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Revision 1

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

June 2020

U.S. Department of Energy

Office of Nuclear Energy

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Prepared for the
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EXECUTIVE SUMMARY

This report describes the collaborative research and development (R&D) projects in which the U.S. Department of Energy's (DOE) Light Water Reactor Sustainability (LWRS) Program engaged with industry, regulatory agencies, and other organizations during Fiscal Year 2019. 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 an 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 submitted applications to the U.S. Nuclear Regulatory Commission (NRC) to begin the license-renewal process, extending the operating license period beyond 60 years from the date of initial licensing. In fact, on December 5, 2019, NRC staff approved Florida Power & Light's application to renew its licenses for its Turkey Point Nuclear Units 3 and 4, allowing the utility to operate the units until 2052 and 2053, respectively. This is the first time the NRC has issued renewed licenses authorizing reactor operation from 60 to 80 years. 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.

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

Under the guidance of four research objectives, NE resolves barriers to technical, cost, safety, security, and proliferation resistance through early stage research, development, and demonstration (RD&D) to:

1. Enhance the long-term viability and competitiveness of the existing U.S. reactor fleet.
2. Develop an advanced reactor pipeline.
3. Implement and maintain national strategic fuel-cycle and supply-chain infrastructures
4. Maintain U.S. leadership in nuclear energy technology.

The LWRS Program is the primary programmatic activity that addresses the first of these objectives. 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 five distinct R&D pathways that are summarized below:

- **Plant Modernization**: R&D to address nuclear-plant economic viability in current and future energy markets through innovation, efficiency gains, and business-model transformation using digital technologies. This includes addressing long-term aging and modernization or replacement of legacy instrumentation and control (I&C) technologies by 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 nuclear power plant owner-operators, vendors, and suppliers to modernize plant systems and processes and transition to a technology-centered business-model that achieves improved performance at lower cost.
- **Flexible Plant Operation and Generation**: R&D to identify opportunities and develop methods for light-water reactors (LWRs) to directly supply energy to industrial processes to diversify approaches to revenue generation. This pathway adapts and uses analysis tools developed by DOE to complete technical and economic assessments of large, realistic market opportunities for producing nonelectrical energy products in close proximity to nuclear power plants. Engineering development and design, testing, and demonstration of integrating nuclear power plants with other industrial processes are carried out. Pertinent safety assessments and licensing approaches are addressed to help support LWR owners with the integration of the new processes.
- **Risk-informed Systems Analysis**: R&D to develop and deploy risk-informed tools and methods to achieve high levels of safety and economic efficiencies. The pathway will: (1) develop technologies that enable better representation of safety margins and use them to characterize the factors that contribute to cost and risk and (2) conduct advanced risk-assessment

applications with industry to enable more cost-effective plant operation. The tools and methods provided by the pathway will support effective safety-margin management for both active and passive SSCs of nuclear power plants.

- **Materials Research**: R&D to develop the scientific basis for understanding long-term environmental degradation and predicting the performance 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. R&D products will be used to inform operational limits and aging-mitigation approaches for materials in nuclear power plant SSCs that are subject to long-term operating conditions, providing key input to both regulators and industry. The intent is to help reduce operating costs, This may be accomplished by offsetting maintenance costs using better predictive models for component lifetime, improved analysis of materials through non- destructive evaluation, reduced costs for repairs, or extended performance of plants through the selection of improved replacement materials.

- **Physical Security**: R&D to develop methods, tools, and technologies to optimize and modernize a nuclear facility's security posture. The pathway will: (1) conduct research on risk-informed techniques for physical security that account for a dynamic adversary; (2) apply advanced modeling and simulation tools to better inform physical-security scenarios and reduce uncertainties in force-on-force modeling; (3) assess benefits from proposed enhancements and novel mitigation strategies and explore changes to best practices, guides, or regulation to enable modernization; and (4) enhance and provide the technical basis for stakeholders to employ new security methods, tools, and technologies.

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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
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
DDS	Dynamic Design Solutions, Inc.
DOE	Department of Energy
DOE-NE	Department of Energy Office of Nuclear Energy
EdF	Électricité de France
EGLTO	Economic, Technical and Policy Aspects
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
I&C	instrumentation and control
IAE	Institute for Applied Energy
IASCC	irradiation-assisted stress corrosion cracking

ICIC	International Committee on Irradiated Concrete
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
METI	Ministry of Economy, Trade, and Industry
MsS	magnetostrictive sensor
NDE	nondestructive 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
PSEG	Public Service Enterprise Group
PWR	pressurized water reactor
PWROG	Pressurized Water Reactor Owners' Group
QA	quality assurance
R&D	research and development
RIAR	Research Institute of Atomic Reactors
RIMM	Risk-Informed Margins Management
RISA	Risk-Informed Systems Analysis
RPV	reactor pressure vessel

RST	Reactor-Safety Technologies
SCC	stress corrosion cracking
SHM	structural-health monitoring
SSC	system, structure, and component
STNP	South Texas Nuclear Project Electric Generating Station
SwRI	Southwest Research Institute
TEA	Technical and economic assessments
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 SSCs so nuclear power plants can continue to operate safely and cost effectively.

The LWRS Program is focused on the following three goals:

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

- **Plant Modernization:** R&D to address nuclear-plant economic viability in current and future energy markets through innovation, efficiency gains, and business-model transformation using digital technologies. This includes addressing long-term aging and modernization or replacement of legacy instrumentation and control (I&C) technologies by 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 nuclear power plant owner-operators, vendors, and suppliers to modernize plant systems and processes and transition to a technology-centered business-model that achieves improved performance at lower cost.
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conditions, providing key input to both regulators and industry. The intent is to help reduce operating costs, This may be accomplished by offsetting maintenance costs using better predictive models for component lifetime, improved analysis of materials through non- destructive evaluation, reduced costs for repairs, or extended performance of plants through the selection of improved replacement materials.

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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 operation 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 2019. 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 RD&D 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 cost 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 which 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. In a few instances, organizations discussed herein are still in planning discussions with the LWRS program and it would not be prudent to identify them until an agreement is finalized. In other instances, the activities discussed are sensitive and formative in nature therefore individual utilities and plants will not be identified in these collaboration descriptions.

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, R&D collaborative activities, participants and their roles or contributions in those activities, and 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. PLANT MODERNIZATION PATHWAY

The U.S. operating nuclear fleet is an important national asset providing approximately 20% of the nation's electricity, as well as providing critical grid stability, carbon-free energy, and fuel-diversity. 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, nuclear power plants have closed 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 power plants have a significant opportunity to lower their operating costs while 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 today is largely based on a state of technology and related operating model that is over 40 years old. 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 critical that proven solutions be identified and become available to nuclear utilities for wide-scale plant modernization that provide near-term cost reductions while resulting in a future state that is operationally and financially sound for decades to come.

2.1 Purpose, Goals, and Research and Development 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 to and 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 three principal areas of activities:

- I&C Architecture
- Online Monitoring and Plant Automation
- Advanced Applications and Process Automation.

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

2.2 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 support alliances. Through these relationships, nuclear plant operators provide experience-based input on R&D priorities and provide technical requirements for technology solutions compatible with the nuclear operating and safety-culture environments. In many cases, they directly collaborate on research projects, providing technical expertise and hosting R&D activities, field demonstrations, and validations of emerging technologies. These direct utility relationships are essential to ensure 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, the Electric Power Research Institute (EPRI), the Nuclear Energy Institute (NEI), and the Institute of Nuclear Power Operations (INPO). Each of these organizations have 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 solicit valuable insights on specific technology developments from a regulatory perspective, facilitate NRC's readiness to evaluate related applications, and enable 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.

2.2.1 Instrumentation and Control Architecture

Currently, the LWR fleet employs a mixture of traditional, analog I&C technology and newer, digital technology. Virtually all U.S. nuclear power plants have undertaken some digital upgrading over the lifetime of the stations. In some cases, digital systems were the only practical replacement for legacy analog components. In other cases, digital systems were the preferred technology in that they could provide more-precise control and greater reliability. The cumulative effect on the LWR fleet has been an ever-increasing presence of digital systems in LWR control rooms and throughout the plant.

Developing and demonstrating an effective and efficient path forward for licensing and deployment of modernizing the LWR fleet through digital I&C has been elusive thus far. Recent safety-related I&C-

upgrade projects at commercial nuclear power plants have cost substantially more than expected, taken longer to perform, and have produced a chilling effect on modernization and investments of this type.

Several challenging issues remain unresolved and require significant R&D for nuclear utilities to move forward with modernization. These key issues include defining the end-state digital architecture, developing a business case for implementation, addressing licensing uncertainty, and developing implementation schedules compatible with short refueling outages.

Introducing digital systems into control rooms creates opportunities for improvements in control-room function that are not possible with analog technology. These can be undertaken in measured ways, preserving the proven features of the control-room configuration and functions and improving others. By applying human-centered design principles, these modifications can enhance plant and human performance and reduce or eliminate the potential for new human errors and their consequences.

The process of designing and implementing digital control-room technologies to replace analog systems serves as an opportunity to implement human-centered design activities throughout the various stages of design, acquisition, and implementation. These design activities and their technical bases (human-factors design standards and cognitive-science research) were not available at the time of the original design of main control rooms. Considerable progress has been made in these fields since the completion of the industry's response to the Three Mile Island 2 Action Plan, and this progress requires a human-factors approach to control-room changes. Replacement digital technologies having more powerful and flexible graphical and informatics capabilities—together with a substantially improved understanding of how to leverage these capabilities to support effective human performance—afford the opportunity to realize a more human-centered main control room.

Research projects and key collaborations that support transformational I&C architectural modernization are listed below.

2.2.1.1 Instrumentation and Control (I&C) Infrastructure Modernization

The nuclear power industry relies heavily on 1980s technology and is challenged by aging I&C infrastructure. Older equipment creates sustainability challenges while providing a minimal level of direct functionality. It requires significant work effort to perform corrective and preventive maintenance to keep these systems operating and to perform necessary surveillances to demonstrate they are operating properly. Material and labor costs to keep these systems performing are rising at an increasing rate. These systems also lack the advanced features that newer systems provide which could significantly reduce operator and maintenance workload.

This research addresses these challenges by identifying methods and techniques to modernize I&C equipment and reduce implementation and life-cycle costs. At the same time, this research identifies methods to maximize the return on I&C modernization investments in terms of reducing operator workload, I&C system-support workload, and overall plant-maintenance workload/costs by providing digitized plant data for advanced diagnostic and prognostic use.

Development of tools to enable evaluation of costs associated with modernizing as well as sustaining current I&C systems is also addressed to inform business-case evaluations.

2.2.1.1.1 Leveraging I&C Modernization Techniques Used in Other Industries

This research leverages advances made in non-nuclear sectors to realize savings and performance improvements through their use in the nuclear industry. Using digital technologies for non-safety applications within nuclear is consistent with 10 CFR 50, Appendix A, General Design Criterion 1. Application of these technologies to nuclear power plant distributed-control-systems represents a target that would provide the maximum aggregate impact to improve plant operational and cost performance.

This research is developing and demonstrating approaches to leverage established vendor processes and experience to minimize costs for a utility to deploy and periodically upgrade I&C systems via a repeatable obsolescence-management cycle. This enables a utility to maximize the benefits of expanded use of digital control systems as part of a plant strategy to eliminate obsolete I&C systems, reduce operating and maintenance costs, improve operational performance, and maximize personnel utilization through digitalization.

Key interactions include the following:

- **Duke Energy** contributed critical information describing the process followed when installing modern distributed process control systems in several of their nuclear plants. Duke also contributed by participating in meetings with the LWRS Program and Honeywell Process Solutions concerning their plans to perform a technology refresh of these systems to address hardware and software obsolescence. In collaboration with Duke Energy, the outcome of this pilot project is documented in the report entitled, *Addressing Nuclear I&C Modernization Through Application of Techniques Employed in Other Industries* (INL/EXT-19-55799). This research will help enable this technology refresh as well as provide lessons learned to the larger nuclear industry in this area.

- **Honeywell Process Solutions** contributed by hosting a meeting with Duke Energy and LWRS Program personnel where they presented their techniques to perform a system-technology refresh with minimal or no plant downtime while maximizing the retention of initial intellectual property investments. This included providing specific data with regard to their products and their associated long-term life-cycle support strategy. This was valuable in that it provided a practical example of methods to upgrade modern distributed control systems that have been deployed by Duke Energy as discussed above. This example was generically described in the aforementioned report.

2.2.1.1.2 Safety-Related Digital I&C Modernization Pilot

The safety-related digital I&C modernization pilot project focuses on reactor protection and emergency-safeguards digital I&C systems. The objective of this research is to demonstrate the economic viability of modernizing these systems. This includes developing generic functional requirements used to inform both the business case cost justification effort and develop the necessary license amendment request using the recently developed alternate review process contained within Digital Instrumentation and Control Interim Staff Guidance (DI&C-ISG-06). Performing safety-related digital I&C upgrades is seen as a key enabler to performing a more comprehensive set of digital I&C upgrades, guided by an advanced concept of operations. This advanced concept of operations establishes requirements and constraints for all plant and work function modernization efforts to ensure strategic business objectives are achieved.

Key interactions include the following:

- **Exelon Generation** contributed by hosting several meetings to support this effort. Outcomes included identifying members of the pilot team, identifying the nuclear station that will participate in the research, and establishing the initial scope of the safety systems to be addressed by the pilot. Subsequent decisions on the use of the license amendment request developed through this research to replace any existing systems will be made apart from the current research.

- **ScottMadden, Inc. and Associates** contributed by providing a business-case model to assess the economic viability of performing digital upgrades. This business-case model was developed in collaboration with the LWRS Program and industry and leverages the Obsolescence Cost Model described in the next section.

- **MPR Associates, Inc.** contributed by providing specific expertise with regard to the alternate approach for license-amendment requests per DI&C-ISG-06, Revision 2. This expertise was leveraged to plan the development of functional requirements for the pilot and the development of the associated license-amendment request.

2.2.1.1.3 Obsolescence Cost Model for Nuclear Power Plant I&C

This research developed a comprehensive, empirical obsolescence cost model to address long-term obsolescence-management concerns for legacy nuclear plant I&C systems. This cost model provides a tool to quantitatively assess different factors impacting I&C obsolescence. This, in turn, supports decision making regarding the path to be pursued to address obsolescence. High-level factors to consider include

whether the components are in a safety or non-safety system, a primary or support system, or an analog or digital system; (2) whether support is provided by the original equipment manufacturer, vendor, or third party, and (3) the availability of spare parts.

The report entitled *Development of an Obsolescence Cost Model for Nuclear Power Plant* (ORNL/TM-2019/1238) summarizes the broader scope of a comprehensive I&C-obsolescence cost model. It then provides a specific, limited cost model to demonstrate the method and viability of cost model development and use. The cost model evaluates the replacement costs of a digital safety-system component.

Key interactions include the following:

- **Paragon Energy Solutions** contributed by hosting meetings with the research team to understand mechanisms to address obsolescence and providing specific obsolescence-management data for a safety-related I&C system to exercise the limited cost model and demonstrate its viability.

2.2.1.2 Control-Room Modernization

The 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 that 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. They apply state-of-the-art standards, guidance, and principles and employ a variety of data-collection methods to provide the basis for design decisions and evidence of human-performance impacts ahead of design activities.

The project is also developing and demonstrating concepts for integration of advanced technologies in the main control room, which includes information in the control system and in the field, and decision support including computerized operator-support tools and online-monitoring information. This integrated concept will increase efficiency of routine operations, ultimately reducing costs and promoting the long-term sustainability of the LWR. This will be achieved as the Pathway assists nuclear utilities in addressing reliability and obsolescence issues of legacy analog control rooms and demonstrates how strategically integrating advanced technologies will achieve those results.

Key interactions include the following:

- **Palo Verde Generating Station** provides engineering, operations, and training support to enable research on control-room modernization’s effect 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. Results from these efforts will provide the LWR fleet considering a partial digital upgrade, commonly referred to as a hybrid approach with an implementable upgrade plan that gives a more consistently advanced and efficient control-room design compared to a like-for-like replacement of components. 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.

- **Westinghouse Electric Company** has provided graphical user interface designs of candidate 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.
- **Institute for Energy Technology (IFE)** developed a flexible software platform for conducting microtasks to support control-room design. stand-alone dynamic microsimulations and with interfaces developed for full-scale plants. This software collects user interactions and synchronizes eye-tracking data. IFE also adapted their Synopticon platform to the Human System Simulation Laboratory (HSSL) to enable eye-tracking studies requiring a minimal amount of data post-processing. IFE has also provided operations expertise to support scenario and experiment design.
- **Argonne National Laboratory** has developed models and tools to support the development of decision support tools for the boric-acid concentrator. LWRS Program researchers will develop advanced interfaces to display the decision support information developed by Argonne National Laboratory and deploy this technology as part of the upgrades to the boric-acid concentrator control room. This will represent the first full-scale demonstration of this technology, which can provide operators with valuable information that can improve their decision making.

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. This project also identifies ways to leverage digital technology in the control room to streamline operations to reduce operations and maintenance (O&M) costs.

2.2.1.3 Full Nuclear Plant Modernization

The Full Nuclear Plant Modernization project evaluates the impact of digital upgrades beyond the control room. This research leverages results from other LWRS research activities, like control room modernization, and safety system I&C modernization, to evaluate a broader application of technology. This research demonstrates the feasibility and benefits of digital upgrades to the full nuclear plant, including commercial nuclear operators, suppliers, and the industry's support community. Full nuclear plant modernization relies on transforming the concept of operations for commercial plants from one that is historically labor-centric to a technology-centric concept of operations to achieve significant reductions in workload and O&M cost savings. Furthermore, 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 market or across markets. Opportunities exist 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 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, 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. The Plant Modernization Pathway conducts R&D activities with nuclear utilities in several separate 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.

Key interactions include the following:

- **Dominion Energy** provided I&C engineering, operations, and training expertise, access to operational-experience databases, access to digital I&C information, and use of their simulator to enable LWRS Program researchers to evaluate the ergonomics of their control-board changes and their new digital human-system interface. This research will enable a strategic approach to perform full-plant digital upgrades for nuclear power plants. Along with participating in this research, Dominion provides lessons learned and implementation data related to their digital upgrades.
- **The Institute for Energy Technology** provided professionals with experience in conducting human-in-the-loop studies with licensed operators in simulator facilities and in developing new I&C interfaces to replace legacy control systems in 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.

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.

In addition, this research initiated a study on how a concept known as integrated operations (IO), which was developed in the North Sea oil and gas industry to address similar concerns, could be adopted to assist the nuclear industry. IO allowed the oil companies to consolidate operations and support resources onshore serving multiple platforms, with a small workforce contingent on the platform for the residual hands-on work. This gave extended life to these valuable revenue-producing assets.

Key interactions include the following:

- **Xcel Energy** is a leading nuclear utility headquartered in Minneapolis, MN, operating the Monticello and Prairie Island nuclear stations. In collaboration with their initiative to lower their nuclear operating costs through business improvement, Xcel has provided detailed information on their nuclear operating and support functions, the costs to conduct these activities, and the resources required to execute them. This information has enabled the project to assess the value of new technologies and processes in transforming a nuclear plant operating model into one that is technically and economically sustainable.
- **Institute for Energy Technology (IFE)** is a world leader in the application of advanced digital technologies for nuclear plant performance improvement and have been instrumental in assisting the North Sea oil industry in transforming their operating models through IO principles and methods. IFE has collaborated with LWRS Program researchers to provide broad understanding of the lessons learned in the application of IO for the oil industry and how they apply to U.S. nuclear operating plants.
- **ScottMadden Management Consultants** contributed by providing a business-case model developed in collaboration with the LWRS Program and industry to assess the economic viability of performing digital upgrades. In addition, they developed rich data resources reflecting nuclear plant operational and staffing requirements that substantiate their findings and recommendations for nuclear plant modernization.

2.2.2 Online Monitoring and Plant Automation

As nuclear power plant systems operate over periods longer than originally anticipated, the need arises for more and better monitoring of material and component performance. This includes the need to move from periodic manual assessments and surveillances of physical components and structures to centralized online condition monitoring. This is an important transformational step in the management of nuclear power plants. It enables real-time assessment and monitoring of physical systems and better management of active electromechanical components, based on their performance. It also provides the ability to gather substantially more data through automated means and to analyze and trend performance using new methods in order to make more-informed decisions regarding maintenance strategies. Of particular importance will be the capability to determine the remaining useful life of a component to justify its continued operation over an extended plant life.

The current technology base for monitoring in the U.S. nuclear industry consists of signal-processing techniques and advanced pattern-recognition programs that are technically mature and commercially supported. The application of advanced analytics is in the early stages of implementation by leading nuclear utilities. The implementation rate has been slow due to requirements for funding and infrastructure development that integrate monitoring programs within the operating and business environments.

The development and advancement of diagnostic and prognostic capabilities is required to achieve an automated ability to directly identify equipment condition from initial warning signatures. This will support analysis of long-term component behavior, related risk, and remaining useful life. The diagnostic and prognostic information will enable realistic estimation of the risk of operating plant components in a degraded state. It will further provide verification of asset condition as evidence of design qualification and economic viability. The work of this project is being coordinated with two other LWRS Program Pathways. The Plant Modernization Pathway is working with the Risk-Informed Systems Analysis Pathway to appropriately incorporate advanced risk-modeling analytical methods and tools. Also, the Plant Modernization Pathway is developing new technologies to enhance and automate monitoring, as well as evaluating methods to do that while the Materials Research Pathway is evaluating materials to better understand what would be considered unacceptable erosion or corrosion, requiring replacement.

Advanced, digital-monitoring technologies will enable early detection of degraded conditions that can be addressed before they significantly contribute to preventable consequences or damage. The early detection of degradation is one of the more-significant factors in extending a component’s lifetime. A timely response to the causes of degradation also can significantly improve nuclear safety and prevent damage to other nearby components and structures. Finally, these new capabilities will reduce the cost of manual diagnostic work.

A gap exists between the state of technology needed and the effective application of diagnostics and prognostics to nuclear plant assets. To address this, research tasks are being conducted to develop and demonstrate technologies and a model to support their implementation that the LWR nuclear industry can use to substantially reduce labor requirements to affordable and sustainable levels.

2.2.2.1 Advanced Remote Monitoring for Operations Readiness

Operations is the main organization accountable for the overall safety of the plant and can often become a bottleneck in the execution of the day-to-day work activities in a plant. With current technological advancements in sensors and data analytics, it is possible to replace a significant portion of operations activities with sensors and a centralized decision-making process.

One objective of this project is to enable operators to detect anomalies that are not usually detectable before their severity escalates. This entails developing methods to analyze plant process and support systems data for use to monitor and manage assets. The results will enable significant cost-avoidance due to drop of unexpected equipment failures and outages. Another objective of this project is automating operator rounds by use of advanced sensing technologies. This entails developing custom sensors that will replace manual data collection and environment sensing.

Key interactions include the following:

- **Utilities Service Alliance (USA)** is an organization representing eight U.S. nuclear utilities that operate 14 plants at nine sites. USA worked with the LWRS Program to develop a plan and roadmap to automate key activities at four nuclear power plants (Comanche Peak, Xcel, Columbia, and Susquehanna).
- **Cooper Nuclear Station** has entered into a cooperative research and development agreement to work on several topics that include machine-based anomaly detection and automation of surveillance activities. Two of the developed technologies were piloted at Cooper Nuclear Station as part of this collaboration. These were 1) anomaly-detection machine-learning method to detect an anomaly in a critical equipment that directly impact operations safety requirements and 2) online-monitoring sensors.
- **Benchmark Electronics** collaborated with the LWRS Program in developing the custom multisensor unit to meet specific nuclear power plants requirements that are associated with surveillances of standby equipment. The multisensor unit enables rapid deployment of advanced monitoring to automate surveillance activities of standby equipment (usually safety related). The unit was piloted at Cooper Nuclear Station.
- **The Ohio State University** developed with the project team, key topics on which to focus. The university hosted a Big Data for Nuclear Power Plants Workshop. During this workshop the project team actively presented, facilitated, and coordinated the workshop effort and leveraged the workshop findings in planning future work with nuclear power plants and academic and research institutions.

Ultimately, this research will provide guidance to owner-operators of nuclear power plants on how to migrate to a data-driven monitoring operations program to enable plants to realize improvements in efficiency through enhanced monitoring capabilities.

2.2.2.2 Advanced Remote 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 a structural-health monitoring (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 nondestructive examination (NDE) of concrete specimens.

Key interactions include the following:

- **Vanderbilt University** researchers are collaborating with the LWRS Program to develop methods for monitoring the structural integrity of concrete structures. The collaboration is aimed at developing advanced data-analytics capabilities to process and integrate heterogeneous data and extract features for diagnosing concrete degradation using machine-learning techniques. 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 will 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.
- **EPRI** researchers collaborate with the LWRS Program 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 technical-exchange meetings and provides input to LWRS Program planning to facilitate the most efficient use of funding and human resources.

- **University of Nebraska–Lincoln** researchers collaborate with the LWRS Program 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.
- **India Civil Nuclear Energy Working Group** researchers collaborate internationally in this area through participation in the **US-India Civil Nuclear Energy Working Group** with the LWRS Program. This collaboration focuses on structural health monitoring. The collaboration engages with the Department of Atomic Energy, to which India records and reports its online-monitoring research results. Along with access to these results, the collaboration allows for direct dialogue 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.

2.2.2.3 Advanced Remote 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 effectively monitor the degradation mechanisms in secondary piping. This research builds advancements in guided-wave monitoring (GWM), which can be adopted in the LWR fleet to continuously monitor buried piping.

GWM is ideal for long straight stretches of piping For pattern recognition of signals recorded with GWM systems, it was demonstrated that support vector machine is the most effective one among artificial intelligence techniques.

Research is continuing in the area of fiber optics, which is better suited for complex geometries such as elbows, tees, and other unique geometries.

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.

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 feedwater 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.
- **Southwest Research Institute (SwRI)** provided guided-wave data recorded by their MsS corrosion-monitoring system on the shell of the low-pressure feedwater Heater 13A at an operating commercial nuclear power reactor. The system collected daily monitoring data for 747 days. SwRI also provided analysis reports on the continued monitoring and analysis of MsS data collected on a heat-exchanger shell, which was also analyzed using new GWM techniques created by LWRS Program researchers.

- **Vanderbilt University** provides results of their research on three-dimensional 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.
- **Dominion Energy Services, Inc.,** provided piping samples affected by different piping-degradation mechanisms. Dominion Energy provides straight piping and elbows replaced during scheduled outages to be instrumented with high-resolution fiber-optic sensors to study sensors' sensitivity and resolution.

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 enabling improved 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.

2.2.2.4 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 online 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:

- **PKMJ Technical Services Inc.** 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. PKMJ also provided access to proprietary functional mapping between work orders associated with preventive and corrective maintenance records of Public Service Enterprise Group (PSEG) nuclear power plant's circulating water system (CWS). This information was used to develop an estimate of total cost associated with maintenance activities of the CWS from 2009 to 2019. The total cost estimate takes into consideration both labor hours, average labor cost per hour, and cost associated with parts. PKMJ purchased and facilitated installation of 60 wireless vibration sensors on the Salem's Unit 1 and Unit 2 CWS as part of their in-kind contributions.
- **PSEG Nuclear, LLC,** is plant owner of Salem Nuclear Power Plant and Hope Creek Nuclear Generating Station. Collaboration with PSEG is critical to develop risk-informed predictive maintenance strategy. PSEG identified the plant systems used to support development of a deployable risk-informed predictive maintenance strategy. They provided access to all procedures, work orders, maintenance logs, notification logs, drawing, and technical documents associated with the subject plant systems. They provided access to the CWS plant-process data from 2009 to 2019 for both the units. In addition, they provided data on condensers and periodic vibration measurements collected on

CWS. PSEG’s Salem Engineering Response Team and Maintenance personnel supported the installation of 60 wireless vibration sensors on Salem’s Unit 1 and Unit 2 CWS pumps and motors. PSEG’s Salem Information Technology provided technical support and oversight to ensure safe and secure communication of the data to a cloud server.

- **KCF Technologies** is a wireless-sensor vendor that is leading the development of bi-axial wireless vibration sensors. They worked with PKMJ and PSEG to ensure safe and secure installation of wireless vibration sensors. They also provided access to their cloud server to study participants to monitor the vibration data in real-time and to use them to develop predictive models in the future.
- **Xcel Energy** provided service-water system plant-process data for an operating plant. LWRS Program researchers are collaborating with an Xcel Energy plant site to optimize their current preventive maintenance strategy associated with the service-water system and provide the foundations to transition it to condition-based predictive maintenance.
- **Technology Resources** is partnering to provide an understanding of the gaps in surveillance-intervals and online-monitoring capability. Technology resources reviewed industry, vendor, and regulatory documents to identify and recommend how NEI 04-10 can be adapted to provide guidelines to perform technical-specification surveillance-interval extension for digital equipment with self-diagnostics capability.

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.

2.2.2.5 Digital Architecture for an Automated Plant

The nuclear power industry needs a standard method for collecting, storing, and using data: a data warehouse. Use of a data warehouse would enable reduced costs through automation of data-collection and analysis activities. This research focuses on integration of data sources, creating a data warehouse—including readiness of data for integration, coupling issues of data, and creating a nuclear data model and ontology (i.e., framework for knowledge management)—that does not now exist for the nuclear industry.

The project created a first-of-a-kind data-integration aggregated model and ontology for nuclear deployment (DIAMOND) in collaboration with Curtiss Wright and using experience gained from a pilot project developed with Knowledge Relay to integrate data from an operating nuclear power plant. The model development used industrial standards and targeted the operational aspects of nuclear power plants. Palo Verde, NextAxiom, and the Procedure Professionals Association have been engaged on a biweekly basis and continue to collaborate on the development of a common dynamic instruction model for work processes that is leveraged by DIAMOND. EPRI was also engaged to complement a new EPRI common-information modeling effort that is aimed at data integration and targets power-generation. Research into inventory optimization was performed in collaboration with Xcel Energy. The effort attracted users and collaborators early in the development process. The DOE Versatile Test Reactor is augmenting the model with a design perspective (vs. the operational perspective developed by the LWRS Program). The DOE Transformational Challenge Reactor plans to contribute to the model through its manufacturing perspective in 2020.

Key interactions include the following:

- **Palo Verde, NextAxiom, and Procedure Professionals Association** have been standardizing the data structure that is associated with the work process of nuclear power plants. This effort has been collaborating with this team to leverage this work in the development of DIAMOND.

- **Cooper Nuclear Station** worked with the LWRS Program and Knowledge Relay on the development of a pilot for data integration of four tools in the plant. The experience gained from the pilot was used in the development of DIAMOND.
- **EPRI** works to create a common-information model for the generation perspective of power plants. This effort engaged EPRI to coordinate efforts to maximize the value of DIAMOND and the common-information model, enabling seamless data flow in nuclear power plants.
- **Curtiss Wright** has been integrating sources of data into their enterprise applications. The project team leveraged this knowledge in developing DIAMOND.
- **Xcel Energy** has been collaborating with the LWRS Program to optimize the use of inventory at a nuclear power plant. This effort commenced the development of tools to integrate inventory-related data in order to use the data with machine learning to reduce the inventory stocking requirements at nuclear power plants.

2.2.3 Advanced Applications and Process Automation

The LWR fleet made significant improvements in human performance over the past decade, reducing the impacts of human error and plant transients. While consequential error rates are low (typically measured in the range of 10−4 consequential errors on a base of 10,000 hours worked), the sheer number of work hours accumulated by plant staff over time means that errors impacting plant safety and reliability infrequently occur.

The traditional approach to improving plant-worker human performance was to focus on correcting worker behaviors. This approach has produced substantial improvement since the time this emphasis began in the mid-1990s. A fundamental shift in approach may further improve human performance for nuclear power plant field workers. Digital technology can transform tedious, error-prone manual tasks in field activities into technology-based structured activities and functions with inherent error-prevention, detection, and correction features. This has the potential to eliminate or reduce human variability in performing routine actions. Technology can perform certain tasks at highly reliable rates while maintaining desired worker roles of task direction, decision making, and work-quality oversight.

A highly automated plant is one in which the most frequent and high-risk control activities are performed automatically under the direction of an operator. Because of higher reliability in well-designed automatic control systems, improvements will be realized in nuclear safety, operator efficiency, and production. The chief impediment to the widespread implementation of this concept is the cost of retrofitting new sensors, actuators, and automatic-control technology to existing manual controls. The goal of this research will be to demonstrate that the resulting improvement in safety and operating efficiencies will offset the cost of making these upgrades. This research will create the necessary framework to provide plant workers with immediate, accurate plant information that allows them to conduct work at plant locations using assistive devices that minimize radiation exposure, enhance procedural compliance and accurate work execution, and enable collaborative oversight and support even in remote locations.

This research develops technologies that will reduce the cost of O&M associated with manually performed activities. Drones were identified as a technology that could have high impact on cost. Drones are mainly designed for outdoor applications, but many activities performed at a nuclear power plant are performed indoors. Indoor deployment requires more-precise control of the drone position than can be achieved by GPS-based solutions (which, when used outdoors result in position accuracy within a few feet). GPS-denied solutions exist, but they are expensive. This research targeted creating an affordable method for drones to navigate indoors with a targeted precision of an inch or less to allow the use of drones indoors with a participating pilot plant. The project collaborated with the University of Idaho in developing and demonstrating the method. Additionally, this effort targeted image-processing methods to automate the fire-watch process at nuclear power plants using machine-learning methods. Fire watch is needed in nuclear power plants whenever a fire hazard exists as part of the work. The aim of this technology is to replace monitoring processes involving operators with machine-performed monitoring. A method and training-data set were researched and customized for industrial environments to achieve high fire-detection accuracies. This effort was performed in preparation for a pilot at a nuclear utility.

Key interactions include the following:

- A nuclear utility has expressed the desire to pilot the indoor navigation technology of drones in plant environments that are hazardous to humans, such as the inspection of containment condition in a nuclear power plant.
- A nuclear utility has articulated an interest to automate fire-watch activities and is collaborating with LWRS Program researchers in creating a custom solution that achieves high fire-detection accuracy. This replaces human visual monitoring for work that results in a fire hazard. Additionally, it substitutes the role of fire protection systems when they are taken out of service due to equipment failure or for maintenance. The LWRS Program plans to use the developed machine-learning fire-detection technology as part of the overall suite of methods that will be piloted.
- LPI, Inc., is a solution and service provider to the nuclear industry. LPI provided consultancy support for the use of drones and applications of the gauge-reading technology in nuclear power plants.

Integrating automation technology with field-worker activities can reduce the costs associated with 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.

2.2.3.1 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 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.

2.2.3.2 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 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.

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. FLEXIBLE PLANT OPERATION AND GENERATION

Flexible plant operation and generation (FPOG) is required to supply energy to an industrial process. FPOG operations provide an offtake opportunity for energy produced by an LWR power-generating station when the price offered for committing electricity to the grid is lower than the cost of producing this electricity. In one model of FPOG operations, a secondary user may benefit by purchasing electrical power, steam, or thermal energy directly from the LWR site at a cost that is lower than can be purchased from the grid at either the electricity transmission-customer level or the electricity distribution-customer level. At a minimum, this requires a tightly coupled connection to the power-generation operations of the nuclear power plant. The LWR hybrid plant may then apportion energy between the industrial user and the electricity grid to optimize the revenue of the nuclear power plant, depending on specific day-ahead electricity-grid capacity commitments and reserve capacity agreement requirements.

Figure 1 illustrates the concept of dispatching power to the grid or sending steam and electricity to an industrial user. In this manner, the LWR can produce non-electric products during periods of excess power-generation capacity when these plants are not able to clear the day-ahead electricity market.

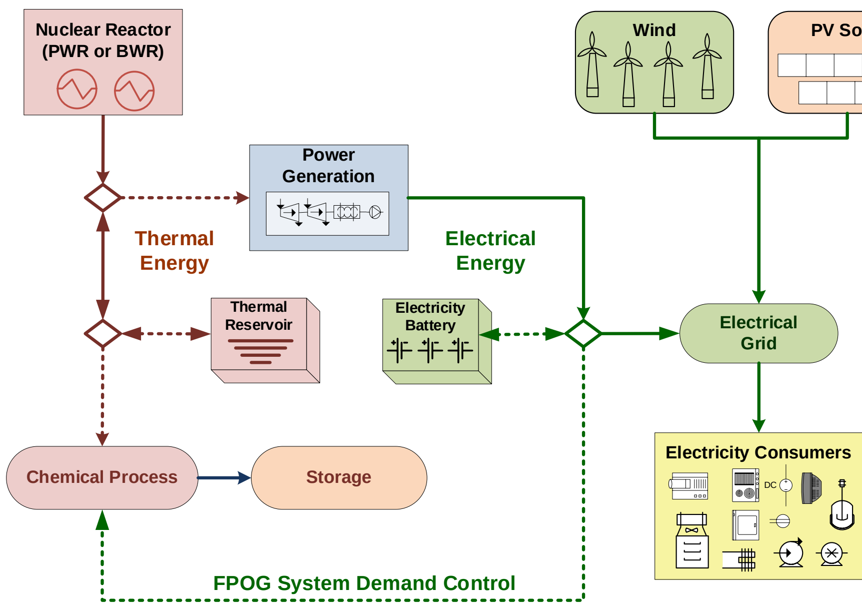

Figure 1. Illustration of LWR FPOG.

3.1 Purpose, Goals, and Research and Development Activities

The FPOG Pathway supports technical and economic assessments (TEAs) to raise an understanding of LWR owners, utilities, industrial manufacturing and transportation sector industries, and investors. It supports essential R&D that is required to enable LWR plants to dispatch both thermal and electrical energy for production of nonelectrical products through flexible plant operations. This research focuses on interfaces between the LWR plant and the industrial energy. It also addresses the safety of co-located hydrogen and chemical plant interactions with LWR operations.

As an emerging activity, the FPOG Pathway is focused on the following three principal area of activities:

1. Safety Assessments
    - Probabilistic risk assessments relative to potential FPOG activities
    - Hydrogen plant safety hazards analysis
    - Other chemical plant safety hazards analysis
2. Thermal and Electrical Energy Dispatch
    - Physical connections with LWR plants; PWR and BWR
    - Energy dispatch operational interfaces
    - Thermal energy management and plant operations stability
3. Design and Economics
    - TEAs of tightly coupled industrial users of thermal and electrical energy
    - New grid services plant transactions and controls
    - Optimization of FPOG systems design and operations.

3.2 Collaborative Research and Development Activities

The R&D activities for the FPOG Pathway involve close collaboration with LWR owners and industrial users of the energy that will be provided. It is also important that grid-balancing authorities be aware and possibly contribute to TEAs in order to accurately capture the value proposition of FPOG that propose to provide grid services. Additionally, this Pathway benefits from leveraging program efforts under the DOE-NE Crosscutting Technologies Development Program and the DOE-EERE Fuel Cell Technology Office, as well as other DOE offices responsible for renewable energy and program offices supporting grid modernization R&D. This Pathway comprises a team of researchers and analysts at INL, ANL, NREL, and Pacific Northwest National Laboratory (PNNL) to complete TEAs and FPOG projects to demonstrate their use.

The following summarize collaborative research projects in which the FPOG Pathway is actively engaged with other organizations.

3.2.1 Safety Assessments

3.2.1.1 Probabilistic Risk Assessments Related to Potential FPOG Activities

The goal of this effort is to assess the proposed FPOG activities to determine how a plant may remain within its licensed operating basis or to anticipate potential licensing modifications that may be necessary. Research includes hazards and safety assessments needed for PRA evaluations of new electricity connections, and thermal energy extraction and delivery to hydrogen and chemical plants as single plants or associated operations as an integrated facility in a new operational concept, such as an energy park that is operated somehow with a nuclear power plant. Additionally, a thermohydraulic analysis with the RELAP5-3D software of the heat extraction system used to supply the industrial plant with process heat will be completed to identify possible unforeseen consequences of thermal energy extraction from the secondary systems of an LWR. These activities will aid LWR power plant owners and reduce the cost and schedule of completing plant-specific PRAs relative to dispatching electricity and thermal energy to closely coupled industry customers.

Key interactions included the following:

- **Operating utilities** began reviewing analyses provided by the FPOG Pathway relative to extracting thermal energy and producing hydrogen near an operating nuclear power plant.
- **GSE Solutions** produced a revision of a Westinghouse three-loop nuclear power plant model to simulate thermal energy extraction and supply to industrial users.

3.2.1.2 Hydrogen Plant Safety Hazards Analysis

Hydrogen plant siting, operating conditions, and engineering measures will be evaluated to identify and assess the issues with FPOG activities associated with an existing NRC operating license based on an updated PRA. One objective is to provide guidance on engineering measures that should be considered when producing hydrogen in any proximity to LWR plants.

Key interactions included the following:

- **Commercial industrial gas supply companies** have been consulted on hydrogen plant operations and safety requirement for plants located near nuclear power plants and within associated industrial users of hydrogen. These companies were also being engaged under the DOE-EERE Program for H2@Scale.
- **Nuclear power plant operating companies** began providing operational requirements relative to existing practices for receiving, storing, and using hydrogen at their nuclear power plants relative to power-generation equipment cooling and BWR water chemistry and conditioning.

3.2.1.3 Other Chemical Plant Safety Hazards Analysis

All chemical plant operations require hazardous operations and safety analysis to comply with Code of Federal Regulations and to meet strict standards for air emissions and environmental releases. Owner-operators of licensed LWRs are evaluating these standards and industrial practices relative to (1) operation of the chemical plant near nuclear power plants, and (2) consideration of the safety hazards and risks on the nuclear power plant operations license and emergency planning basis. In some cases, a hydrogen plant may be closely coupled to a chemical plant, such as a methanol production plant. In this situation, the overall safety and industrial planning and permitting may need to be addressed with state industrial siting authorities.

Key interactions include petrochemical companies, including ExxonMobil and Shell, and OCO Corporation engaged with the FPOG Pathway staff to discuss hydrogen and CO_2 as feedstock for producing formic acid, methanol, and synthetic motor fuels and lubricants near nuclear power plants.

3.2.2 Thermal and Electrical Energy Dispatch

3.2.2.1 Physical Connections with LWR Plants; PWR and BWR

The purpose of this activity is to address reactor-operator human factors and control-systems R&D that are needed to dynamically extract and deliver thermal energy from a nuclear power plant for use by an industrial process. This research is needed to ensure both electricity diversion and thermal energy extraction and delivery to a close-coupled industrial user can be performed in a manner that is consistent with standard approaches for safe reactor operations. This research will help LWR owners develop instrumentation and controls and needed interfaces to ensure reactor operators will be aware of, and effectively manage, plant conditions involved with interactions with new FPOG systems and activities.

Industrial collaboration under this research area is mainly being completed with the support of engineering companies that have been contracted by nuclear power plant owners to complete assessments of thermal energy extraction from their individual plants.

Key interactions include the following:

- An **operating utility** has provided technical input to the FPOG Pathway on thermal energy delivery from nuclear power plants for potential high-temperature steam electrolysis demonstration project and future scale-up.
- **FuelCell Energy** provided technical and functional requirements to supply thermal energy to high-temperature steam electrolysis plants. This information was used to complete a Technical and Economic Assessment (TEA) of the nuclear interfaces and steam generation unit operations.

3.2.2.2 Energy Dispatch Operational Interfaces

Energy dispatch from a nuclear power plant creates a new operating paradigm for nuclear power plant operators and electricity dispatch operations. In the past, nuclear power plants have only provided electricity to the gird as baseload plants operating near their nameplate capacity. In most cases, nuclear power plant output is scheduled to match the projected day-ahead grid profile. In a few situations, nuclear power plants are participating in the hour-ahead market as determined by their grid operators. With FPOG, hybrid nuclear power plants that are tightly coupled with an industry process may be called on to support reserve capacity markets and grid regulation services by responding more frequently to hour-ahead and also to minute-ahead, and possibly with second-by-second adjustments to power diversion between the grid and the industrial user. This new mode of operation requires industrial collaboration with grid operators, utilities, and the FPOG industrial energy users to understand how these responses can be efficiently and effectively carried out without affecting normal operation of the nuclear power plants.

Key industrial interactions include the following:

- **EPRI** is collaborating with the FPOG Pathway through a subcontract for consultations on flexible operations involving thermal energy extraction, electrical power offtake as house loads and hotel loads, and operator actions and feasible plant maneuvers.

3.2.2.3 Thermal Energy Management and Plant Operations Stability

Thermal energy extraction from a nuclear power plant will impact the power-generation system, including energy flows to the steam turbines sets, steam reheat drums and returns, steam condenser systems, and interaction with the main steam heat exchanger (PWR) and primary coolant loop (BWR). It is imperative to evaluate how thermal energy extraction will affect the stability of the plant as a function of the methods and amount of energy removed from the power-generation systems.

Key interactions include EPRI providing important understanding and key outcomes from the EPRI LWR Flexible Plant Operations. By providing a technical review of program activities, EPRI is also providing guidance on best practices, nuclear power plant operational experiences, and potential technical issues that need to be addressed by the FPOG Pathway.

3.2.3 Design and Economics

The purpose of this activity is to complete TEAs to evaluate market opportunities for LWRs to supply electricity and steam or heat to produce non-electricity products. The goal is to produce investor-grade reports that will help introduce LWR owners to industries that can exploit the clean, affordable energy supplied by nuclear power plants. It also considers large energy storage systems that can help LWR plants shift electricity production to periods when demand exceeds the net generation capacity of the systems.

Analyses are being performed for FPOG applications on a region-specific basis in both regulated and deregulated markets.

3.2.3.1 Technical and Economic Assessments of Tightly Coupled Industrial Users of Thermal and Electrical Energy

In 2019, the FPOG Pathway began TEAs that are intended to evaluate the benefits and business case of FPOG operations. The focus in 2019 was on hydrogen generation and associated markets in vicinity of nuclear power plants in the Upper Midwest and Southwest. Additionally, a TEA for the production of polymers in the Upper Midwest and Southeast was completed.

Key interactions include the following:

- **Energy Harbor** (formerly FirstEnergy Solutions) supported a TEA focused on hydrogen market opportunities in their service provided plant specifications and grid market data for the TEA.

- **EPRI** is collaborating on the plant-specific TEAs by providing in-house knowledge and analysis of energy storage and grid markets.
- **Strategic Analysis** is supporting the FPOG Pathway with evaluations of large chemical market assessments. Strategic Analysis is validating the case for large capital projects by investment firms and energy companies, including large industrial gas supply companies and the ammonia industry.
- **Methanol Association** has agreed to serve as a conduit to methanol companies that have an interest in receiving hydrogen from a nuclear sourced plant.
- **Ammonia Association** is communicating with ammonia companies that have an interest in receiving hydrogen from a nuclear sourced plant.

3.2.3.2 New Grid Services Plant Transactions and Controls

The rise of variable renewable energy power generation is changing the role of baseload power generation plants and will require these plants provide more load-following electricity to the grid. The FPOG Pathway is addressing opportunities for nuclear power plants to optimize revenue generation by dispatching electricity to the grid when the local marginal price is relatively high. The INL RAVEN model is being applied to integrated energy system scaling and dynamic operations analysis and optimization. A new plug-in, Holistic Energy Resources Optimization Network (HERON), is being developed with support of utility collaborators. The RAVEN/HERON tool will be provided to LWR plant owners and utilities to support strategic planning relative to capital projects that will change the market for nuclear power plants. A model for either regulated or deregulated electricity markets is being developed. Industrial collaboration is critical to development and use of this tool.

Key interactions include the following:

- **An operating utility** is providing grid price data from their respective markets that are impacted by the buildup of renewable energy. This collaboration supports development of the RAVEN/HERON tool for regulated markets.
- **EPRI** is supporting the FPOG Pathway with an assessment of future grid market pricing using REGEN—a capacity expansion tool developed by EPRI. In addition, EPRI is providing capital equipment and operation cost data on energy storage options that are necessary for energy storage for energy arbitrage.

3.2.3.3 Optimization of FPOG Systems Design and Operations

With the goal of ultimately stabilizing the grid with FPOG as more renewables are increasingly added to the grid and providing clean energy to the industrial sector, it is important to understand how to coordinate electricity generation with direct energy supply to an industrial user or complex of industries. Tradeoff studies are needed to understand the best methods for sending energy to industry as a function of location, schedule, and form of energy. The role of energy storage is important and needs to be considered in the total systems analysis. Industry participation and community involvement are needed to evaluate practical solutions that involve siting new plants power lines and pipelines.

Key interactions include the following:

- **Several utilities** have been in contact with the FPOG Pathway to discuss regional industrial markets relative to nuclear power plants. Four of these utilities are actively discussing specific business interests with refineries, chemical companies (e.g., fertilizer and polymer producers), steel manufacturers, and fleet owners.
- **University of Toledo** began planning a workshop with industries, nuclear power plant owners, and regional/national industries to discuss industrial complexes R&D needs. The FPOG Pathway lead

helped structure the meetings and provided industrial contacts who were invited by the university to a meeting held January 14–15, 2020.

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 risk-informed tools and methods that enable better representation of safety margins and the factors that contribute to cost and safety and

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 of nuclear power plants.

The RISA toolkit will be applied in industry-application pilot projects. These pilot projects were developed through discussions with U.S. nuclear utilities. They represent 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 being conducted through the RISA Pathway. They represent studies using selected applications of the risk-informed tools and methods. The research will also address needed technical maturity of the tools and methods that are used in the pilot projects by assessing verification and validation status and support immediate improvement of the RISA toolkit. 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 Research and Development 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.
3. To accomplish the above RISA Pathway goals, the Pathway:
4. Conducts research to develop and demonstrate industry applications in pilot projects that employ the RISA methodology collaboratively with organizations from the U.S. commercial nuclear power industry.
5. 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 RISA tools and methods will support U.S. nuclear industry for an effective margin-management strategy application which will improve economics, reliability, and sustainability for longer-term operation.

Three focus areas under the RISA Pathway are:

- Enhanced resilient nuclear power plant concepts
  - Demonstrate the safety benefits associated with technologies including 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 safety preservations and operating costs reduction.
- Margin recovery and operation cost reduction
  - Apply risk-informed tools and methods to accident analysis, O&M 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 nuclear power plant owner-operators. The focus areas represent groups of applications of risk-informed technology to assist operating nuclear power plants in their efforts to reduce costs and otherwise adapt to the changing economic and generating-mix environment. Focus-area 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 risk-informed 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 to support applications by a larger community of users.

In May 2018, the LWRS Program organized a meeting with participation from U.S. nuclear utilities to discuss and develop pilot projects. These address 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 team communicates 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 consist of pilot projects that aim to enhance both the safety and economics of existing nuclear power plants, using advanced, near-term technologies that provide substantial improvements to plant safety margins. The value of enhanced resilient plant concepts lies in providing greater safety margins to operating plants, which, in turn, allow 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 can subsequently be used as a basis for requalifying plant SSCs with significant cost savings. Today, the industry is developing ATF, implementing FLEX, and promoting 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 and plant systems.

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

The objective of this research effort is to use risk-informed tools and methods in industry applications to support development and early demonstration. The research will 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 progressing in this focus area.

4.2.1.1 Enhanced, Resilient Plant Systems

This research focuses on using risk and cost-benefit analysis on a 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. The analyses use both deterministic (e.g., RELAP5-3D, TRACE, MELCOR, MAAP) and probabilistic (e.g., SAPHIRE, HUNTER) tools, as well as LOTUS and RAVEN controller software. The pilot project will include FLEX equipment in analyses to optimize resiliency during beyond design-basis accidents. In 2019, increasing the safety margin was demonstrated by using combined advanced safety features of near-term ATF concepts, FLEX equipment, and passive cooling systems, along with risk-informed method, to a generic resilient plant and pressurized water reactor (PWR). Key interactions include the following:

- **Southern Nuclear Company** collaborated on the study of the impact of partial and full ATF reactor-core configuration by using probabilistic risk assessment (PRA) models. This collaboration is critical to understand licensing issues of ATF implementation to the existing LWRs.
- **Xcel Energy** supported the study of the optimal use of FLEX to improve a nuclear power plant's availability and efficiency and to reduce operating costs. Xcel Energy has provided plant-level PRA models and FLEX-equipment specifications and procedures. The RISA Pathway is using Xcel Energy's plant-specific information to investigate ways to credit FLEX operations.
- **EPRI** supported an evaluation of the economics of using ATF in existing LWRs. These features will provide additional evaluation of enhanced resilience plant system study.

4.2.1.2 Enhanced Operation Strategies for System Components

Research into the operation of Terry turbines from the component to the system level, both computationally and experimentally, will enhance knowledge of the operating limits of reactor-core-isolation cooling and turbine-driven auxiliary feedwater systems. The results of this research will provide the technical basis for or "credit" extended emergency core cooling performance of these systems. The component-level demonstration was performed in 2019 by both analytical and experimental studies. Key interactions include the following:

- **Texas A&M University** performed Terry turbine nozzle experiments. Data generated from the experiment is critical to the RISA Pathway research on crediting the expanded operation band of the Terry turbine systems.
- **Sandia National Laboratories** supported the Terry turbine experiment performed at Texas A&M university by providing technical advice, data analysis, and interfaces with stakeholders.
- **BWR and PWR Owners Group** supported experiments and computational work by providing feedback, guidance and the necessary data to the RISA Pathway.

- **EPRI** manages a Terry Turbine Users Group for the industry, develops products to support maintenance of Terry turbines, and provides hands-on training to utilities. For the RISA Pathway, EPRI shares its knowledge on Terry turbine-related technologies..
- **Institute of Applied Energy of Japan** has provided financial and technical expertise contributions.

4.2.2 Cost and Risk-Categorization Applications

The objective of this research area is to develop and test risk-informed approaches 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 recategorization based on 10 CFR 50.69. In current deterministic regulations, SSCs are categorized as "safety-related" or "non-safety-related." Safety-related SSCs need special treatment. Safety-related SSCs, under deterministic methods, 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 using the following risk-informed safety categorization (RISC):

- RISC–1: Safety-related SSCs that perform highly safety-significant functions.
- RISC–2: Non-safety-related SSCs that perform highly safety-significant functions.
- RISC–3: Safety-related SSCs that perform minimally safety-significant functions.
- RISC–4: Non-safety-related SSCs that perform minimally safety-significant 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 research area is to develop an innovative framework on risk categorization to enhance economics. The approach combines 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 included 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. In 2019, a demonstration was performed on the combined data-analytics and risk-assessment tool for long-term capital SSC refurbishment and replacement for an existing nuclear power plant. Key interactions include:

- **Jensen Hughes** is a subcontractor to the RISA Pathway. Jensen Hughes provided technical advice on the development of the analytic framework and industry implementation of asset-management technology which the RISA Pathway is developing.
- **Northwestern University** and **Texas State University** are subcontractors of the RISA Pathway. They are developing algorithms and methods to optimize plant resources. The RISA Pathway will perform validation of asset-management methods developed in INL by using these collaborators' output.
- **EPRI** conducted related research from the early 2000s. The concept was developed to provide a systematic approach to the assessment and analysis of plant economic performance while maintaining high degree of confidence that adequate levels of safety were maintained.
- **Dominion Energy** is an energy utility company. Dominion proposed using its a pilot-project plant for this research. Dominion has its own asset-management program, through which they will use 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). The RISA Pathway collaborating to develop industry-use cases based on Dominion Energy's input.

4.2.2.2 Plant Health Management

This research will develop technologies that enable owner-operators to manage equipment and system-performance data and their financial risk, with an objective to reduce the costs associated with monitoring and regulatory compliance and advance monitoring-technology development. In 2019, a risk-informed framework was integrated into a proposed system-health program to reduce costs and improve engineering effectiveness of the systems. Key interactions include the following:

- **Jensen Hughes** is a subcontractor to the RISA Pathway. They provided an analysis of existing plant data in order to link risk-informed applications and the plant system-health management system of Exelon’s equipment-reliability data.
- **Exelon** provides plant system-health program data to Jensen Hughes. Jensen Hughes analyzes the plant health program data for RISA Pathway.
- **Idaho State University** is a subcontractor to the RISA Pathway. They are developing generation risk models for RISA Pathway use. They use existing PWR plants and perform a generation risk analysis that focuses on the risk of lost generation due to component failures.

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 focuses on developing risk-informed, multiscale, and multiphysics high-fidelity tools and methods 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. It 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 important nuclear power plant systems problems to be solved with high efficiency and speed. This approach will be 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 savings.

4.2.3.1 Enhanced Fire Probabilistic Risk Assessment

The goal of the project is to conduct R&D to improve use and advancement of fire-PRA models by combining physics simulation methods with visualization tools. A data analysis activity was completed in 2019 to understand modeling uncertainties. A testing version of three-dimensional fire-modeling software Fire Risk Investigation in 3D (FRI3D) was developed and demonstrated with the Vogtle nuclear power plant model. Key interactions include the following:

- **Southern Company** provided plant data and fire-PRA models and its analysis process based on an operating plant model**.** These data are used for validating FRI3D fire-simulation software developed by the RISA Pathway. The data are also used for developing test cases for advanced risk-informed fire-hazard models.
- **Jensen Hughes** provided technical advice and performed testing and verification of the FRI3D software as a third-party reviewer. This work will improve credibility and capabilities of FRI3D.
- **Sandia National Laboratories** is a project subcontractor, working for fire-PRA-related experimental data uncertainties, which will be used for optimizing the advanced fire-PRA model.

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

The goal of this project is 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. In 2019, research was performed for the fuel-rod non-burst-potential evaluation under loss-of-coolant accident (LOCA) conditions with extended burnup exceeding the current burnup limit. Key interactions include the following:

- **South Texas Nuclear Project Electric Generating Station (STNP)** is a nuclear power plant at Bay City, Texas, comprising two Westinghouse PWRs. STNP provided guidance on core design with extended fuel burnup plant data. The RISA Pathway will use their data for core design simulation with the VERA-CS code.

4.2.3.3 Digital I&C Risk Assessment

This research focuses on defining a risk-informed analysis process for a digital replacement of the reactor-protection system in an existing plant. The approach being developed will complement other approaches to deploying digital I&C technologies and emphasizes risk-informed approaches that can facilitate the adoption and licensing of safety-related and non-safety-related digital instrumentation and controls. A risk-assessment strategy for digital I&C upgrades using current digital-technology information was completed in 2019. Key interactions include the following:

- **Framatome** and **Westinghouse**: both vendors provided digital I&C hardware and software failure probability data to support the reliability studies. The RISA Pathway is using these data to perform digital system reliability studies.
- **Duke Energy** has developed its own PRA models with digital I&C incorporated. The RISA Pathway is referencing this study for LWRS Program digital I&C PRA model.

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. In 2019, the technical basis was developed for a risk-informed framework to optimize the existing reload-licensing process for an operating PWR. Key interaction include the following:

- **FPoliSolutions, LLC,** is a subcontractor to the RISA Pathway. They support development of the project detail plan and proposed use of risk-informed tools and methods to evaluate efficiencies in the plant reload licensing and operational cycle management. FPoliSolutions will develop a superplant model to integrate the entire framework in NUREG Chapter 15 licensing requirements.

4.2.4 International Collaborations

The following summarizes the collaborations that the RISA pathway participates in with other international organizations:

- **NEA Working Group on Natural External Hazards (WGEV)**: The Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation and Development (OECD) sponsors an expert group on natural hazards: the CSNI WGEV. The RISA Pathway participates in the WGEV in order 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. A recently completed collaboration activity focused on frequency-based screening, factoring in physical conditions that limit the frequency of magnitude of a natural hazard. This activity identified ways in which risk- analysis models can be simplified through a systematic screening approach, thereby lowering the developmental costs of these types of models. The RISA Pathway has participated in the group to collect up-to-date information on external-hazard issues and to share Pathway activities related to the working group.
- **NEA Expert Group on Maintaining Low-Carbon Generation Capacity through Long-Term Operations (LTO) of Nuclear Power Plants: Economic, Technical and Policy Aspects (EGLTO):** Under guidance of the NEA Nuclear Development Committee, a new NEA *ad hoc* EGLTO was formed in April 2018. The expert group will review the technical and economic aspects of LTO in 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, and absent or ineffective carbon pricing
    - The impact of operational lifetime on the costs and funding of waste management and decommissioning.

The expert group analyzes nuclear power plant life extension and its impact under decarbonization policy perspectives and is producing a report to OECD/NEA members and others on the issues associated with LTO of nuclear power plants and the role of national policies, economics, markets, and anticipated developments on the prospects for long-term operation. LWRS Program-funded staff participate in the expert group and are providing input from the U.S. perspective and experience to be reflected in the consensus report.

- **NEA Expert Group on Uncertainty Analysis Method (EGUAM):** Under guidance of NEA Nuclear Science Committee, NEA EGUAM has performed a comprehensive benchmark study of various nuclear systems to implement uncertainty analysis method through the "Benchmark for Uncertainty Analysis in Best-Estimate Modeling." The goal of the activity is to determine modeling uncertainties for reactor systems under steady-state and transient conditions, quantifying the impact of uncertainties for each type of calculation in the multiphysics analysis for neutronics, thermal-hydraulics and nuclear fuel performance. The RISA Pathway uses benchmark specifications of EGUAM activity for developing risk-informed analysis capability of RELAP5-3D.
- **Institute of Applied Energy (IAE):** IAE of Japan is sharing its experience on Terry turbine expanded-operating band and related experiments, as well as simulations. Their data gives high benefit to the RISA Pathway for shaping risk-informed approach to expand Terry turbine operation analysis.
- **Central Research Institute of Electric Power Industry (CRIEPI)**: CRIEPI of Japan collaborates with the RISA Pathway for enhanced fire-PRA method development. CRIEPI is also initiating fire-hazard-related PRA method development through its proprietary experimental facility and fire-simulation software. CRIEPI is participating bilateral benchmark study with INL for fire simulation. They will also provide experimental data for this benchmark.

5. MATERIALS RESEARCH PATHWAY

Nuclear reactors present very challenging service environments to materials. Many components in an operating reactor must tolerate high-temperature water, stress, vibration, and an intense neutron field.

Degradation of materials in these environments 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 environmental 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 the 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 mechanisms (or processes) particularly important for consideration during continued operation. While extending operation will add additional exposure time, neutron fluence, and gamma dose, the primary impact will be material changes that lead to 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.

5.1 Purpose, Goals, and Research and Development Activities

The Materials Research Pathway performs R&D activities that are critical for 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 ensures that aging during long-term operation of nuclear power plants does not affect the safety and reliability of U.S. operating nuclear power plants. The strategic goals of the Pathway are to (1) understand and predict the environmental and service mechanisms that age and degrade materials during continued operation, (2) predict their effects on the performance of SSCs, and (3) develop methods and tools for characterizing and mitigating damage to achieve safe and economical operation of nuclear power plants. Such strategic goals are vital to ensure the continued safe operation of nuclear power plants.

Identifying, formulating, and prioritizing all of the competing needs for effective aging materials management is done in a collaborative manner with other organizations that provide regular input. Through continued dialogue and collaborative and cooperative research activities with the EPRI, NRC, vendors, utilities, and other international institutions, this information is used to prioritize emerging needs that are addressed in the following four principal areas of activities:

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

5.2 Collaborative Research and Development Activities

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, establish programmatic priorities, and focus efforts of LWRS Program Materials research activities.

Through collaborative and cooperative cost-sharing efforts, the Materials Research Pathway and the EPRI 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 to operate the existing fleet for periods beyond 60 years and aging management of plant materials. 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 closely with the NRC to coordinate research needs and activities to address those needs. NRC research efforts are considered carefully during annual LWRS Program planning in order to effectively coordinate activities. In addition, cooperative efforts such as NUREG/CR-7153 and the formation of annual research roadmapping meetings among EPRI, NRC, and Materials Research Pathway have provided valuable sources of additional input to planning. The Materials Research Pathway also coordinates research activities with the EPRI LTO and Materials Reliability Programs.

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.

5.2.1 Reactor Metals

5.2.1.1 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 reactor pressure vessels (RPVs) 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 also incorporates the examination of RPV materials harvested from the Zion Unit 1 nuclear power plant in 2016 to provide data that addresses knowledge gaps and benchmarks model predictions. Furthermore, work in this subject area addresses new techniques in materials testing to improve fracture-property evaluations of RPV materials and specimen-size 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 by the LWRS Program to determine high-fluence effects on material properties. Westinghouse, in cooperation with the PWROG, has provided high-copper surveillance material from a currently operating nuclear power plant that was irradiated to various doses for microstructural characterization.
- **PWROG** has provided a large piece of archived surveillance weld for Zion Unit 1 to Oak Ridge National Laboratory (ORNL) for characterization of the Zion WF-70 weld in the unirradiated

condition to complement current LWRS Program efforts in characterizing the beltline weld from the decommissioned Zion Unit 1. Based on this interaction, the Materials Research Pathway and the PWROG have initiated efforts to collaborate on updating high-fluence RPV embrittlement codes and standards.

- **Rolls Royce** has provided collaborative support for testing new advanced steels that may be less sensitive to embrittlement over long service lifetimes or high fluences. This includes providing materials used in experimental reactor tests (e.g., the ATR-2 Project) and financial support to an LWRS Program university contractor for the post-irradiation examination of advanced steel alloys.
- A **nuclear laboratory partner** has provided model RPV alloys for the high-fluence experimental testing of RPV steels and continued technical support on RPV performance.
- **The Central Research Institute of Electric Power Industry (CRIEPI), Japan** has provided complementary testing of minicompact 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 U.S. DOE-NE / Japan METI, Civil Nuclear Working Group (CNWG).
- 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 has been critical to the development of embrittlement models for RPV steels at 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 assist utilities and regulators make more-informed aging-management decisions and identify additional options for extended operations.

5.2.1.2 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 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 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 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 to evaluate the influence of radiation-induced void swelling on crack growth rate (CGR) in austenitic stainless steel. Westinghouse also provided 304L stainless steel control-rod material from the Barsebäck 1 boiling water reactor (BWR) in Sweden that is being used in LWRS Program research to evaluate the mitigating effect of post-irradiation annealing on CGR.
- **Nippon Nuclear Fuel Development Corporation (Japan)** 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.

5.2.1.3 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. The goal is to develop a mechanistic understanding of precursor states on crack initiation to develop strategies for mitigation.

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 PNNL, which was supported by the LWRS Program.
- **EPRI**: The LWRS Program SCC-initiation project, performed at PNNL, collaborates with an EPRI/NRC cosponsored project on quantitative characterization of SCC-initiation times in Ni-base alloys in simulated PWR primary water. Selected LWRS Program test systems have been improved, expanding experimental capabilities for both projects. The LWRS Program SCC-initiation research laid the groundwork for advancing the state of the art in SCC-initiation testing. Moreover, the scientific insights gained through LWRS Program SCC research are often readily applicable to results obtained in the EPRI/NRC cosponsored project. The LWRS Program benefits from having access to a greater range of SCC-initiation data that assists in codeveloping mechanistic understanding.
- **EPRI** and the **NRC** coordinate work on SCC-initiation testing through independent projects on Ni-base weld alloys and share the data 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 enable 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.

5.2.1.4 Aging and Radiation-induced Damage in Structural Materials

This subject area covers several research projects that include analysis of experimental reactor test data, the examination of harvested core internals (i.e., baffle-former bolts from a 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** has 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 the analysis of ex-service, high-fluence baffle-former bolts by performing atom-probe tomographic studies of specimens.

The generated data and mechanistic modeling studies are being 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.

5.2.1.5 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 of PWR components in the primary water system. 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. Future work will focus on the implementation of the Argonne National Laboratory (ANL)-developed evolutionary (time/cycle dependent) stress-analysis framework that can be used for predicting the life of large components/assemblies.

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.

Experimental data can be used to 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 2019, a system-level framework for fatigue life prediction of a pressurizer-surge-line nozzle under design-basis loading cycles was completed.

5.2.1.6 Thermal Aging of Cast Austenitic Stainless Steels

Cast austenitic stainless steel (CASS) and austenitic stainless steel welds (ASSW) are extensively used for many large LWR primary-coolant-system components, including coolant piping, valve bodies, pump casings, and piping elbows. The performance of these materials beyond 40 and 60 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 power plant operations. The final results of this task, which was completed in 2019, was the analysis and simulations of aging of CASS components and ASSW and the delivery of a predictive capability for aging management of components under extended-service conditions.

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 used 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 were 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. Understanding trends in mechanical property changes will assist industry in the development of appropriate aging-management plans for CASS and ASSW components.

5.2.2 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).

5.2.2.1 Radiation and Environmentally Induced Damage to Concrete Structures

The objective of this task is to provide data and information in support of continuing the service of safety-related nuclear power plant concrete structures. Structural research topics include

1. Compilation of material-property data for long-term performance and trending, evaluation of environmental effects, and assessment and validation of NDE methods
2. Evaluation of long-term effects of elevated temperature and radiation
3. Improved damage models and acceptance criteria for use in assessments of current as well as the future condition of the structures

4. Improved constitutive models and analytical methods for use in determining nonlinear structural response (e.g., accident conditions)
5. Nonintrusive methods for inspection of thick, heavily reinforced-concrete structures and basemats
6. Global inspection methods for metallic pressure-boundary components (i.e., liners of concrete containments and steel containments) including inaccessible areas and the back side of a liner
7. Data on application and performance (e.g., durability) of repair materials and techniques
8. Utilization of structural reliability theory incorporating uncertainties to address time-dependent changes to structures to ensure that minimum accepted performance requirements are exceeded and to estimate ongoing component degradation to estimate end-of-life
9. Application of probabilistic modeling of component performance to provide risk-informed criteria to evaluate how aging affects structural capacity.

Recent work has been directed at the development of the microstructure-oriented scientific analysis of irradiated concrete (MOSAIC) software tool to assess the susceptibility of plant-specific concrete damage due to radiation-induced structural degradation.

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 multiyear 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. Both EPRI and NRC are leveraging LWRS Program research to develop models to assess the aging of structural concrete that take into account service conditions and environmental factors that may diminish the residual life of the concrete.
- **NRC**, through coordinated research activities with the LWRS and EPRI Programs, has supported research into the concrete bio-shield. NRC's confirmatory research is continuing at ORNL and ANL. 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.
- **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 irradiated and unirradiated specimens for characterization as well as information for expansion 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 the effects of radiation 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 the industry with an improved capability to assess potential changes in the safety-related performance of aged concrete structures.

5.2.2.2 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. In FY 2018, the monitoring and initial nondestructive testing campaign of the large ASR-affected concrete test blocks was completed and in FY 2019, the microstructural characterization of the ASR- affected concrete test blocks at the University of Tennessee, Knoxville (UTK) was completed.

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 for its member utilities and organizations.
- **NRC** has supported research, coordinated with the LWRS and EPRI Programs, through ASR testing and modeling at the University of Colorado and Northwestern University. NRC is also conducting research at NIST that includes (a) ASR beam testing, (b) the seismic performance of ASR affected structures, and (c) prediction of ASR expansion and ultimate expansion of ASR for concrete material mixes.
- **UTK** has contributed to ASR work in the LWRS Program through facility support and testing of large-scale ASR test blocks.

Through this research, the LWRS Program provides the 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.

5.2.2.3 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, which specializes in condition-monitoring activities. Recent developments have focused on data-processing techniques of linear-array ultrasonic testing, such as the synthetic aperture-focusing technique, model-based image reconstruction, and deep directed learning for the characterization of EPRI test samples.

Key interactions include the following:

- **EPRI** and the LWRS Program have developed a coordinated research concrete NDE roadmap. EPRI is conducting R&D guidelines on applications for and limitations to commercially available NDE methods to detect voids and delaminations within concrete structures and corrosion of concrete reinforcement.
- **UTK**, the **University of Alabama**, **University of Nebraska**, and the **University of South Carolina** have each 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.

5.2.3 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 with 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.

5.2.3.1 Cable Aging and Degradation

This research provides an understanding of the role of material type, history, and the environment on the degradation of cable insulation, understanding of accelerated testing limitations; and support to partners in modeling activities, surveillance, and testing criteria. Moreover, it provides the experimental characterization of key forms of cable and cable insulation in a cooperative effort with NRC and EPRI. Testing includes evaluations of cable integrity following exposure to elevated temperatures, humidity, and ionizing irradiation. Exposure to these stressors over time can lead to degradation that, if not appropriately managed, could cause insulation failure. The experimental data will be used to evaluate mechanisms of cable aging and determine the validity or limitations of accelerated-aging protocols. The experimental data and mechanistic studies can be used to help identify key operational variables related to cable aging, optimize inspection and maintenance schedules to the most-susceptible materials/locations, and design tolerant materials in the out years.

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 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 5.2.3.2).
- **EnergySolutions** 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 in 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.

5.2.3.2 Nondestructive 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 includes 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. Continued research involves the development of a physics-based model for NDE signal response of compromised or degraded cables. This includes techniques for both global (long-length) cable NDE techniques such as frequency-domain reflectometry and local techniques such as interdigital spectroscopy. Recent activity included experimental testing and analysis of dielectric spectroscopy of aged low-voltage cables in FY 2019.

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 practices and issues.
- **Analysis and Measurement Services (AMS) Corporation** has supported the benchmarking of frequency-domain reflectometry measurements on common cable sets, providing the 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 DOE, EPRI, and NRC working group meetings. They are a resource for information on current cable NDE methods and issues for the 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.

5.2.4 Mitigation Technologies

Mitigation technologies involve the development of techniques, new technologies, 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.

5.2.3.1 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 in collaboration with EPRI 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.

Research is also focusing on weld process development and post-weld characterization. Detailed characterization of the welds is necessary to provide feedback on necessary weld parameter changes to assure weld quality and to determine the limits of these welding techniques for irradiated materials.

Confirmation of weld quality (cracking in the heat-affected zone due to helium-induced embrittlement) and weld properties (mechanical strength, microstructural stability) is necessary to gain industry acceptance.

Key interactions include the following:

- **EPRI** is collaborating in this multiyear 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.
- **Canadian Nuclear Laboratories** and the Materials Research Pathway initiated a collaboration in FY 2019. Modeling work associated with this effort will be used to support the optimization of welding parameters in order to minimize welding defects associated with high residual stress that may, in combination with heat, increase helium-bubble formation on grain boundaries.

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.

5.2.3.2 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). Void swelling, IASCC susceptibility, and decreased fracture toughness are the major concerns at high levels of radiation damage. However, most in-core structures consist of austenitic stainless steels, which are susceptible to degradation at a relatively low dose. The focus of this research is 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. The ultimate objective of the work is to select at least one low-strength and one high-strength alloy for future reactor core-internal support components and fasteners, respectively. The alloys that are emerging from this study offer the potential for greater safety margins and resistance to key forms of degradation at high fluences and long component lifetimes than are seen in the current generation of materials. Furthermore, it is anticipated that the EPRI/LWRS Program collaboration will continue with a focus on downselecting candidate alloys after assessing the effects of neutron irradiation on alloy mechanical properties.

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.

5.2.5 International 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,[1] 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 International Nuclear Energy Research Initiative (INERI) projects with KAIST on the aging of ASSW material, and the University of Bologna, Italy, on advanced nondestructive 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 that 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 cosponsorship of proposals through the Nuclear Science User Facilities 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 of minicompact 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.

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1. RILEM (http://www.rilem.org/gene/main.php)

6. PHYSICAL SECURITY

Physical security of nuclear power plants is an important aspect of maintaining a safe, secure, resilient, and reliable nuclear energy fleet. The events of September 11, 2001 saw changes to the design basis threat (DBT) and significant increases of physical security at nuclear power plant sites. As U.S nuclear power plants modernize their infrastructure and control systems and consider ways to enhance their physical-security postures, an opportunity exists to apply advanced tools, methods, and automation that leverage these modernizations and their benefits. These include higher-fidelity models that reduce conservatisms in security models, leverage automation as a force multiplier, optimize security postures, and leverage advances in risk-informed methods to evaluate physical security to achieve needed security postures. The requirements for U.S. nuclear power plants, after September 11, 2001, to maintain a large onsite physical-security force ranks high in comparison to other plant operational costs. Recently, one utility identified that 12% of the overall cost (~$560 million) for decommissioning their site is directly related to physical security.[2] U.S. nuclear power plants are seeking novel physical-security methods and technologies to help deliver on the Nuclear Promise. [3]

Regulatory requirements and associated guidance documents from the NRC prescribe what is required today to maintain a physical-security posture to protect against the DBT. However, there is insufficient technical knowledge to enable development of a rigorously optimized physical-security posture, which may potentially result in nuclear power plants adopting an overly conservative posture. This has significant economic consequences for utilities trying to compete in a complex energy market. Nuclear power plant stakeholders are engaged with the LWRS Program in collaborative R&D efforts to develop the technical basis (safety, security, and reliability) necessary to evaluate and consider potential changes in nuclear-facility security postures for use by the industry and the regulator. On March 21, 2019, the NRC held a public meeting on risk-informed security.[4] In this meeting, the NRC helped define risk-informed physical security and their intent to accept different ways to evaluate risk for physical security.

DOE and its national laboratories have extensively studied physical security to deliver detect, delay, and response capabilities to achieve physical security of nuclear assets. Additionally, they have extensive experience developing and using advanced computational tools and data sets that could provide benefit in developing a strong technical basis for physical security. The Physical Security Pathway seeks to create tools, methods, and technologies that will:

- Apply aspects of risk-informed techniques for physical-security decision making and activities to account for a dynamic adversary.
- Apply advanced modeling and simulation tools to better inform a physical-security posture.
- Assess benefits from proposed enhancements, novel mitigation strategies, and potential changes to regulations.
- Enhance the technical basis necessary for operating utilities to reevaluate their physical-security posture while meeting regulatory requirements.

6.1 Purpose, Goals, and Research and Development

The purpose for the Physical Security Pathway is to leverage, develop, and apply advanced methods, tools, and technologies to provide the technical basis for optimized plant-security postures. This may

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2 Pacific Gas & Electric Company, "PG&E Company 2018 Nuclear Decommissioning Costs Triennial Proceeding Prepared Testimony – Volume 1," December 13, 2018.

3 Nuclear Energy Institute, "Delivering the Nuclear Promise," 2016-2019 https://www.nei.org/resources/delivering-the-nuclear-promise

4 https://www.nrc.gov/pmns/mtg?do=details&Code=20190192

include reducing conservatisms in current postures to reduce security costs for the nuclear industry while maintaining necessary physical security. This effort will analyze the existing physical-security regime (regulations, personnel, technologies, etc.) and current best fleet practices, and compare insights derived from these activities with alternatives that leverage advanced modeling and simulation, modern security technologies, and other advanced techniques to optimize domestic nuclear power plant physical security. The primary deliverables would include: (1) validated methods that can be used to implement an updated physical security regime and optimize physical security at domestic nuclear power plants; (2) developing tools that create a robust risk-informed technical basis for physical security decisions by security stakeholders; (3) exploring and evaluating security architectures that incorporate technology to optimize human in-the-loop activities; and (4) implementing the results of this research into national consensus standards or other industry reference guides.

The goal of the physical security pathway is to develop and demonstrate an industry-wide strategy of sustaining a long-term, optimized, effective, and efficient physical security regime with significantly reduced financial and regulatory risks. Much of this work will leverage advances in technology such as advanced adversary-based risk-informed tools to minimize uncertainties for evaluating security effectiveness for use in making physical security decisions. This research will reduce current conservatisms in physical security postures resulting in potential reductions in required security posts.

Utilization of advances in technologies for lethal and non-lethal denial systems and advanced detection systems developed for use in Department of Defense and National Nuclear Security Administration (NNSA) sites could be applied to the nuclear security domain. An example of one technology being explored in 2020 includes the use of Remote Operated Weapons System utilized by other high-security facilities.

Other areas being explored include evaluating changes required to be implemented at nuclear facilities following the Fukushima Daiichi accident in 2011 for use in post attack response. These include exploring the use of on-site FLEX equipment that could mitigate the impact of a physical attack. By effectively leveraging FLEX equipment, operator actions, and off-site responders during or after an attack, the time between a successful attack and radiological release could be mitigated or prevented.

6.2 Collaborative Research and Development Activities

The Physical Security Pathway was established in October 2019 following a physical-security initiative to explore the challenges that the nuclear industry faces related to the cost of implementing physical security at nuclear utilities. Three stakeholder meetings have been held since January 2019 and through these meetings, physical-security R&D activities have been identified for and with U.S. nuclear utilities. The industry has been reliant on adapting physical-security R&D performed by the U.S. Government in other areas—specifically Department of Defense, DOE NNSA, and Department of Homeland Security—to their needs and has not had significant R&D performed specifically for their needs.

The Physical Security Pathway Working Group was established in 2019 and comprises nuclear enterprise physical-security stakeholders. The Working Group’s objectives are (1) to identify physical-security R&D needs and priorities; (2) to provide status updates on the Physical Security Pathway; and (3) to discuss the status of ongoing and future cost-shared R&D and other engagement activities. These working group meetings to date have included utilities representing almost two-thirds of all nuclear power plants in the U.S., NRC, NEI, EPRI, security vendors, and other DOE laboratories. The impact of establishing (or forming, assembling) this broad working group has been the ability to gain significant insight to stakeholder needs as well as sharing with them the Physical Security Pathway R&D efforts and results.

6.2.1 Advanced Technologies

The objective of this activity is to perform R&D and leverage previous results from other organizations (i.e., the Department of Defense or DOE-NNSA) that will enable the LWR fleet to incorporate advanced security technologies used in other high-consequence security environments. This can be achieved using lethal- and non-lethal-denial sensor technology incorporated into the LWR fleet physical-security posture. The application of advanced weapon technologies into LWR physical-security postures potentially provides significant force multipliers for the industry, thus enabling an optimized physical-security posture without negatively impacting required physical-security capability.

6.2.1.1 Remote Operated Weapon System

Use of advanced technology, such as remote operated weapon system, could potentially be a significant force multiplier. Adoption of these types of advanced technologies utilized by other government sectors has the potential to act as force multipliers that could potentially enhance a site's security posture while optimizing the mixture of manned security posts and advanced technology. Efforts are directed at (1) creating force-on-force models to understand the technology's impact on a utility's security posture, its potential impact on the required number of security posts necessary to implement the system, and how the information could be used in a cost-benefit model; (2) developing a safety basis for a system to be utilized at a nuclear facility.

Key interactions include the following:

- Engagement with a nuclear-utility site for potential use of the technology. Currently, a utility has self-identified as being interested in the technology and is supportive of a pilot project with the LWRS Program in this area.

The research outcomes will identify how to deploy a remote weapon system to optimize physical security postures for nuclear facilities. The results of this research will produce necessary information to support a demonstration. This effort will provide the nuclear industry with modeling tools necessary to design the system and develop the technical basis needed to realize the economic benefits of these advanced weapons.

6.2.2 Risk-Informed Physical Security

This refers to developing risk-informed approaches to physical-security topics for creating the technical basis in support of decision making. This area focuses on the development and demonstration of tools for creating risk-informed physical-security methods by utilizing dynamic risk methods, physics-based modeling and simulation, security personnel, non-security personnel actions, and the use of FLEX equipment. This also extends to adversarial timelines for response-force success. The tools are intended to enable commercial utilities to incorporate increased realism in their force-on-force models, take credit for operator actions and FLEX equipment, and move towards greater use of quantitative measures of performance in their security posture. Efforts in this will provide the technical basis to optimize a utility's security posture. This effort is intended to support the technical basis for physical- security postures at nuclear power plants.

Key areas of research identified to date in this area include:

- Develop and integrate tools for inclusion of non-security operator actions and the use of FLEX equipment into force-on-force models utilizing dynamic risk assessment tools.
- Develop performance measures of system effectiveness based on force-on-force modeling and dynamic risk assessment.
- Conduct research with tools that can be used to extend security-related timelines or improve accurate detection of an attack for use in developing dynamic risk tools.

Key interactions for this effort started in 2019 with several utilities offering to pilot results of this research in 2020. The research outcomes will create tools that help the industry risk-inform their security decisions. The results of this research will enable the utilities to benefit economically by removing unnecessary security posts while maintaining required security obligations.

6.2.3 Security-Cost Drivers

The objectives of this research are to identify utility and regulatory physical-security drivers impacting the economics of nuclear power plants, inform the Physical Security Pathway on areas that would benefit from R&D, and identify the near-term impact of R&D. This research will develop a generic security cost-benefit framework that can be used to inform the utility and the LWRS Program by incorporating the cost and organizational data obtained from utility collaborators as applied to a cost model.

Key interactions include the following:

- One utility has offered security-cost data for use in piloting the cost-benefit framework developed under this task.

The research outcomes will be used to produce a framework for evaluating the economic impact of physical security decisions. The results of this research will produce information to support a demonstration with a collaborating utility. This effort will provide nuclear power plants with a tool to evaluate the best economic security decisions while meeting their security commitments.