

Theoretical and practical models and failure criteria are being developed for the changes in mechanical properties that, in certain conditions, can result in an increased embrittlement potential for the long-term aging of CASS and ASSW alloys. The trends in mechanical property changes will help industry develop appropriate aging-management plans for CASS and ASSW components.

2.2.2 Concrete

Concrete makes up the largest volume of material used in nuclear power plants and is exposed to a variety of environmental conditions. Some data on service performance are available, and in general, the performance of reinforced concrete structures in nuclear power plants has been very good. Although the vast majority of these structures will continue to meet their functional or performance requirements during the current and any future licensing periods, it is reasonable to assume there will be isolated examples in which, as a result of primarily environmental effects, the structures may not exhibit the desired durability (e.g., water-intake structures and freeze-thaw damage of containments) without some form of intervention. Furthermore, the change in safety margin under normal or accident scenarios needs to be examined for structures that experience effects of irradiation or have been affected by other degradation phenomenon, such as the alkali-silica reaction (ASR).

2.2.2.1 Radiation and Environmentally Induced Damage to Concrete Structures

The objective of this task is to provide data and information in support of the continuing the service of safety-related nuclear power plant concrete structures. Potential activities include (1) the compilation of material-property data; (2) the evaluation of long-term effects of elevated temperature and irradiation; (3) the identification of improved damage models and acceptance criteria; (4) the development of improved constitutive models and analytical methods for evaluation of non-linear response; (5) the investigation of non-intrusive inspection methods for thick reinforced concrete sections and global inspection methods for containment liners and their inaccessible regions; (6) the identification of data and information on the performance of repair materials and methods; and (7) the formulation of structural-reliability methodology to address time-dependent changes in concrete structures and evaluate how aging affects structural reliability.

Key interactions include the following:

- **EPRI**, the LWRS Program, and the **NRC** are conducting coordinated research on concrete performance as part of a roadmap or multi-year plan for concrete research. EPRI has utilized data available from LWRS Program research and database evaluations to develop a preliminary, simplified, finite-element model to evaluate the loss of margin due to irradiation of concrete support structures near the reactor. Current work at EPRI is focused on providing utilities with guidance on performing site-specific structural assessments of concrete biological shields.
- **NRC**, through coordinated research activities with the LWRS and EPRI Programs, has supported research into the concrete bio-shield. Furthermore, NRC provided feedback on fluence calculations, and the simplified structural model for irradiation effects on the concrete bio-shield under a research memorandum of understanding (MOU).
- **Japan Concrete Aging Management Program (JCAMP)**, a consortium comprising Kajima Corporation, Mitsubishi Research Institute, and Nagoya University through the CNWG project agreement, and with support from the Japanese Ministry of Economy, Trade, and Industry (METI), has provided information for development of a database on irradiation of concrete constituents, results of irradiation experiments, and information for the constitutive models that support the development of tools and procedures for evaluating concrete affected by long-term exposure to radiation.

This work establishes a fundamental understanding of radiation's effects on concrete, which is being used to develop a modeling tool that can be used to assess the potential impacts of radiation on concrete that accounts for temperature, moisture, irradiation exposure, concrete composition, structural constraint, creep, and the possible debonding of concrete from rebar. The products of this research, in the form of models, codes, and tools, will provide industry with an improved capability to assess potential changes in the safety-related performance of aged concrete structures.

2.2.2.2 Alkali-silica Reactions in Concrete Structures

The goal of this activity is to study the development of ASR expansion and induced damage of large-scale specimens that are representative of structural concrete elements found in nuclear power plants. This is done by experimentally validating models of the structural capacity of ASR-affected structures like the biological shield, the containment building, and the fuel-handling building.

Key interactions include the following:

- **EPRI** and LWRS Program are conducting coordinated research in the area of ASR. EPRI uses the results from the LWRS Program and develops the technical basis for detecting, evaluating, and managing the effects of ASR.
- **NRC** conducts coordinated research with the LWRS and EPRI Programs through confirmatory confined ASR beam testing and modeling at the University of Colorado and Northwestern University in the assessment of the degree of ASR reaction and prediction of expansion in ASR-affected blocks at the National Institute of Standards and Technology.
- **University of Tennessee–Knoxville (UTK)** has contributed to ASR work in the LWRS Program through facility support for the testing of large-scale ASR test blocks.

Through this research, the LWRS Program provides industry with guidance on the structural significance of ASR damage. This is applied to the development of plant-management systems for concrete containments and an approach for evaluation of the performance of aging safety-related concrete SSCs. This work also provides risk-informed guidelines for evaluation of the performance of aging safety-related concrete structures.

2.2.2.3 Nondestructive Evaluation of Concrete Structures

The objective of this research is to develop new techniques that provide detection of concrete damage in thick highly reinforced concrete, representative of nuclear structures, and identifies techniques that may be applied for condition monitoring. This effort includes developing techniques to perform volumetric imaging on thick reinforced-concrete sections, determining physical and chemical properties as a function of depth, developing techniques to examine interfaces between concrete and other materials, developing models and validation-acceptance criteria, and developing automated scanning systems. This task collaborates with the Plant Modernization Pathway that specializes in condition-monitoring activities.

Key interactions include the following:

- **EPRI** and the LWRS Program are working on a coordinated research roadmap in this area. EPRI is conducting R&D guidelines on applications for and limitations to commercially available non-destructive examination (NDE) methods to detect voids and delaminations within concrete structures, as well as corrosion of concrete reinforcement.
- **UTK**, the **University of Alabama**, and the **University of South Carolina** have all provided technical contributions towards monitoring of the ASR-affected test blocks at UTK through additional, non-LWRS Program resources.

The development of NDE techniques for monitoring concrete and civil structures could be revolutionary and allow for an assessment of performance that is not currently available or feasible via core-drilling in operating plants. Through the early detection and monitoring of defects and degradation in concrete, a reduced uncertainty in safety margins of structural concrete is possible.

2.2.3 Cable Systems

Understanding the mechanisms of cable aging—resulting in changes to cable performance and improved means to accurately assess these property changes—is an important area of study to ensure the safe and efficient operation of nuclear power plants. This effort also provides plant operators the necessary information to conduct more-accurate and cost-effective inspections in determining when mitigation or replacement is required. Degradation of these cables is primarily caused by long-term exposure to high temperatures, though synergistic effects with irradiation and moisture may induce additional long-term aging results. While wholesale replacement of cables is economically undesirable; incorporating more-accurate condition-monitoring techniques is a strategic investment in continuing safe and reliable operation.

2.2.3.1 Cable Aging and Degradation

This research provides data on and insights into the role of material type, history, and environment on cable-insulation degradation and accelerated testing limitations. It supports interactions with participating organizations in modeling activities, surveillance, and testing criteria. This research will provide experimental characterizations using key forms of cable and cable insulation. Tests will include evaluations of cable integrity following exposure to elevated temperature, humidity, and ionizing irradiation. These data will be used to evaluate mechanisms of cable aging and determine the validity or limitations of accelerated aging protocols. This research may be used to identify operational factors related to cable aging and to optimize inspection and maintenance schedules for the most-susceptible materials and locations and, in the long-range, design more tolerant cable-insulation materials.

Key interactions include the following:

- **EPRI**, the LWRS Program, and **NRC** conduct coordinated research on cables as part of a shared roadmap for cable aging and cable NDE research. EPRI contributes through coordinated research on medium-voltage cable submergence qualification, materials handbooks for analysis of service-aged cables, obtaining actual operating-environment data, and both coordinating and facilitating harvesting opportunities and activities at various nuclear power-generating stations. EPRI also provides technical input and practical information to LWRS Program on their cable-research plans.
- **NRC** conducts coordinated research with the LWRS and EPRI Programs, including comparative submergence testing of medium-voltage cable and comparative research on synergistic effects of thermal and radiation damage on cable insulation. In addition, NRC is planning to perform loss of coolant accident (LOCA) testing of low-voltage cables.
- A **commercial nuclear utility**, in coordination with EPRI, has provided cable material from a PWR undergoing decommissioning for use in cable-aging and cable NDE research activities of the LWRS Program (see Section 2.2.3.2).
- **Energy Solutions** has provided cable material (used in cable-aging and NDE evaluations), equipment-qualification reports, annual in-service inspection reports, and other documents related to cable systems from the decommissioned Zion Unit 1 nuclear power-generating station.
- **The Okonite Company** has provided information on the history of ethylene-propylene rubber (EPR) cable and materials and documentation for historical EPR cable qualification. They have also provided stamped mats of EPR insulation and chlorinated polyethylene jacket material for LWRS Program research.
- **Marmon Engineered Wire and Cable** has provided initial cross-linked polyethylene (XLPE) cable and XLPE mats for use in LWRS Program research. They are a source of information on the state of cable qualification and have provided documentation for historical XLPE cable qualification.

- **General Cable** sourced vintage-formulation XLPE cable for LWRS Program research, provided qualification documentation, and shared knowledge and understanding of cable-aging gaps.
- **Energy Northwest** allowed participation in the relicensing plant walkdown of Columbia Generating Station and has provided information on their cable-aging management practices and issues.

Completing research to identify and understand the degradation modes of cable insulation is an essential step to predicting the performance of cable insulation under extended-service conditions. These data are critical to develop and deliver a predictive model for cable insulation degradation. Data and models will enable more-focused inspections, material replacements, and better-informed regulations.

2.2.3.2 Non-destructive Evaluation of Cables

The objectives of this task include the development and validation of new NDE technologies to monitor the condition of cable insulation. Research in this task will include an assessment of key aging indicators, development of new and transformational NDE methods for cable insulation, and the use of NDE signals and mechanistic knowledge from other areas of the LWRS Program to predict remaining useful life. A key element underpinning these three thrusts will be harvesting aged materials for validation.

Key interactions include the following:

- **EPRI** contributes to NDE research with the LWRS Program by providing ex-service cable materials, performing research on new condition-monitoring methods to evaluate cable-insulation degradation, and coordinating research with the LWRS Program on dielectric spectroscopy.
- **NRC** coordinates with the LWRS and EPRI Programs on research activities and provides technical support to the program on cable NDE technologies.
- **STP Nuclear Operating Company** has hosted LWRS Program researchers for NDE technology demonstration and serves as a resource on cable-aging-management practice and issues.
- **Analysis and Measurement Services (AMS) Corporation** has supported the benchmarking of frequency-domain reflectometry measurements on common cable sets, providing in-kind provision of staff time and labor. AMS has shared its knowledge and experience in cable testing, including in-house testing protocols and results from contracted plant cable remaining-life analysis activities at a DOE, EPRI, and NRC working group meetings. They are a resource for information on current cable NDE methods and issues for in-plant application.
- **Fauske and Associates, LLC,** and **Wirescan** have shared data and insight with LWRS Program researchers on the use of the line resonance analysis frequency-domain reflectometry instrument and on data analysis and interpretation.
- **Kinetrics** has provided information and advice on plant cable evaluation, as well as the evaluation of cables and cable materials in the laboratory. The LWRS Program collaborates through sharing cable dielectric-spectroscopy data and analysis and confers with Kinetrics on research methods and approaches.

Reliable NDE and in-situ approaches are needed to objectively determine the suitability of installed cables for continued service. The ultimate goal of this work is to provide guidance for utilities and regulators, leading to more-robust cable-aging-management programs that can assure in-service cable integrity under the anticipated design-basis events.

2.2.4 Mitigation Technologies

Mitigation technologies involve the development of techniques, new technology, and materials that are designed to increase the lifetime of SSCs by reducing or suppressing degradation phenomena that otherwise may increase operating costs due to increased repairs, inspections, or maintenance. Mitigation technologies include post-irradiation annealing, water chemistry modifications to reduce SCC, the replacement of materials in components to provide superior resistance to damage under LWR conditions, and improved methods for weld repair. Research on post-irradiation annealing and water chemistry modifications as mitigation technologies are integrated into the research activities on high-fluence embrittlement of RPV steels and the mechanisms of IASCC in stainless steels.

The use of alternative alloys that provide superior degradation resistance compared to conventional Types 304/316/347 stainless steels and X-750 Ni-base alloys is another mitigation technology option in which the LWRS Program is actively involved. The following section provides details on the research and industry interactions for the welding and advanced replacement materials projects.

2.2.4.1 Advanced Weld Repair of Irradiated Materials

Welding is commonly used during the repair and upgrades of nuclear components. However, as the service lives of nuclear reactors are extended, the amount of helium in the structural materials increases, eventually reaching levels at which conventional welding technologies cannot reliably be used. The objective of this research is to develop advanced welding technologies that can be used to repair highly irradiated reactor internals without helium-induced cracking. Techniques currently being investigated with irradiated materials include friction stir welding (FSW) and auxiliary-beam stress-improved (ABSI) laser welding.

Key interactions include the following:

- **EPRI** is collaborating in this multi-year effort in the design, construction, and development of a weld cubicle used in the testing of advanced weld technologies. EPRI has developed the operating procedures and parameters for ABSI laser welding and FSW. The collaborative research between the LWRS Program and EPRI is managed through an R&D plan. EPRI has provided the specialized raw-material stock containing boron additions, which is used in the production of test coupons fabricated by the LWRS Program at ORNL and then irradiated by the program at the High Flux Isotope Reactor to produce stock material of varying helium content for the weld studies. EPRI contributes to the technical discussion and material characterization, and it supports additional coordinated laser welding (non-ABSI) work with **Westinghouse** and **Purdue University** through the Nuclear Energy University Program (NEUP). EPRI is also involved in developing prototype field-deployment systems for advanced welding systems.
- **Dynamic Design Solutions, Inc. (DDS)**, with ORNL and EPRI input, was contracted to be the system designer and equipment and software integrator. DDS designed the welding cubicle to contain the FSW system and laser welding system while providing necessary radiological confinement and laser safety. They designed, manufactured and integrated the FSW system inside the welding cubicle, including software control of welding equipment, a welding table, and necessary welding fixtures. In addition, DDS designed and produced laser-welding fixtures and integrated laser-welding heads and fixtures in the cubicle. DDS provided and developed the software to control and monitor both welding systems, radiological-safety interlocks, and laser-safety systems. Software documentation was provided to meet ORNL software quality-assurance requirements.
- **MegaStir** was contracted to produce tooling used on the friction stir welder and produced water-cooled tool heads for both cold- (i.e., nonirradiated) and hot- (irradiated) material welding systems. They continue to provide parts and guidance for the upkeep and maintenance of the FSW systems**.**

The technology developed in this work will enable new upper boundaries on the weldability of highly irradiated materials and establish guidance for industry on optimized heat input and the procedures necessary to produce quality welds. This gives commercial utilities new options to extend the lifetimes of their plants through expanded methods for repair of critical, life-limiting components.

2.2.4.2 Advanced Replacement Materials

The Advanced Radiation Resistant Materials project, a cooperative research effort initiated by EPRI, DOE, and a nuclear laboratory partner in 2012 and 2013, was created to develop advanced alloys that could potentially replace Type 304, 316, and 347 stainless steels and Ni-base alloy X-750 internals (the reference alloys used in this work). The objectives of this research are to identify radiation-resistant alloys within current commercial alloy specifications and a new advanced alloy with superior degradation resistance to a range of LWR environmental conditions over that of the reference alloys.

Key interactions include the following:

- **EPRI** is sharing the costs with the LWRS Program to support testing of materials at the **University of Michigan**. EPRI also supports consultants from the nuclear materials field to provide advice and project coordination.
- **A nuclear laboratory partner** has provided materials used in the study and is performing metallurgical evaluation and consulting on the project.
- A **commercial nuclear company** has provided initial starting material used in the project.

The identification of new commercial and advanced alloys with superior properties to conventional stainless steels and X-750 Ni-base alloys offers improved operating performance for SSCs that will result in increased safety margins and reduced inspection requirements.

2.2.5 Additional Collaborations

- **Membership in technical committees and organizations:** Research on irradiated concrete and correlated reactor-aging issues are part of the **Réunion Internationale des Laboratoires et Experts des Matériaux, systèmes de construction et ouvrages** (RILEM), Technical Committee 259-ISR; "Prognosis of deterioration and loss of serviceability in structures affected by alkali-silica reactions," within RILEM,[b] the **International Union of Laboratories and Experts in Construction Materials, Systems, and Structures**.
- **Bilateral International Collaborations:** The LWRS Program is involved in several bilateral international collaborations related to nuclear materials research. The LWRS Program has active work in two separate **INERI** projects with **KAIST** on the aging of ASSW material, and the University of Bologna, Italy, on advanced non-destructive methods for cable lifetime management.

  The Cooperative Action Plan between DOE and the **Department of Natural Resources of Canada** and **Atomic Energy of Canada Limited** provides the framework for bilateral cooperation in the area of nuclear energy research. The action plan outlines the desire to facilitate cooperative R&D of advanced civilian nuclear energy technologies, which will provide positive impacts for the development of commercial nuclear power. Several meetings have taken place between the LWRS Program and the **Canadian Nuclear Laboratory** on several topics of mutual interest with co-sponsorship of proposals through the Nuclear Science User Facilities (NSUF) Rapid Turnaround Experiment solicitation for the continued post-irradiation examination of materials of mutual interest. Furthermore, the Canadian Nuclear Laboratory has utilized the LWRS Program developed Radiation-Induced Microstructural Evolution Code to estimate radiation-induced swelling in garter-spring materials subjected to high fluences.

  The LWRS Program is also highly engaged in the CNWG with several entities in Japan, including **CRIEPI**, **Nagoya University**, the **Mitsubishi Research Institute**, the **Kajima Corporation**, and the **Chubu Electric Power Company**. Activities are generally managed through CRIEPI and include RPV collaborative testing of the Zion-harvested material, involvement in round-robin test validation

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[b]. RILEM (http://www.rilem.org/gene/main.php)

of mini-compact tension specimen design, microstructural support of high-fluence core internals (including baffle former bolts) with CRIEPI, and aging management of concrete with the **JCAMP** consortium.

- **Multilateral International Collaborations:** Through the **International Committee on Irradiated Concrete** (ICIC) framework, collaborations between European and Japanese entities have been on research to study degradation mechanisms and properties of irradiated concrete. Furthermore, a multilateral international collaboration between the LWRS Program, the Halden Reactor Project, EdF, and RIAR facilitated the incorporation of very high-fluence stainless steel test samples into LWRS Program activities that assess mechanisms of IASCC degradation. These two recent examples demonstrate the importance of multilateral international collaborations to achieve open scientific discovery and advancement that benefits civilian nuclear energy power generation.
- **University Collaborations:** Collaborations with U.S. and international universities is important to the Materials Research Pathway's scientific discovery through direct LWRS Program-funded projects and through relevant and co-sponsored projects through the NEUP, the NSUF, the Nuclear Energy Enabling Technology Program, and the above-mentioned international involvements of the ICIC and CNWG. University involvement provides a mechanism for new scientific theories, techniques, and technologies, which complement the strengths of the national laboratory system, to be incorporated into the LWRS Program. There are over twenty U.S. and seven international universities actively involved in the LWRS Program Materials Research Pathway projects or relevant DOE programs on topics such as high-fluence RPV aging and modeling, examination of the mechanisms for IASCC, concrete and cable degradation, and NDE techniques. These universities include:

U.S. Universities
Georgia Institute of Technology
Iowa State University
Purdue University
Texas A&M University
University of Alabama
University of California–Berkeley
University of California–Santa Barbara
University of California–Los Angeles
University of Cincinnati
University of Colorado–Boulder
University of Delaware
University of Illinois at Urbana-Champaign
University of Maryland, College Park
University of Michigan
University of Minnesota–Duluth
University of Nebraska
University of Pittsburgh
University of South Carolina
University of Tennessee–Knoxville
University of Wisconsin–Madison
Vanderbilt University
Washington State University

International Universities
Czech Technical University (Czech Republic)
Nagoya University (Japan)
Shanghai Jiao University (China)
University of Bologna (Italy)
Université de Lorraine (France)
University of Manchester (United Kingdom)
Waseda University (Japan)

3. PLANT MODERNIZATION PATHWAY

The U.S. operating nuclear fleet is an important national asset providing approximately 20% of the nation's electric supply, as well as providing critical grid stability, carbon-free energy, and generation fuel-diversity. However, the economic viability of the fleet is challenged by the abundance of low-cost shale gas generation and heavily subsidized renewable generation. Electricity capacity markets today do not compensate nuclear plants for distinct operational contributions they make in addition to baseload generation. As a result, there have been nuclear plant closings due to unprofitable operations, continued economic challenges for many plants in the operating fleet, and an overarching need to address improvements to the underlying efficiencies for production.

Nuclear plants have a significant opportunity to lower their operating costs while actually improving operational performance through plant modernization. Most sectors of the industrial economy renew and modernize their infrastructure on a periodic basis, adjusting to new market conditions and applying new technologies, particularly digitally based innovations. The operating nuclear fleet, by contrast, is largely based on a state of technology and related operating model that is over 40 years old. It is characterized by analog technology and a large operating staff, performing manual activities for most plant functions. Over the lives of these operating plants, nuclear utilities acted on a number of non-discretionary capital investments to address safety and regulatory issues. This has resulted in the deferral of much-needed reinvestment in the plants to address their aging systems and improve their operational efficiency. This reinvestment is now vital to their long-term sustainability.

It is therefore critical that proven solutions be identified and become available to nuclear utilities for wide-scale plant modernization that provides near-term cost reductions while resulting in a future state that is operationally and financially sound for decades to come.

3.1 Purpose, Goals, and R&D Activities

The Plant Modernization Pathway provides the technological foundations for a transformed nuclear power plant operating model that improves plant performance and addresses the challenges of future business environments. Strategic goals are:

1. To develop transformative digital technologies for nuclear plant modernization that renew the technology base for an extended operating life beyond 60 years
2. To enable implementation of these technologies in a manner that results in broad innovation and business improvement in the nuclear plant operating model, thereby lowering operating costs.

The focus of these research activities is on near-term opportunities to introduce new digital technologies into costly plant work activities, eliminating some labor-intensive activities altogether while making remaining work activities far more efficient. Likewise, the development and application of smart technologies allows a focus on reducing human error, which often results in production losses, nuclear safety challenges, and regulatory impacts. Finally, the research addresses inefficiencies in the operation and support of nuclear plants due to antiquated communication, collaboration, and analytical methods that have largely been replaced in other business sectors with modern digital capabilities.

This Pathway is focused on five principal areas of activities:

1. Performance Improvement for Nuclear Power Plant Field Workers
2. Outage Safety and Efficiency
3. Centralized Online Monitoring
4. Automated Plant
5. Hybrid Control Room.

These five areas of enabling capabilities, each comprising targeted technology-development projects, are discussed in the following subsections.

3.2 Collaborative Research and Development Activities

This research program is closely coordinated with the nuclear utility industry to ensure responsiveness to the challenges and opportunities in present and future operating environments. The Pathway engages nuclear power plant owner-operators, suppliers, industry support organizations, other research organizations, and regulatory agencies in identifying and prioritizing research objectives and requirements for plant modernization technology developments. These interactions include collaboration, coordination, in-kind contributions, technical-information exchanges, and cost-sharing for research activities. By leveraging resources and research results from industry and other organizations, the pathway aims to maximize the results from its own research activities.

In its research projects, the Plant Modernization Pathway directly engages most U.S. nuclear utilities and nuclear support alliances. Through these relationships, nuclear plant operators provide experience-based input on R&D priorities, provide technical requirements for technology solutions compatible with the nuclear-operating and safety-culture environments and, in many cases, directly collaborate on research projects, providing technical expertise and hosting research and development activities, field demonstrations, and validations of emerging technologies. These direct utility relationships are essential to ensuring that the pathway's research developments address real operational needs and are consistent with all operating requirements.

The Plant Modernization Pathway also collaborates with other major nuclear industry groups—namely, EPRI, the Nuclear Energy Institute (NEI), and the Institute of Nuclear Power Operations (INPO). Each of these organizations has active efforts in plant modernization, and, collectively, they address technology requirements, regulatory barriers, and standards of excellence for a transformed nuclear operating model. These organizations provide substantial technical knowledge and published technical documents to the pathway, in addition to participating directly in collaborative research.

Ultimately, it will be the role of the nuclear industry suppliers to provide commercial products based on technologies developed through this research program. The Plant Modernization Pathway develops strategic relationships with key suppliers to address emerging technologies from the standpoint of technical readiness and appropriate means of technology transfer that are advantageous to the operating plants. These include joint developments of technology, technology commercialization, and new service models based on these advanced technologies.

Periodic informational meetings are held with the NRC to communicate program objectives and research results of the technology projects. These meetings provide valuable insights on specific technology developments from a regulatory perspective, as well as enabling the pathway to coordinate with and leverage the results of the NRC's own research projects.

The following sections provide information on the importance and objectives of the Plant Modernization Pathway technology projects, and how the results of research contribute to important industry outcomes.

3.2.1 Performance Improvement for Nuclear Power Plant Field Workers

Labor remains the largest contributor to the operating costs and the cost per kilowatt hour of generated electricity from nuclear power. The goal of this research is to develop advanced mobile technologies for nuclear power plant field workers to enable more-efficient work and less-expensive work processes. The objective of this research is to demonstrate how to seamlessly connect workers to plant information and plant processes, thereby reducing reliance on outdated paper-based systems that are cumbersome to work with in the field, expensive to maintain, and error-prone in practice. This research includes evaluations of emerging and innovative technologies, and assessments of their effectiveness to improve power-plant field-worker performance. A key consideration is the human-system implementation issues of technologies. Research includes human-factors studies that evaluate how human-system implementation impacts worker effectiveness.

3.2.1.1 Automated Work Packages

The Plant Modernization Pathway collaborates with a **commercial nuclear utility** to research and develop enhanced work-package processes through automation of activities normally performed by plant personnel. The objective of this research is to develop technologies that will reduce the cost of operation and maintenance (O&M) associated with verification and checking of manually performed activities. The current scope of work aims to analyze the work process of a typical nuclear power plant to determine how technology can have the greatest impact for reducing O&M costs. One of the technologies specifically analyzed is the use of image-processing methods to automatically track, log, and verify manual actions in the control room and the field. Researchers are collaborating with Xcel Energy and EPRI to develop methods for enhanced automation of the work-package process, which governs work-planning, development and execution at all plants. Work packages are the core element of the work process in a nuclear power plant, and they directly impact labor costs associated with operating nuclear power plants. Automating activities of the work-package development process may result in improved human performance, increased worker productivity, greater cost savings, and enhanced nuclear safety.

Key interactions include the following:

- **Xcel Energy** has been hosting user evaluations of candidate technologies developed by this project, and providing insight into areas where automation would have a high impact on reducing costs in a typical nuclear power plant. The outcome of this research documents results and provides a technical basis for introducing image-processing technology into the work process.

Research conducted in this area directly supports the modernization goals of the LWR fleet. Integrating automation technology with field-worker activities can reduce the costs associated with both O&M activities. Coordinating research and collaborating with industry has significantly accelerated results in this area that can be shared and implemented in the LWR fleet in the near term.

3.2.2 Outage Safety and Efficiency

The objective of this research is to develop methods and approaches to integrate information about plant status and work activities from distributed locations during ongoing plant refueling outages into centralized outage control centers, and to synthesize those data into real-time, actionable information that enables high-quality, timely decision making. Through the development of advanced data-processing and analytics techniques, significant improvements can be made to resource allocation and outage safety performance. The Human Systems Simulation Laboratory (HSSL) is used to develop concepts for outage risk management. The biggest challenges to achieving outage safety and resource optimization is the large amount of data created and used during a plant outage. Research is being conducted using the Outage System Status and Requirements Monitor software application in the HSSL. This research will develop and define the best possible approaches to integrate nuclear power plant outage data. This can be used to track the status of critical equipment, plant configurations, work orders, checklists, and procedures in use.

3.2.2.1 Outage Risk Management Improvement

Outage risk is currently managed by scheduling outage work within windows that align with requisite plant conditions. The objective of this research is to evaluate the application of natural-language processing for managing the amounts of data associated with maintaining plant conditions within requirements, reducing errors in configuration management, and reducing costs, which accrue when configuration-management errors occur. This research will coordinate vendor software-development expertise along with nuclear-utility outage-management expertise to evaluate applications that process the data and effectively alert outage management personnel of potential risks, as well as possible opportunities to improve resource efficiencies.

Key interactions include the following:

- Working with **Arizona Public Service** personnel at the Palo Verde Generating Station, LWRS Program researchers developed a number of advanced outage management technologies and methodologies. These technologies have been credited with efficiency gains and cost reductions. Notably, the application developed to manage emergent outage issues was credited in a NEI Top Industry Practice (TIP) award to Arizona Public Service's Palo Verde Generating Station. In the ongoing collaboration, Arizona Public Service provides access to the Palo Verde Generating Station facility for observation during outages to gather data and to supply data needed for the ongoing research effort.
- **Atøs** provides data scientists and software experts with the ability to collaborate on research in developing state-of-the-art data-analysis systems and data-management techniques for outage information technology. Software staff from Atøs participates with LWRS Program researchers in developing outage applications to improve outage risk management through a combination of data visualization, natural-language text mining, and logic models to detect potential conflicts between ongoing and upcoming work activities during outages.

Outage safety and efficiency are critical elements in effectively controlling costs associated with refueling and extended maintenance activities. The research and collaboration with utilities and vendors have provided recognizable results and were credited with measurable efficiency gains and cost reductions. They have also resulted in new outage-support software becoming available to the industry, enabling improved efficiency and reduced risk during outage maintenance activities.

3.2.3 Centralized Online Monitoring

The goal of this research area is to conduct R&D to enable structural-health monitoring (SHM) of a nuclear power plant's active and passive components. This will enable continuous assessment of critical plant components and materials during long-term operation for purposes of decision making and asset management. This improved approach will enable substantially lower costs associated with nuclear power plant maintenance activities by automating much of what is performed manually today, based currently upon time-based prescriptive requirements for equipment maintenance, surveillance, inspection, and tests. Enhanced monitoring techniques are critical and needed to enable an overall risk-informed maintenance strategy, which will ultimately drive down plant maintenance costs.

The Plant Modernization Pathway conducts research into new methods and technologies to support the transition of nuclear power plants from sample-based periodic testing to condition-based maintenance. By clearly identifying a comprehensive data-driven condition monitoring approach and the required infrastructure for the data life cycle, the LWR fleet can transition to a technology-enabled, risk-informed maintenance strategy. This transition will significantly reduce both operating and maintenance costs. LWRS Program researchers conduct research with commercial suppliers who have expertise in both asset management and data-life-cycle architecture. They participate in research with dynamic real-time applications that collect and evaluate the many sources of component- and material-health data. The Plant Modernization Pathway also collaborates with a commercial nuclear utility that provides expertise in current nuclear-maintenance programs. This may provide the opportunity to demonstrate a data-driven condition-monitoring approach using automatic data collection and analysis as the mechanism to evaluate plant equipment condition and influence actual maintenance decisions for a pilot plant component.

3.2.3.1 Structural Health Monitoring of Concrete Structures

Ways to monitor and detect the degradation of concrete structures due to aging-related phenomena are needed as the LWR fleet approaches continued operation beyond their initial operating periods. This requires the development of an SHM framework that includes monitoring, modeling, data analytics, and uncertainty quantification. To achieve this, research is conducted to monitor concrete performance and detect indications of degradation. This research employs acoustic monitoring techniques and aims to predict the remaining useful life of the concrete structures impacted by aging mechanisms. This research involves collaboration with the Materials Research Pathway, which is involved in performing NDE of concrete specimens.

Key interactions include the following:

- LWRS Program researchers are collaborating with **Vanderbilt University** to develop methods for monitoring the structural integrity of concrete structures. The collaboration is aimed at developing advanced data analytic capabilities to process and integrate heterogeneous data and extract features for diagnosing concrete degradation. Vanderbilt University will periodically interrogate the large concrete sample at UTK (under the direction of the LWRS Program), using the digital-image correlation technique and analyze the data to detect any deformation due to ASR. This support is critical to develop science-based approaches to understand, detect, characterize, and monitor changes in concrete that may affect its structural health.
- LWRS Program researchers collaborate with **EPRI** in areas related to both concrete and secondary piping SHM. In the area of concrete structural health, EPRI collaborates with LWRS Program researchers to develop methods for full field imaging and other techniques to detect and monitor chemical degradation in concrete structures caused particularly by ASR. EPRI participates in periodic interpathway collaboration and technical-exchange meetings, provides regular updates on research activities, plans, and results, and provides input to LWRS Program planning personnel to facilitate the most efficient use of funding and human resources. In the areas of secondary-piping SHM, the research collaboration established with EPRI allows access to unique facility, instrumentation, and research expertise in this area. A multi-year joint R&D plan, INL/INT-16-38821, *Joint Research Plan on Structural Health Monitoring with the Electric Power Research Institute*, was developed between the LWRS Program and EPRI for secondary-piping SHM. The collaboration with EPRI also facilitated access to industry data and proprietary diagnostic software, which are being used by LWRS Program researchers to develop new signal processing algorithms for monitoring *in situ* changes to pipe-wall thickness.
- LWRS Program researchers collaborate with the **University of Nebraska–Lincoln** to provide several additional concrete samples, each with unique reactive aggregates. These samples, as well as access to independent university research results, are very useful in developing methods for full-field imaging and other techniques that are the main goal of this research effort.
- LWRS Program researchers collaborate internationally in this area through participation in the **US–India Civil Nuclear Energy Working Group**. This group currently focuses on SHM. The collaboration allows access to the Department of Atomic Energy, where India records and reports its online monitoring research results. Along with access to these results, the collaboration allows for direct dialogue and influence on activities being selected for follow-on research.

Diagnostic and prognostic models developed in the project will inform aging-management plans of nuclear power plants through optimal sensor-placement strategies to achieve early detection of degradation and allow a quantitative and risk-informed decision on affected structures.

3.2.3.2 Structural Health Monitoring of Secondary Piping

The implementation of various nuclear power plant inspection programs has a significant impact on LWR maintenance costs. The LWRS and EPRI Programs collaborated on the development of on-line monitoring and diagnostics in order to develop prognostics capabilities to monitor effectively the degradation mechanisms in secondary piping. This research builds advancements in guided-wave monitoring (GWM), which can be adopted in the LWR fleet continuously to monitor buried piping.

GWM is ideal for long straight stretches of piping. Research is beginning in the area of fiber-optics, which is better suited for complex geometries such as elbows, tees, and other unique geometries.

Key interactions include the following:

- **EPRI** provided technical reports used to develop the testing regime conducted through LWRS Program research for guided-wave signal processing algorithm development. The information provided on magnetostrictive sensor (MsS) SHM for feed-water heat-exchanger shells, along with information on piping degradation mechanisms other than flow-assisted corrosion, validated and informed the testing performed by LWRS Program researchers. EPRI also facilitated transfer of GWM data from Southwest Research Institute (SwRI) to the LWRS Program.
- **SwRI** provided guided-wave data recorded by their MsS corrosion-monitoring system on the shell of the low-pressure feedwater Heater 13A at Exelon Corporation's Braidwood Nuclear Generating Station. The system collected daily monitoring data for 747 days between January 27, 2011, and February 12, 2013, from 17 ultrasonic guided-wave sensors. SwRI also provided analysis reports on the continued monitoring and analysis of MsS data collected on the Braidwood heat-exchanger Shell 13A, which was also analyzed using new GWM techniques created by LWRS Program researchers.
- **Vanderbilt University** provides results of their research on 3-D chemo-mechanical degradation state monitoring, diagnostics, and prognostics of corrosion processes in nuclear power plant secondary-piping structures used in developing evaluation techniques based on various degradation mechanisms.
- **University of Pittsburgh** provides results of their research on SHM of nuclear pipe components using high-spatial-resolution fiber-sensor-enabled artificial intelligence, which provides initial understanding and influences the scope of LWRS Program research using fiber optics.

R&D of an online monitoring framework that continuously monitors a variety of degradation mechanisms is transitioning from initial research in GWM to also include modalities that can be monitored using fiber-optics. The industry is already adopting phase one technology and transitioning from manual inspections to continuous monitoring using guided-wave solutions. Expanding the ability to continuously monitor complex piping configurations using fiber optics will further reduce the cost to implement the in-service inspection programs in the LWR fleet.

3.2.3.3 Data-Driven Condition Monitoring

Maintenance activities in nuclear power plants are largely scheduled using a sample-based periodic testing methodology. Researchers are investigating methods and technologies that may enable a transition from the sample-based periodic testing process to a condition-based maintenance program. The research will identify the needed data as well as the requirements to provide high-fidelity data analytics to support a condition-based maintenance program. Researchers collaborate with utilities and vendors to create and evaluate a technology roadmap that could be used by industry to systematically migrate to a data-driven condition-monitoring approach. This roadmap involves multiple phases that span several timeframes. During the initial phase, researchers will investigate existing means and gaps to automate data collection used in planning plant maintenance activities. During subsequent phases, the LWRS Program will collaborate in two unique activities. In the first, a business case will be developed on the basis of Luminant Power Optimization Center historical data collected during the project, comparing the current methods of ensuring system and component reliability to the cost and results of online monitoring. It is expected that the business case will substantiate that online monitoring is less expensive and more effective. In the second, the LWRS Program will develop and evaluate new monitoring technologies that will expand the role of nuclear plant monitoring, thus further reducing O&M costs.

Key interactions include the following:

- **Luminant–Vistra Energy** is a representative of the Utilities Service Alliance of eight U.S. nuclear utilities that operate 14 plants at 9 sites. These will be used as a case study to provide access to their

Power Optimization Center to support research on cost savings and operational improvements to be achieved by implementation of advanced online monitoring techniques. This research will evaluate the roadmap against the approach adopted by Luminant–Vistra Energy and identify industry wide gaps and challenges to target in future research. Luminant–Vistra Energy will provide resources and information to achieve this mission.

- **Atøs** has worked with nuclear power plants in Europe and performed efforts to migrate plants towards data-driven condition monitoring in both the nuclear and fossil industries. This collaboration will provide LWRS Program researchers with good practices and lessons learned from these previous projects, which will be incorporated into this research effort. Atøs will provide resources and information to achieve this mission.

The results of this research are aimed at reducing the costs of sample-based periodic testing and migrating to a new approach for equipment maintenance. Specifically, the objective is to optimize the development of data-driven condition-monitoring capabilities to reduce the required resources, costs, and risks, thereby maximizing benefits. These tools and methods include a modern computational framework that combines risk and cost information from selected nuclear power plant SSCs, enabling risk- and cost-based decision making for improving plant reliability and ensuring cost efficiency. Results will support the continuous assessment of critical plant components and materials in nuclear power plants during long-term operation for purposes of decision making and asset management. Ultimately, this research will provide guidance to nuclear power plants on how to migrate to a data-driven condition-monitoring maintenance program to enable plants to realize improvements in efficiency through enhanced monitoring capabilities.

3.2.4 Automated Plant

This research aims to develop methods and technologies that enable nuclear power plants to effectively automate activities and processes using digital architectures. The goal is to integrate plant systems, processes, and workers in a manner that maximizes efficiency and uses of plant information. While automation may bring clear benefits, such as reduced staffing levels, poorly introduced automation can actually have adverse effects on performance. Plant Modernization Pathway research focuses on these challenges and works with commercial nuclear utilities to develop and apply new automation solutions.

Current automation research includes collaboration with Rolls-Royce to develop and evaluate candidate methods that enable integration of work-management automation with dynamic risk-informed maintenance modeling. Significant nuclear power plant operating costs accrue to time-based maintenance, surveillance, inspection, and testing activities. The as-found conditions discovered in these activities often reveal that no activities needed to be performed at that time, but could have been deferred. Together with a commercial nuclear utility, Rolls-Royce and the LWRS Program are conducting R&D to create a predictive maintenance strategy for a selected plant component based on statistical, risk-assessment, and on-line monitoring capabilities. This predictive maintenance strategy will enable risk-informed deferrals of time-based preventive maintenance, eliminating unnecessary O&M costs. This will identify broader cost reductions that can be achieved if this new predictive maintenance strategy is adopted by utilities.

This research will coordinate with the Risk-Informed Systems Analysis Pathway, which will demonstrate the technologies and insights that, leveraged together, reduce the safety significance of selected plant systems and components, with a commensurate reduction on O&M requirements. These are expected to reduce the risk of design-basis events and lead to the recovery of plant safety margins. The applications created will interface data evaluations into a risk-informed maintenance program, as well as provide data in a new way that can support an advance service-oriented business model. These applications and services will be developed in collaboration with industry experts from both the vendor and utility communities.

This research will create the necessary framework to support a new maintenance model aimed at reducing maintenance costs associated with unnecessary maintenance activities. The results will provide the nuclear industry with the information needed to support a transition to a risk-informed maintenance program.

3.2.4.1 Technology-Enabled Risk Management Strategy

A significant portion of maintenance costs pay for time-based maintenance and testing activities. This research project will develop a predictive maintenance strategy for selected plant components based on statistical, risk-assessment, and on-line monitoring capabilities. This predictive maintenance strategy will enable automated risk-informed deferrals of time-based preventive maintenance, eliminating unnecessary O&M costs. This will form the basis for broader cost reductions that can be achieved using this new predictive maintenance strategy if it is adopted by utilities.

Key interactions include the following:

- **Rolls-Royce Nuclear** is a world leader in the area of asset monitoring and predictive asset maintenance. They contribute expertise in risk-informed maintenance and access to a broad range of equipment data with which to develop, test, and validate advanced equipment-monitoring techniques. Rolls-Royce will also provide access to proprietary analytic tools, allowing researchers expanded testing capabilities during this research project.

The research outcomes will identify a predictive-maintenance strategy to replace the time-based approach commonly used in the industry. The results of this research will produce necessary information to support a demonstration piloted at a utility. This effort will provide nuclear power plants with recommendations and evidence to support transition to a new maintenance model.

3.2.5 Hybrid Control Room

Control room modernization is a much-needed, but very difficult, aspect of nuclear power plant modernization due to the many factors that must be addressed, such as upgrades to the underlying control and protection systems (both safety and non-safety), operator human factors, licensing basis and regulatory requirements, the safe modification of an operating plant, and the significant cost of making such changes. Nuclear operating companies have been very reluctant to attempt anything more than minor control-room modifications due to the perceived complexity and risks in doing so; they thereby forego many operational advantages that would lower operating costs and improve operational performance. The Plant Modernization Pathway provides a viable migration path for control-room modernization that addresses all of these issues, resulting in a comprehensive and systematic approach that enables initial steps in hybrid control rooms (i.e., a mixture of analog and digital systems) with a continuous path to full digital modernization.

The objective of this research is to enable large-scale control room modernization efforts. U.S. owner-operators face unique challenges that heavily influence plans to modernize. The Plant Modernization Pathway conducts research, development, and demonstrations with nuclear utilities in several separate large-scale, long-term control-room modernization projects. These projects are conducted with nuclear utilities that operate in substantially different market settings. These, in turn, affect the business case and decision making for capital investment projects. These disparate utilities will provide data and results that are representative for the majority of the U.S. operators who face I&C aging and pending obsolescence concerns. They also represent an approach to asset management conducted over a longer time horizon and favoring a staged analog-technology replacement approach to accomplish obsolescence management with an end state in mind, rather than a piecemeal approach that is reactive to incipient failures. The research works with first-movers in the nuclear sector to address legacy analog-technology issues of reliability and obsolescence, as well as to enable improved operator and plant performance. This will demonstrate the feasibility and benefits of control-room modernization to other commercial nuclear operators, suppliers, and the industry's support community. These projects will also help resolve some of the legacy I&C technology issues that may impact long-term operation of the LWR fleet.

The LWRS Program has been able to leverage these various collaboration opportunities to conduct research on a spectrum of technical and regulatory issues key to control-room and plant modernization, with this knowledge and technology accruing to the benefit of the entire operating nuclear fleet as more and more plants eventually undertake needed analog I&C technology replacement and look for opportunities to increase the economic efficiencies of their plants.

This research and these demonstrations will inform control-room modernization projects at other utilities and can reduce the uncertainty and risk associated with adopting beneficial cost-saving technologies, and this will enable utilities to transition from existing analog I&C technologies to modern digital technologies for their long-term plant operation.

3.2.5.1 Single-site Control-room Modernization

This control-room modernization project addresses challenges in managing obsolescence of I&C and enhancing efficiency and human performance to enable the continued safe and economical operation of existing commercial nuclear power plants in the U.S. It is based on research into a single site or a limited number of units from which returns are obtained on investments from modernization outcomes or savings may be extrapolated across future planned modernization efforts. Human-factors experts conduct research in control-room modernization to ensure potential designs support human-system performance and focus on reducing regulatory uncertainty and risk by incorporating needed human-factors inputs in each phase of design and development; applying state-of-the-art standards, guidance, and principles; and employing a variety of data-collection methods to provide the basis for design decisions and evidence of human-performance impacts ahead of design activities.

Key interactions include the following:

- **Palo Verde Generating Station** provides engineering, operations, and training support to enable research on control-room modernization effects on human and system performance in nuclear power plant operation. They also provided their control room simulator, which allows for full-scale evaluation of the control-room interfaces, at no cost. Palo Verde Generating Station is a key collaborator, assisting the research team in developing a strategic plan to achieve a desirable end-state for plant modernization. The research team has developed the end-state main control-room layout, alarm-system design, and a human-system interface design for upgraded control systems that is being adopted by Palo Verde Generating Station and is available to the nuclear industry as a roadmap for similar modernization efforts. In addition to the end-state design, Palo Verde Generating Station has assisted in a detailed human-factors analysis. Results from these efforts will provide the LWR fleet considering a hybrid approach with an implementable upgrade plan, providing consistent advanced and efficient control-room design compared to a like-for-like replacement of components. LWRS Program researchers were given the ability to perform studies on the implementation of advanced visualizations for chemical and volume control and turbine control systems at their site. This research demonstrates how incorporating advanced technologies, such as advanced human-system interface design, advanced alarms, and computer-based procedures can enhance operations in other areas of plant operation as well. This work serves as a proof-of-concept for digital-technology migration and integration into prevailing analog environments, thereby enabling their adoption in other control-room-upgrade projects. The research also considers new technologies for the main control room, such as how overview displays, common in advanced LWR designs, can be used in existing LWRs to support efficiently plant- and system-level operations and to illustrate how they can be used to provide advanced visualization in today's LWRs existing systems.
- **Palo Verde Generating Station** provides extensive operations and training support, enabling this research to conduct evaluations and partial validations of the design concepts with licensed operators.

This research will inform control-room modernization projects at other utilities and can reduce the uncertainty and risk associated with adopting beneficial cost-saving technologies, which will enable utilities to transition from existing analog I&C technologies to modern digital technologies for their long-term plant operation.

- **Westinghouse Electric Company** has provided graphical user interface screenshots of turbine control-system graphics, standard-display design examples, and human-system interface style guides. This information was used to develop a basis for comparison between the proposed Westinghouse systems, the existing analog controls, and other concepts developed by LWRS Program researchers and collaborators.
- The **Institute for Energy Technology** (Halden Reactor Project) developed a flexible software platform for conducting microtasks to support control-room design. This platform can be used to collect data in small-scale studies during which operators respond to focused questions about a static interface example with stand-alone dynamic microsimulations and with the interfaces developed for full-scale plant interfaces. This software collects user interactions and syncs eye-tracking data. They also adapted their Synopticon platform to the HSSL to enable eye-tracking studies requiring a minimal amount of data post-processing.

This project is developing a framework for managing regulatory, technical, and human factors risks associated with control room modernization and the need to incorporate effective human-system interface designs into modernized control rooms, which can be applied across the commercial nuclear power industry.

3.2.5.2 Fleet-Based Control Room Modernization

Projects conducted with nuclear utilities evaluate the impact of digital upgrades. These will demonstrate the feasibility and benefits of control-room modernization to commercial nuclear operators, suppliers, and the industry's support community. Some of the plants in the U.S. operate as part of a larger fleet of nuclear power assets owned and managed by a single owner-operator in a single electricity capacity market or across markets. Opportunity exists for fleet operators to leverage insights, lessons-learned, and other experience to standardize approaches to large capital and engineering projects—like control-room modernization activities. This would produce great value through economies of scale and standardization. This is reflected not only in technologies that are the subject to acquisition and procurement, but to end states and goals for such projects, intermediate states of modernization if selected, engineering processes, and regulatory issues addressed through design. In addition to addressing legacy-technology replacement and refurbishment needed to sustain existing plants during extended periods of operations, considerable opportunities exist to create value through innovative research on economies of scale that can be shared by fleets of other owner-operators.

The objective of this research is to enable large-scale control-room modernization efforts in fleet settings. U.S. owner-operators face unique challenges that heavily influence plans to modernize. The Plant Modernization Pathway conducts research and development activities with nuclear utilities in several separate large-scale, long-term control-room modernization projects and will leverage these collaborations to conduct research on a spectrum of technical and regulatory issues key to control-room and plant modernization. Information will be captured, and this knowledge and technology will continue accruing to the benefit of the entire operating nuclear fleet as more and more plants undertake needed analog I&C technology replacement.

Key interactions include the following:

- **Exelon** provides I&C engineering, operations, and training expertise; engineering change drawings; sections of their 10 Code of Federal Regulations (CFR) 50.59 licensing documentation; access to digital I&C system testing at their vendor location; copies of their simulator software; the use of their simulators to enable LWRS Program researchers to evaluate the ergonomics of their control board changes and their new digital human-system interface; and an ability to conduct operator-in-the-loop studies to identify potential human-factors engineering (HFE) issues and validate the planned control-room I&C upgrades with licensed operators. Exelon has participated in research on the existing main control-room layout and their planned digital I&C upgrades to understand and eliminate potential human error traps. This research will enable a strategic approach to perform large-scale digital upgrades for nuclear power plants. Along with participating in this research, Exelon provides operational experience, lessons learned, and implementation data related to their digital upgrades. These data are based on their non-safety related nuclear steam-supply systems and digital upgrades to their balance of plant systems.

- **Duke Energy** provided extensive HFE, I&C engineering, operations, and training expertise; engineering-change drawings; simulator-software documentation; copies of the simulator software; and the use of their glass-top simulators to enable LWRS Program researchers to evaluate the ergonomics of their control board changes and the design of their new digital human-system interface. They also provided LWRS Program researchers with access to conduct operator-in-the-loop studies with licensed operators to identify potential HFE issues and validate the planned control-room I&C upgrades. Duke Energy contributed significantly to research underway to develop a fleet-level HFE program and modernization strategy. LWRS Program researchers with expertise in human factors have collaborated with Duke throughout the entire HFE life cycle to ensure control-room upgrades are performed consistent with regulatory human-factors review criteria and human-factors best practices. Results of the HFE R&D include new industry guidance on how to develop effective human-factors program-management plans, perform quality operational experience reviews, and evaluate new advanced human-system interfaces when they are in the early stages of development. This guidance will be used to map HFE activities to NUREG-0711, which the nuclear industry can further use to understand and catalog the value of the different phases in the HFE process.
- **The Institute for Energy Technology** (Halden Reactor Project) provided professionals with experience in developing simulator facilities and in developing new I&C interfaces for legacy nuclear power plant control rooms. They also provided nuclear human-factors and operations experts with experience in performing large-scale digital upgrades of European nuclear power plant control rooms to facilitate LWRS Program researchers' efforts to use the HSSL as a research tool in early design-phase operator-in-the-loop studies. Halden experts also support control room validation studies performed at the utility's control room simulator.

The research results are being used to support nuclear power plants in their life extension efforts and will be the technical basis to develop, demonstrate, and support deployment of new Plant Modernization technologies.

3.2.5.3 Safety-Related Digital I&C Qualification Strategy

Qualification of safety-significant digital I&C systems is a barrier to modernizing operating nuclear plants needed to address obsolescence of legacy analog systems and reduce operating costs. The objective of this research will be to develop effective new means to qualify these systems as a part of a comprehensive strategy for implementing safety-significant digital I&C modifications. This involves the developing new analytical methods for detecting and preventing digital failure modes and collaborating with industry participants to ensure that candidate methods and strategies are acceptable on a technical and regulatory basis with approaches they are able to employ and implement.

Key interactions include the following:

- **Exelon Corporation** has provided a variety of in-kind contributions in technical, regulatory, and cost-savings requirements and related nuclear plant technical documents for full nuclear power plant modernization and associated requirements for safety-related I&C upgrades.

- **Virginia Commonwealth University** has provided technical analysis and device architecture descriptions for investigation into the feasibility of exhaustive testing of digital devices for software defects.
- **NEI** is pursuing a transformation plan for digital regulation and has provided technical information on acceptable regulatory approaches related to the objectives of this research.

Two candidate methods of qualifying digital I&C systems will be described for follow-on proof-of-concept testing and validation. A strategy for digital modernization based on these and existing qualification methods, as well as other planning considerations, will be developed for use by leading nuclear plant operators to move forward with needed modernization for economic viability and improved plant performance.

4. RISK-INFORMED SYSTEMS ANALYSIS

The Risk-Informed Systems Analysis (RISA) Pathway focuses on optimizing safety margins and minimizing uncertainties to achieve high levels of safety and economic efficiencies. The RISA Pathway will provide enhanced capabilities for analyzing and characterizing LWR system performance by developing and demonstrating methods, tools, and data to enable risk-informed margins management (RIMM). The goals of the RISA Pathway are twofold: (1) deploy the RISA toolkit of technologies that enable better representation of safety margins and the factors that contribute to cost and safety; and (2) conduct advanced risk assessment applications with industry to support margin management strategies that enable more cost effective plant operation. The methods and tools provided by the RISA Pathway support effective margin management for both active and passive SSCs.

The RISA toolkit will be applied in industry-application pilot projects. These pilot projects were developed through discussions with U.S. nuclear utilities. These pilot projects are in the following three Focus areas, corresponding with key industry challenges: (1) enhanced resilient nuclear power plant concepts; (2) cost- and risk-categorization applications, and (3) margin recovery and operating-cost reduction. A total of eight pilot projects are currently conducting through the Pathway. They represent studies using selected applications of the risk-informed tools and methods. The research will also address needed verification and validation of the tools and methods that are used in the pilot projects. The RISA Pathway will continue communicating with stakeholders to identify emerging issues and challenges faced by the operating fleet and to identify opportunities to conduct applied research with risk-informed methods and tools to improve margin management and plant economics.

4.1 Purpose, Goals, and R&D Activities

The RISA Pathway provides enhanced capabilities for analyzing and characterizing LWR systems performance by developing and demonstrating methods, tools, and data to enable RIMM.

The purpose of RISA Pathway R&D is to develop advanced tools, methods, and data that can support plant owner-operator decisions with the aim to improve economics and reliability and maintain the high levels of safety of current nuclear power plants over periods of extended plant operations. The goals of the RISA Pathway are twofold:

1. Deploy the RISA toolkit of technologies that enable better representation of safety margins and the factors that contribute to cost and safety.
2. Conduct advanced risk-assessment applications with industry to support margin management strategies that enable more cost-effective plant operation.

A strategy to accomplish the above RISA Pathway goals:

1. Conducts research to develop and demonstrates industry applications in pilot projects that employ the RISA methodology collaboratively with organizations from the U.S. commercial nuclear power industry.
2. Leverages industry pilot demonstration projects to address the needs of the entire industry, demonstrating how the use of risk-informed techniques can improve plant efficiency and increase confidence in their use.

The R&D activities of the RISA Pathway will focus on demonstration of risk-informed tools and methods which will provide benefit on margin optimization and minimize over-conservatism of nuclear power plant safety features. Deployment of validated risk-informed systems analysis tools and methods that will support U.S. nuclear industry for effective margin management strategy application which will improve economics, reliability and sustainability for longer-term operation.

Three focus areas are proposed under RISA Pathway:

- Enhanced resilient nuclear power plant concepts
  - Demonstration of the safety benefits associated with accident tolerant fuel (ATF), diverse and flexible coping strategy (FLEX), passive cooling system, etc
- Cost and risk categorization applications
  - Identify, prioritize, and apply the risk-informed tools and methods to assess alternative margin recovery strategies and operating costs reduction.
- Margin recovery and operation cost reduction
  - Application of the risk-informed tools and methods to analyze accident analysis, operation and maintenance cost, and plant modernization

4.2 Collaborative Research and Development Activities

The RISA Pathway performs within the framework of specific focus areas that represent key challenges identified by NPP owner-operators. The focus areas represent groups of applications of risk-informed technology to assist operating nuclear power plants to reduce costs and otherwise adapt to the changing economic and generating-mix environment. Focus-areas demonstrations are in the areas of (1) enhanced resilient nuclear power plant concepts, (2) cost- and risk-categorization applications, and (3) margin recovery and operating-cost reduction. Scalable pilot projects for RISA methodologies and technologies are planned in each of these focus areas, coordinated through U.S. nuclear utilities and industry stakeholders. Upon successful demonstration, the technology may then be scaled up to support applications by a larger community of users.

In May 2018, LWRS organized a meeting with participation from U.S. nuclear utilities to discuss and develop the pilot projects. These are the most relevant industry topics that can significantly impact plant operations in the near future, making them valuable and relevant applications for the RISA toolkit. The RISA Pathway will continue to communicate with various U.S. nuclear stakeholders to obtain feedback on current research, identify new issues, and develop a long-term plan for R&D that is responsive to the challenges of sustaining the existing LWR fleet.

4.2.1 Enhanced Resilient Nuclear Power Plant Concepts

Enhanced resilient nuclear power plant concepts consists of pilot projects that aim to enhance both the safety and economics of existing nuclear power plants through the use of advanced, near term technologies that provide substantial improvements to plant safety margins. The value of enhanced resilient plant concepts are in providing greater safety margin to operating plants which, in turn, allows plants greater flexibility in managing operations within their current safety margins. This may result, for example, in greater time to cope with design-basis accidents that, in turn, can be used as a basis for requalifying plant SSCs with significant cost savings. Today, the industry is developing accident-tolerant fuel (ATF), implementing a diverse and flexible coping strategy (FLEX) and an industry-wide initiative entitled, "Delivering the Nuclear Promise: Advancing Safety, Reliability, and Economic Performance." The enhanced resilient plant systems concept may incorporate combinations of ATF, optimal use of FLEX, enhancements to plant components and systems, and the incorporation of augmented or new passive cooling systems, as well as improved fuel cycle efficiency to establish improvements in plant safety margins that can be used to requalify or reclassify plant SSCs or otherwise obtain greater flexibility in plant operation with attendant cost reductions.

Key metrics used to evaluate the resiliency enhancements for a nuclear power plant include:

- Increased coping time as compared to the current state of fuel/plant systems
- Decreased Core Damage Frequency and Large Early Release Frequency, as compared to the current state of fuel/plant systems

- Increased safety margins, such as more margins on fuel/clad temperature or reduced hydrogen gas generation, as compared to the current state of fuel/plant systems
- Improved plant economics during normal operations.

The objective of this research effort is to use RISA methods and toolkit in industry applications, including methods development and early demonstration of technologies, in order to enhance existing reactor safety features (both active and passive) and to reduce operating costs through risk-informed approaches to plant-design modifications and their characterization. High-value evaluations of proposed ATF, together with enhanced resilient plant-system concepts, will be performed to identify both the technical and the economic advantages associated with industry adoption of the technologies. Two industry-application pilot demonstrations are proposed in this focus area.

4.2.1.1 Enhanced Resilient Plant Systems

This research focuses on using risk and cost benefit analysis of combination of plant resiliency enhancement technologies including ATF, FLEX, and passive cooling to extract additional economic, operational, and safety performance benefits for the existing fleet.

4.2.1.2 Enhanced Operation Strategies for System Components

Research into the operation of Terry turbines from the component level to the system level, both computationally and experimentally, will enhance knowledge of the operating limits of reactor-core-isolation cooling and turbine-driven auxiliary feed-water systems. The results of this research will provide the technical basis for or “credit” extended emergency core cooling performance of these systems. Key interactions include the following:

- **Texas A&M University** performs Terry turbine nozzle experiments.

4.2.2 Cost and Risk Categorization Applications

The objective of this focus area is to conduct research with risk informed approaches to develop and test methods to decrease operational costs of nuclear power plants. Two cost-sensitive areas have been identified as initial targets—component reclassification and repurposing (see 10 CFR 50.69) and component testing and maintenance.

The first area of interest is component re-categorization based on 10 CFR 50.69. In current deterministic regulations, the SSCs are categorized as “safety related” or “non-safety related.” Safety related SSCs need special treatment. Safety related SSCs, under deterministic method, will increase the cost of SSC design, licensing, and operation. By using a probabilistic risk-informed method under 10 CFR 50.69, both safety and non-safety related SSCs could be recategorized into following risk-informed safety categorization (RISC):

- RISC–1: Safety-related SSCs that perform high safety-significance functions
- RISC–2: Non-safety-related SSCs that perform high safety-significance functions
- RISC–3: Safety-related SSCs that perform low safety-significance functions
- RISC–4: Non-safety-related SSCs that perform low safety-significance functions.

Under the guidance of 10 CFR 50.69 risk-informed categorization, SSCs in the safety-related category could be recategorized into the high (RISC–1) or low (RISC–3) safety-significance categories. Then the SSCs in category RISC–3 could avoid special treatment. This recategorization can enhance plant economics. By using the RISA tools and methods, the technical basis of the SSC categorization will be enhanced and could be linked to observable engineering margin metrics.

The second area of interest is optimizing component testing and maintenance costs while maintaining plant safety and plant performance. A large portion of the cost to U.S. nuclear power plants comes from maintenance and testing, which is driven by regulatory and reliability requirements to ensure safe and continuous operation. Cost reduction could be achieved by optimizing plant safety, incorporating plant dynamics, physical aging, and degradation processes into the safety analysis in a single consistent analysis framework.

Given these two areas of interest, the objective of this focus area is to develop an innovative framework on risk categorization to enhance economics. The idea is to combine physics, risk, and cost information to enable a risk- and cost-based decision-making process for optimizing maintenance activities and achieving the greatest cost efficiency. Two pilot demonstrations are identified in this focus area.

4.2.2.1 Risk-informed Asset Management

This research will develop a comprehensive enterprise risk-analysis framework that encompasses refurbishment and replacement of plant components with the goal of decreasing the operational cost of nuclear power plants. The applications for this framework will target SSC refurbishment and replacement scheduling and testing and maintenance procedure optimizing. Key interactions include:

- **Dominion:** Dominion Energy is an energy utility company. Dominion proposes to use its North Anna Power Station as a pilot-project plant. Dominion will provide data related to SSC predicted failure times, costs related to each SSC (e.g., replacement, testing, and maintenance costs) and the consequences associated to the failure of the SSC (e.g., reduced power outputs and regulatory consequences).

4.2.2.2 Plant Health Management

This research will develop technologies that enable owner-operators to manage equipment and system-performance data, its financial risk, and reduced costs associated with monitoring and regulatory compliance. Key interactions include the following:

- **Exelon:** Exelon proposes to use Peach Bottom Nuclear Generating Station as a pilot demonstration plant. The plant will provide data and information on their plant system-health program.

4.2.3 Margin Recovery and Operation Cost Reduction

Existing U.S. nuclear power plants are designed and constructed based on defense-in-depth safety principles for critical systems needed to fulfill safety functions. Design-basis safety analyses are performed using deterministic approaches which normally employ conservative models and assumptions to provide tolerances to account for uncertainties. However, the accumulation and aggregation of uncertainties arising from these conservatisms in current deterministic design approaches may result in overly conservative operating requirements that limit the operational flexibility of the current fleet and can result in inflated operating costs.

Research in margin recovery are focused on to developing risk-informed, multiscale, and multiphysics high-fidelity tools and methods to conduct a comprehensive investigation of plant safety requirements and their method of implementation to assess approaches to recover margins associated with conservatisms of legacy licensing, design, and analysis. A goal of this research is to identify and develop the technical bases that may permit existing nuclear power plants to operate more efficiently, with more operational flexibility and less cost due to unnecessarily restrictive requirements. The general objective of this focus area is to develop an integrated evaluation approach that combines plant PRA methods with a multiphysics best-estimate plus uncertainty (MP-BEPU) or a risk-informed multiphysics best-estimate plus uncertainty (RI-MP-BEPU) approach. The RI-MP-BEPU framework will employ modern high-fidelity probabilistic and best-estimate modeling and simulation tools with consistent uncertainty propagation and rigorous uncertainty quantification and sensitivity analysis in a multiscale, multiphysics environment. RI-MP-BEPU will integrate various simulation tools across a full spectrum of plant-analysis activities, including core design, fuels performance, component aging and degradation, systems analysis, containment response, radionuclide transport, and release and risk assessment. This will allow complex multiphysics and risk-informed approaches to be implemented so that important nuclear power plant systems problems can be solved with high efficiency and speed. This approach is used to identify the actual margins that are available in licensing-case scenarios so that decision makers, both plant owners and regulators, can identify areas of available margin. This will provide the potential for nuclear power plants to reallocate that margin to other applications and provide commensurate operational cost reductions.

4.2.3.1 Enhanced Fire Probabilistic Risk Assessment

The goal of the project is to conduct research and development for improved use and advancement of fire probabilistic risk assessment (PRA) models by combining physics simulation methods with visualization tools. Key interactions include the following:

- **Southern Company:** Southern Company will provide plant data and fire PRA models and its analysis process**.**

4.2.3.2 Modernization of Design-basis Accidents Analysis with Application on Fuel Burnup Extension

This project will conduct research to develop a risk-informed, high-fidelity, multiphysics analysis framework to modernize design-basis accident analyses for existing nuclear power plants to reduce uncertainties and conservatisms associated with legacy licensing, design, and analysis. Demonstrating this approach to fuel burnup extension can reduce fuel-cycle costs for an existing operating plant and quantify cost savings. Key interactions include the following:

- **South Texas Project**: South Texas Project Electric Generating Station (STNP) is a nuclear power plant at Bay City, Texas, comprising two Westinghouse PWRs. STNP will provide guidance on core design with extended fuel burnup and plant data and information.

4.2.3.3 Digital I&C Risk Assessment

The research will focus on defining a risk-informed analysis process for a digital replacement of the reactor protection system (RPS) for an existing plant. This approach complements other approaches being developed for deploying digital I&C technologies and emphasizes risk-informed approaches used to facilitate the adoption and licensing of safety-related and non-safety-related digital instrumentation and controls.

4.2.3.4 Plant Reload Process Optimization

The goal of the project is to develop a risk-informed and efficient process for a reload licensing and operating-cycle management application of an existing plant to reduce the utility's costs associated with reload-licensing analysis, fuel cycle, and operating margins. Key interactions include the following:

- **FPoliSolutions**: FPoliSolutions will use RISA tools and methods to evaluate efficiencies in the plant reload licensing and operational cycle management.

4.2.4 International Collaborations

A variety of international researcher interactions are of potential interest to the RISA Pathway, including:

- **NEA Working Groups under Committee on the Safety of Nuclear Installations (CSNI):** This Nuclear Energy Agency (NEA) committee aims to assist member countries in maintaining and further developing the scientific and technical knowledge required to assess the safety of nuclear reactors and fuel-cycle facilities. The NEA is under the framework of the Organisation for Economic Co-operation and Development (OECD). The U.S. is a member of both organizations. One of the task groups in CSNI is primarily working on safety margin applications and assessment: the Working Group on Risk

Assessment, which advances the understanding and use of PRA tools. Another working group in CSNI, the Working Group on Analysis and Management of Accidents addresses safety analysis research, including uncertainty and sensitivity evaluations of best-estimate methods program. Benchmarking activities and international collaboration are organized through these working groups.

Since 2013, NEA has organized a dedicated expert group on natural hazards: the CSNI Working Group on Natural External Hazards (WGEV). The mission of WGEV is to improve the understanding and treatment of external hazards in ways that would support the continued safety performance of nuclear installations and improve the effectiveness of regulatory practices. Dr. Curtis Smith (Idaho National Laboratory [INL]) is member of this Working Group. One of the active areas of research within the WGEV is a CSNI Activity Proposal for a science-based approach to screening for external events. The objective of the CSNI Activity Proposal is to build on the existing experience base within member countries and identify best practices and any gaps. Currently, three types of screening processes exist: (1) deterministic screening based on standard practice; (2) absolute frequency (or probability) screening; and (3) relative probabilistic considerations conditional upon plant design (e.g., conditional core damage probabilities for potential initiating events). The CSNI activity proposal is focused on absolute frequency screening, factoring in physical conditions that limit the frequency or magnitude of a natural hazard.

- **NEA Ad Hoc Expert Group on Maintaining Low-Carbon Generation Capacity through LTO of Nuclear Power Plants: Economic, Technical and Policy Aspects (EGLTO):** Under guidance of NEA Nuclear Development Committee, a new NEA Ad Hoc Expert Group on Maintaining Low-Carbon Generation Capacity through LTO of Nuclear Power Plants: EGLTO was formed in April 2018. Dr. Ronaldo Szilard (INL) is the member of the expert group. The expert group will review the technical and economic aspects of LTO of existing nuclear power plants and their interactions, taking into account:
  - Needs for major investments in maintenance and refurbishment, including those brought about by regulatory changes, as well as additional safety requirements due to the Fukushima Daiichi accident
  - Changes in O&M costs (e.g., higher personnel costs)
  - Changes in market conditions—e.g., decline in wholesale electricity or decreasing capacity factors due to competing technologies (subsidized renewables, cheap fossil fuels), tax regimes, absent or ineffective carbon pricing
  - The impact of operational lifetime on the costs and funding of waste management and decommissioning.

The expert group will also analyze nuclear power plant life extension and its impact under decarbonization policy view point.

- **Sustainable Nuclear Energy Technology Platform (SNETP):** Established in September 2007 with the backing of the European Commission (EC), the SNETP promotes and coordinates research activities in the field of nuclear fission. Over 100 members are drawn from industry, research and safety organizations, universities, and non-governmental bodies based in Europe, sharing a common interest in developing safe and sustainable nuclear power.
- **NUGENIA: Nuclear Generation II&III Association:** NUGENIA is an international non-profit association supported by SNETP dedicated to the R&D of nuclear fission technologies, with a focus on Generation II and III nuclear plants. It provides scientific and technical basis to the community by initiating and supporting international R&D projects and programs. The association gathers stakeholders from industry, research, safety organizations and academia, committed to develop joint R&D projects in the field.

- **Civil Nuclear Energy Research and Development Working Group (CNWG):** The CNWG is bilateral agreement established by DOE and METI and Japan's Ministry of Education, Culture, Sports, Science, and Technology. In addition, participants from Japan included the Japan Atomic Energy Agency (JAEA) and CRIEPI. The goal of the group is to foster cooperative efforts and collaboration on nuclear R&D in various fields, including fast reactors, high-temperature gas reactors, nuclear fuel cycle and waste management, and LWRs. DOE, JAEA, and CRIEPI also jointly launched a new project to conduct safety analysis on metal-fueled fast reactors. Related to the RISA Pathway, CNWG has shown high interest on risk-informed and advanced seismic PRA applications.
- The RISA research team has engaged in collaboration activities with a variety of international stakeholders, including joint activities with the Korea Atomic Energy Research Institute (KAERI), the India-U.S. Civil Nuclear Energy Research and Development Working Group (CNEWG) bilateral working group, and the Japan Nuclear Risk Research Center.

5. REACTOR SAFETY TECHNOLOGIES

In the aftermath of the March 2011 multi-unit accident at the Fukushima Daiichi nuclear power plant (Fukushima) in Japan, the nuclear community has been reassessing certain safety assumptions about nuclear power plant design, operations, and emergency actions, particularly with respect to extreme events that might occur and are beyond each plant's current design basis. Because of its significant domestic investment in nuclear reactor technology (e.g., 99 reactors in the fleet of commercial LWRs with others under construction), the U.S. has been a major leader internationally in these activities. The U.S. nuclear industry has voluntarily pursued a number of additional safety initiatives. The NRC continues to evaluate and, where appropriate, establishes new requirements for ensuring adequate protection of public health and safety in the occurrence of low probability events at a licensed commercial nuclear facility (e.g., mitigation strategies for beyond-design-basis events, such as extreme external events that could include seismic or flooding initiators).

DOE has played a role in the U.S. response to the Fukushima accident. Initially, DOE worked with the Japanese government and industry, as well as the international community, to develop a more complete understanding of the Fukushima accident progression and its consequences, and to assist in the response to emerging safety concerns regarding the nature of, and effects from, the accident. DOE efforts have focused on providing scientific and technical insights, data, and analysis methods that ultimately support industry efforts to better characterize the safety performance of currently operating plants, as well as future U.S. nuclear power plants. In pursuing this research, DOE recognizes that the commercial nuclear industry is ultimately responsible for the safe operation of licensed nuclear facilities. As such, this research pathway works closely with industry to ensure that research products are properly characterized and that results can be scaled and implemented in operational settings.

5.1 Purpose, Goals, and R&D Activities

The purpose of the RST Pathway R&D is to improve understanding of beyond-design-basis events and reduce uncertainty in severe accident progression and phenomenology and in outcomes using existing analytical codes and information gleaned from severe accidents—in particular, the Fukushima Daiichi event. This information has been used to aid in developing mitigating strategies and improving severe-accident management guidelines for the current LWR fleet. The RST Pathway's activities evolved from an initial coordinated international effort to assist in the analysis of the Fukushima accident progression and accident response into the following two areas of current research:

1. Severe Accident Analyses: This research has focused on analyses using existing computer models and their ability to provide information and insights into severe-accident progression that aid in the development of severe-accident management guidelines (SAMGs) and training operators on these SAMGs; an auxiliary benefit can be informing improvements in these models.
2. Accident-tolerant Components: This research has focused on analyses of experimental efforts for hardware-related issues, including SSCs with the potential to prevent core degradation or mitigate the effects of beyond-design-basis events.

5.2 Collaborative Research and Development Activities

5.2.1 Severe Accident Analysis

The overall objective of this activity is to improve our understanding of severe accident progression, phenomenology, and outcomes using existing analytical codes. Insights gained from this work are being used to improve SAMGs for the current LWR fleet.

5.2.1.1 Severe Accident Analysis Crosswalk and SAMG Validation

The first phase of a crosswalk study, completed in 2015, identified a number of areas in which the industry and NRC severe-accident analysis codes (i.e., Modular Accident Analysis Program

(MAAP)5 and MELCOR, respectively) have implemented different modeling choices for core degradation phenomena inside the RPV. These modeling differences reflect uncertainty that persists in the understanding of severe-accident phenomena, principally due to a lack of experimental data that can be used to resolve such differences. Phase II of the crosswalk, which was completed in 2017, examined accident sequences involving water injection into a degraded core prior to vessel failure in order to identify modeling differences that can impact predictions of the effectiveness of core-recovery actions, a critical part of accident-management planning. The results of this study revealed that modeling uncertainties associated with core-degradation phenomena propagate to the later phase of the accident, leading to divergent predictions of the effectiveness of in-vessel core recovery actions.

The main objectives of severe-accident analysis are to: (1) better understand differences in the model physics and eliminate modeling uncertainties and (2) use these severe-accident simulations to inform SAMG development and training, with consideration of the inherent uncertainties in model predictions. The motivation for this work is the NRC's Mitigation of Beyond Design Basis Event (MBDBE) Rule (10 CFR 50.155 and NEI Guides 13-06 and 14-01) requiring industry to train on SAMGs.

Key interactions include the following:

- **EPRI** collaborates in this research. With its own funding, EPRI exercises MAAP5 for severe accident scenarios, which are similarly analyzed using MELCOR by Sandia National Laboratories (SNL) and sponsored by the LWRS Program. The specific objective of this work is to use severe-accident analysis accident signatures to inform symptom-based SAMGs and confirm they can address a wide-range of accident signatures, given model differences and uncertainties, and achieve a safe, stable state. EPRI and SNL compare and synthesize the results obtained from these two codes and document the results in technical reports that are used by the BWR and PWR owners' groups to identify potential simplifications to accident-management guidelines in order to reduce the number of operator actions and decisions and inform training programs for licensed operators and technical support centers (TSCs).
- **Boiling Water Reactor Owners' Group (BWROG)** and **Pressurized Water Reactor Owners' Group (PWROG)** representatives provide technical guidance and insights on particular accident sequences of importance to analyze, as well as technical reviews of the results obtained. This interaction is conducted by LWRS Program staff attending and presenting results of research at owners' groups meetings.

5.2.1.2 Severe Accident Analysis Support Guideline Validation and Software Development

Current BWR industry practice is to develop generic spreadsheet-based calculations in technical support guidance (TSG) for the TSC to assist operators with emergency operating procedures and SAMGs. These generic calculations must still be converted to plant-specific calculations. The objective of this research is to develop a software tool for TSG calculations to support the TSC for both BWRs and PWRs. The benefit to industry is an intuitive tool that can be easily transferred between groups (i.e., TSC, operators, and emergency operating procedure and SAMG BWROG support) to support operators in responding to a severe accident. In particular, this tool should facilitate the use of TSGs by operators during a severe accident and reduce the possibility of errors associated with input of real-time plant data needed to evaluate and forecast plant conditions.

Key interactions include the following:

- The **BWROG** is the principal industry participant involved with this research. It collaborates and provides consultation to the research, modeling reviews, software beta testing, and travel and interacts with LWRS Program staff during committee review meetings to support the tool development. It also provides plant data, its technical support guideline calculations, and technical manuals and drawings needed to support this research. The PWROG is interested in this work and is considering how best to be involved.

5.2.1.3 Ex-vessel Behavior

The objective of this research is to improve existing analytical tools (i.e., MELTSPREAD and CORQUENCH—used in the Fukushima accident analyses) to provide a technical basis for supporting the development of water-management strategies for BWRs. Water-management strategies aim to keep ex-vessel core debris covered with water while preserving the wetwell vent path. The motivation for this research is the NRC severe-accident-capable vent Order EA-13-109, requiring containment protection and risk reduction. Industry has adopted a severe-accident water-management (SAWM) strategy as an alternative to installing filters on containment vents. The primary benefit to industry from this research is a validated set of tools to support plant implementation of plant-specific SAWM strategies.

Key interactions include the following:

- **EPRI** contributed to this research by identifying modeling improvements needed for MELTSPREAD and CORQUENCH to achieve physically realistic tools that can be used to support development of plant-specific SAWM strategies. EPRI has carried out a beta test of MELTSPREAD and provided feedback on code usability and performance. EPRI developed and contributed software to simplify importing MAAP melt pour results into the MELTSPREAD input file.
- **BWROG** representatives provide technical guidance and insights on particular accident sequences of importance, as well as technical reviews of the results obtained. This interaction is conducted by LWRS Program staff attending and presenting results of research at owners' group meetings.

5.2.2 Accident-tolerant Components

The objective of this research is to improve the capabilities of nuclear power plants to monitor, analyze, and manage conditions leading up to and occurring during a beyond-design-basis event. Availability of appropriate data and the operators' ability to interpret and apply those data to respond and manage the accident were issues during the Fukushima accident. The damage associated with the earthquake and subsequent flooding inhibited or disabled the proper functioning of the needed safety systems or components.

5.2.2.1 Terry Turbine Testing and Analysis

The specific objectives of this research are to: (1) develop dynamic system models for Terry turbo-pump systems; (2) apply these models to characterize system response during beyond-design-basis accident conditions; and (3) conduct a test program to provide data for model validation and to demonstrate an extended reactor-core isolation cooling (RCIC) operational envelope. The motivation for this work is based on Fukushima reconstruction studies, which revealed the extraordinary long-term operation of the RCIC system at Daiichi's Unit 2 that prevented core damage over the first three days of the accident. The expected benefit to industry will be an expanded operating range for RCIC providing more bridging time to implement FLEX. PWRs have an analogous issue with the steam generator auxiliary feedwater pump that is also driven by a Terry turbine.

Key interactions include the following:

- **EPRI** participates in this collaborative research by providing detailed computer-aided design models of the Terry turbine that are used to support industry maintenance efforts on Terry turbine systems. In this research, these computer-aided design models support detailed computational fluid dynamic modeling of Terry turbine performance under water ingestion conditions that are being analyzed as part of the program.
- The **BWROG** provides project management for laboratory research at Texas A&M University using staff and students, testing equipment, quality assurance (QA) peer review of procedures, and subject-

matter expert support in receipt, maintenance, and use of the equipment. They also provide guidance and insights on particular sequences of importance, as well as technical reviews of the results obtained. This interaction is achieved by BWROG personnel interacting with Texas A&M staff and students, laboratory staff, and representatives from the Institute for Applied Energy in Japan at regularly scheduled Terry Turbine Extended Operating Band committee meetings.

- **Institute for Applied Energy** collaborates with the LWRS Program on this research. They provide subject-matter expertise on equipment performance issues, QA peer review of procedures, and contribute to Terry turbine analysis through a parallel modeling effort, which is being coordinated with the research conducted at SNL and Idaho National Laboratory.